

# A Pitot-type Waterflow Sensor System for Biologging of Marine Animals

February 2026

Takuto Kishimoto

A Thesis for the Degree of Ph.D. in Engineering

A Pitot-type Waterflow Sensor System  
for Biologging of Marine Animals

February 2026

Graduate School of Science and Technology  
Keio University

Takuto Kishimoto

# Thesis Abstract

In this study, a Pitot-type waterflow sensor is proposed to measure the relative waterflow velocity of marine animals, a key indicator for evaluating swimming performance in biologging studies. Although various sensors have been used, relative waterflow velocity must be measured by attaching a flow sensor directly to the animal and has conventionally been obtained using propeller-type sensors. However, these sensors rely on moving parts, making them susceptible to suspended particles and biofouling and limiting stable long-term measurements. In addition, mechanical inertia limits temporal response, and additional moving parts required for multi-axis measurements reduce reliability.

Accordingly, this doctoral thesis presents the design and fabrication of a Pitot-type waterflow sensor without moving parts that enables high temporal resolution and multi-axis measurements. To demonstrate robust, high temporal resolution waterflow measurement under natural underwater conditions, a single-axis sensor was developed with the inlet covered by a membrane and an incompressible liquid sealed within the internal pipeline connecting the inlet to the differential pressure sensor element. The dynamic pressure generated by the flow is transmitted through the membrane and the sealed liquid to the sensor element, allowing measurement of the relative waterflow speed along the animal's forward direction. This structure prevents the intrusion of suspended particles and biofouling, suppresses sensor failure under hydrostatic pressure, and enables high temporal resolution owing to the absence of mechanical components.

Furthermore, to demonstrate the extensibility of the Pitot-type waterflow sensor to multi-axis measurements, a two-axis sensor was designed and fabricated by extending the single-axis concept. The two-axis configuration employs a spherical housing that incorporates three pairs of closed inlets and corresponding differential pressure sensor elements. Because the relationship between the surface pressure distribution and the flow velocity is nonlinear, a neural network was used to predict the waterflow velocity vector from the three sensor outputs. Training data were obtained in controlled water-tunnel experiments, and evaluation using independent datasets confirmed the effectiveness of the proposed multi-axis sensor architecture.

The fabricated sensors exhibited responses consistent with theoretical predictions and were shown to be suitable for biologging applications. Field experiments on wild loggerhead sea turtles demonstrated good agreement between the proposed single-axis sensor and a conventional propeller logger, while also enabling reliable low-speed measurements below 0.2 m/s and high temporal resolution capture of flipper-stroke-induced speed fluctuations. No clogging or malfunction due to suspended particles or biofouling was observed, indicating robust performance under natural underwater conditions. These results demonstrate that the developed Pitot-type waterflow sensor system enables stable, high-temporal-resolution measurement of relative waterflow speed and is extensible to multi-axis measurements for marine animal biologging.

# Table of Contents

|                                                                                               |           |
|-----------------------------------------------------------------------------------------------|-----------|
| <b>Table of Contents.....</b>                                                                 | <b>i</b>  |
| <b>CHAPTER 1. GENERAL INTRODUCTION.....</b>                                                   | <b>1</b>  |
| 1.1 PURPOSE OF THIS STUDY .....                                                               | 1         |
| 1.2 BACKGROUND AND PREVIOUS STUDIES .....                                                     | 3         |
| 1.2.1 Biologging research.....                                                                | 3         |
| 1.2.2 Biologging research of marine animals.....                                              | 5         |
| 1.2.3 Relative waterflow speed measurement in conventional biologging .....                   | 5         |
| 1.2.4 Conventional waterflow sensors .....                                                    | 8         |
| 1.3 PROPOSED METHOD FOR MEASURING RELATIVE WATERFLOW VELOCITY .....                           | 10        |
| 1.3.1 Design concept of the Pitot-type waterflow sensor.....                                  | 10        |
| 1.3.2 Extension to a two-dimensional waterflow sensor .....                                   | 11        |
| 1.3.3 Overview of the waterflow sensor system.....                                            | 13        |
| 1.4 SIGNIFICANCE OF THIS STUDY.....                                                           | 14        |
| 1.5 THESIS STRUCTURE.....                                                                     | 15        |
| <b>CHAPTER 2. Principle, Design, and Fabrication of the Pitot-type Waterflow Sensor .....</b> | <b>18</b> |
| 2.1 INTRODUCTION .....                                                                        | 18        |
| 2.2 SWIMMING OF THE LOGGERHEAD TURTLE .....                                                   | 18        |
| 2.2.1 Flipper-based locomotion of the loggerhead turtle.....                                  | 18        |
| 2.2.2 Sensor system requirements .....                                                        | 20        |
| 2.3 PROPOSED SYSTEM STRUCTURE.....                                                            | 23        |
| 2.3.1 Sensor system structure .....                                                           | 23        |
| 2.3.2 Pitot-type waterflow sensor structure .....                                             | 24        |
| 2.4 PRINCIPLE OF WATERFLOW DETECTION.....                                                     | 24        |
| 2.5 EFFECTS OF REYNOLDS NUMBER.....                                                           | 26        |
| 2.6 EFFECTS OF FLUID COMPRESSION ON SENSOR RESPONSE.....                                      | 28        |
| 2.6.1 Comparison of Membrane and Incompressible Fluid Deformation under Dynamic               |           |



---

Table of Contents

---

|                                                                                          |           |
|------------------------------------------------------------------------------------------|-----------|
| Pressure .....                                                                           | 28        |
| 2.6.2 Comparison of compression between incompressible liquid and compressible gas ..... | 31        |
| 2.7 EFFECTS OF HYDROSTATIC PRESSURE ON SENSOR RESPONSE.....                              | 32        |
| 2.7.1 Effect of hydrostatic pressure in the case with a compressible gas .....           | 33        |
| 2.7.2 Effect of hydrostatic pressure in the case with an incompressible liquid.....      | 36        |
| 2.7.3 Case considering the compression of an incompressible liquid .....                 | 37        |
| 2.8 EFFECT OF DYNAMIC PRESSURE DUE TO WATERFLOW ON SENSOR RESPONSE .....                 | 39        |
| 2.8.1 Effect of dynamic pressure in the case with a compressible gas.....                | 40        |
| 2.8.2 Effect of dynamic pressure in the case with an incompressible liquid.....          | 41        |
| 2.9 EFFECT OF TEMPERATURE CHANGE.....                                                    | 42        |
| 2.10 DISTURBANCES COMPENSATION .....                                                     | 48        |
| 2.11 DEVELOPMENT OF THE PITOT-TYPE WATERFLOW SENSOR .....                                | 50        |
| 2.11.1 Design of the pitot-type waterflow sensor.....                                    | 50        |
| 2.11.2 Design of the sensor circuit.....                                                 | 53        |
| 2.11.3 Fabrication process of the sensor .....                                           | 54        |
| 2.11.4 Bit-to-Voltage Conversion.....                                                    | 58        |
| 2.12 DEVELOPMENT OF LOGGING SYSTEM .....                                                 | 59        |
| 2.12.1 Design of the Ninja data logger.....                                              | 60        |
| 2.12.2 Fabrication of the Ninja data logger.....                                         | 61        |
| 2.12.3 Design of high time resolution (HTR) logger .....                                 | 62        |
| 2.12.4 Fabrication of a waterproof case for the HTR logger.....                          | 63        |
| 2.12.5 Design of the sensor case .....                                                   | 69        |
| 2.13 ENGINEERING NOVELTY OF THE PITOT-TYPE WATERFLOW SENSOR.....                         | 69        |
| 2.14 CONCLUSION .....                                                                    | 71        |
| <b>CHAPTER 3. Fundamental Characteristics of the Pitot-Type Waterflow Sensor .....</b>   | <b>72</b> |
| 3.1 INTRODUCTION .....                                                                   | 72        |
| 3.2 PRESSURE RESISTANCE TEST .....                                                       | 73        |
| 3.2.1 Experimental setup.....                                                            | 73        |
| 3.2.2 Experimental result .....                                                          | 74        |
| 3.3 CALIBRATION OF THE DIFFERENTIAL PRESSURE.....                                        | 75        |

---

Table of Contents

---

|                                                                             |                                                                                                                                        |            |
|-----------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------|------------|
| 3.3.1                                                                       | Experimental setup.....                                                                                                                | 75         |
| 3.3.2                                                                       | Experimental evaluation of the influence of membrane thickness and internal fluid on sensor sensitivity for differential pressure..... | 75         |
| 3.3.3                                                                       | Calibration of sensor P-R.....                                                                                                         | 79         |
| 3.3.4                                                                       | Calibration of sensor D.....                                                                                                           | 81         |
| 3.4                                                                         | DYNAMIC RESPONSE EVALUATION UNDER STEP PRESSURE INPUT.....                                                                             | 84         |
| 3.4.1                                                                       | Experimental setup.....                                                                                                                | 84         |
| 3.4.2                                                                       | Experimental result .....                                                                                                              | 85         |
| 3.5                                                                         | EVALUATION OF TEMPERATURE CHARACTERISTICS OF THE PITOT-TYPE WATERFLOW SENSOR .....                                                     | 86         |
| 3.5.1                                                                       | Experimental setup.....                                                                                                                | 87         |
| 3.5.2                                                                       | Experimental result of the sensor P-R.....                                                                                             | 87         |
| 3.5.3                                                                       | Experimental result of the sensor D .....                                                                                              | 90         |
| 3.6                                                                         | EVALUATION OF SENSOR RESPONSE TO ACCELERATION .....                                                                                    | 92         |
| 3.6.1                                                                       | Experimental setup.....                                                                                                                | 92         |
| 3.6.2                                                                       | Experimental results.....                                                                                                              | 93         |
| 3.7                                                                         | WATER TUNNEL EXPERIMENT .....                                                                                                          | 95         |
| 3.7.1                                                                       | Experimental setup.....                                                                                                                | 95         |
| 3.7.2                                                                       | Experimental result of sensor P-R.....                                                                                                 | 96         |
| 3.7.3                                                                       | Experimental result of sensor D .....                                                                                                  | 108        |
| 3.8                                                                         | VERIFICATION OF SENSOR PERFORMANCE AGAINST THE SENSOR SYSTEM REQUIREMENT ...                                                           | 113        |
| 3.9                                                                         | CONCLUSION .....                                                                                                                       | 114        |
| <b>CHAPTER 4. Multi-Inlet Two-Dimensional Waterflow Vector Sensor .....</b> |                                                                                                                                        | <b>116</b> |
| 4.1                                                                         | INTRODUCTION .....                                                                                                                     | 116        |
| 4.2                                                                         | SENSOR DESIGN .....                                                                                                                    | 117        |
| 4.2.1                                                                       | Sensor system requirement.....                                                                                                         | 117        |
| 4.2.2                                                                       | Design of the two-dimensional waterflow sensor .....                                                                                   | 120        |
| 4.3                                                                         | WATERFLOW VECTOR DETECTION PRINCIPLE .....                                                                                             | 121        |
| 4.3.1                                                                       | Theoretical analysis of the pressure distribution around a spherical sensor housing ..                                                 | 121        |
| 4.3.2                                                                       | Effect of the Reynolds number.....                                                                                                     | 125        |

---

Table of Contents

---

|                                                                                                   |                                                                                   |            |
|---------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|------------|
| 4.3.3                                                                                             | Construction of the neural network.....                                           | 127        |
| 4.4                                                                                               | DEVELOPMENT OF THE TWO-DIMENSIONAL WATERFLOW SENSOR .....                         | 129        |
| 4.5                                                                                               | EXPERIMENTAL PERFORMANCE EVALUATION OF THE TWO-DIMENSIONAL WATERFLOW SENSOR ..... | 132        |
| 4.5.1                                                                                             | Pressure resistance experiment.....                                               | 132        |
| 4.5.2                                                                                             | Calibration of the differential pressure.....                                     | 132        |
| 4.5.3                                                                                             | Water tunnel experiment.....                                                      | 134        |
| 4.5.4                                                                                             | Conversion to waterflow speed and angle.....                                      | 138        |
| 4.6                                                                                               | MULTI-INLET TWO-DIMENSIONAL WATERFLOW VECTOR SENSOR SYSTEM .....                  | 143        |
| 4.7                                                                                               | ENGINEERING NOVELTY OF THE TWO-DIMENSIONAL WATERFLOW VECTOR SENSOR .....          | 144        |
| 4.8                                                                                               | CONCLUSION .....                                                                  | 145        |
| <b>CHAPTER 5. Field and Experimental Validation of the Developed Waterflow Sensor System.....</b> |                                                                                   | <b>147</b> |
| 5.1                                                                                               | INTRODUCTION .....                                                                | 147        |
| 5.2                                                                                               | AQUARIUM EXPERIMENT FOR BIOLOGGING VALIDATION .....                               | 148        |
| 5.2.1                                                                                             | Experiment setup.....                                                             | 150        |
| 5.2.2                                                                                             | Experimental result .....                                                         | 152        |
| 5.3                                                                                               | ELECTRIC FISHING REEL EXPERIMENT .....                                            | 157        |
| 5.3.1                                                                                             | Experimental setup.....                                                           | 158        |
| 5.3.2                                                                                             | Experimental result .....                                                         | 159        |
| 5.4                                                                                               | SETUP OF A BIOLOGGING EXPERIMENT.....                                             | 166        |
| 5.4.1                                                                                             | Carapace tag.....                                                                 | 168        |
| 5.4.2                                                                                             | Towed tag .....                                                                   | 171        |
| 5.4.3                                                                                             | Timeline of the experiment and release of the sea turtle .....                    | 173        |
| 5.4.4                                                                                             | Recovery of the sensor system .....                                               | 177        |
| 5.5                                                                                               | RESULTS OF THE BIOLOGGING EXPERIMENT .....                                        | 179        |
| 5.5.1                                                                                             | Outputs of the various sensors.....                                               | 179        |
| 5.5.2                                                                                             | Preprocessing of Sensor Data.....                                                 | 183        |
| 5.5.3                                                                                             | Calculation of the waterflow speed .....                                          | 190        |
| 5.5.4                                                                                             | Results from the other three biologging trials .....                              | 197        |

---

Table of Contents

---

|                                                                                                                                         |            |
|-----------------------------------------------------------------------------------------------------------------------------------------|------------|
| 5.5.5 Cross-validation of the Pitot-type waterflow sensor against the Propeller logger using multiple sea turtle biologging trials..... | 203        |
| 5.6 CONCLUSION .....                                                                                                                    | 208        |
| <b>CHAPTER 6. Concluding Remarks .....</b>                                                                                              | <b>211</b> |
| 6.1 CONCLUSION .....                                                                                                                    | 211        |
| 6.2 IMPACT OF THE PROPOSED WATERFLOW SENSOR ON BIOLOGGING METHODOLOGY .....                                                             | 213        |
| 6.3 FUTURE PERSPECTIVES .....                                                                                                           | 215        |
| <b>Acknowledgments .....</b>                                                                                                            | <b>218</b> |
| <b>References .....</b>                                                                                                                 | <b>223</b> |
| <b>Appendix A Equipment.....</b>                                                                                                        | <b>231</b> |
| <b>Appendix B Water Tunnel Experiment of Sensor P-S .....</b>                                                                           | <b>236</b> |
| <b>Appendix C Supplementary Raw Sensor Data from the Biologging Experiments .....</b>                                                   | <b>239</b> |

# CHAPTER 1.

## GENERAL INTRODUCTION

### 1.1 Purpose of this study

---

The objective of this study is to develop Pitot-type waterflow sensor systems for biologging applications in sea turtles. Biologging is a research approach that investigates the behavior and physiology of wild animals by attaching miniature sensors and data loggers. It has been widely applied to marine animals such as penguins and sea turtles. Although various behavioral and physiological parameters have been measured using this technique, accurate evaluation of the swimming performance of marine animals requires measurement of their relative waterflow velocity, that is their velocity relative to the surrounding water.

Several methods have been used for these measurements, among which propeller-based waterflow sensors have been the most widely employed. However, propeller-based waterflow sensors have several limitations arising from their moving parts. They are highly susceptible to clogging by suspended particles and biofouling in marine environments, which restricts long-term operation. Their sensitivity can vary over time due to clogging or corrosion, leading to reduced measurement accuracy. The inertia of the moving parts limits the temporal resolution. In addition, achieving multi-axis measurements requires additional moving parts, which further reduces robustness and practical applicability. Thus, accurate measurement of relative waterflow speed requires a new sensing approach without moving parts. At the same time, marine animal biologging requires strict sensor system design requirements, including low mass, compact size, low power consumption, and robustness in

marine environments, which conventional waterflow sensors have struggled to meet simultaneously.

To address these challenges, this study proposes a new waterflow-sensing approach based on the Pitot-tube principle that does not rely on moving parts and is specifically designed to enable robust, high-time-resolution, and multi-axis measurement of the relative waterflow velocity of marine animals. First, a one-axis waterflow sensor based on the Pitot principle will be developed, in which a thin membrane is attached to the Pitot inlet and pressure is transmitted through a chamber filled with an incompressible liquid to a differential pressure sensor element. This configuration enables robust operation in natural environments by preventing clogging from suspended particles, while also maintaining stable sensitivity and enabling high-time-resolution measurements.

Next, the proposed sensor exhibits high extensibility to multi-axis measurements by increasing the number of inlets and sensing elements. To demonstrate this extensibility, a two-axis waterflow sensor will be designed and fabricated to measure both the magnitude and direction of waterflow velocity. The performance of this two-axis sensor will be evaluated through controlled water-tunnel experiments, and a neural-network-based estimation model will be constructed to estimate flow speed and direction from the measured pressure distribution.

Finally, the one-axis Pitot-type waterflow sensor will be integrated into a biologging system capable of autonomous underwater operation. Field experiments using wild loggerhead turtles (*Caretta caretta*) will be conducted to verify their performance in natural marine environments. These experiments will demonstrate that the proposed sensor system can accurately measure the turtles' relative waterflow speed with high temporal resolution, directly capturing fine-scale velocity fluctuations produced by individual flipper strokes.

Through these developments, this study aims to establish a new methodology for measuring the relative waterflow speed and direction of marine animals, contributing to a more detailed understanding of their locomotion and hydrodynamic behavior in the wild.

## 1.2 Background and previous studies ---

### 1.2.1 Biologging research

There have long been many challenges associated with studying the ecology of wild animals. Because wild animals tend to avoid humans and often inhabit environments that are difficult to access or observe directly, early behavioral studies were primarily conducted indoors or under controlled captive conditions. However, it remains unclear whether behavior observed under captive or otherwise artificial conditions are representative of those expressed by animals in the natural behaviors [1]–[3]. To truly understand their ecology, it is essential to study animal behavior in the wild, free from external constraints.

To address this need, a new research field known as biologging emerged, in which small data loggers composed of sensors and recording devices are attached to animals to collect information about their natural behaviors and surrounding environments [4], [5]. The earliest developments in biologging arose from efforts to quantify the diving behavior of free ranging marine animals using time depth recorders, commonly referred to as TDRs. The first TDR was created by modifying an ordinary mechanical kitchen timer [6]. Following this pioneering work, various types of analog TDRs were developed worldwide and applied to wild animals [7], [8]. Subsequent miniaturization and performance improvements in computer chips enabled a gradual transition from analog instruments to digital recording systems. As biologging devices evolved, recording duration increased and device size decreased [9]. At the same time, the number of measurable parameters expanded. As a result of these technological advances, biologging techniques were applied not only to marine animals but also to a wide range of animals, including flying birds [10], [11], terrestrial mammals [12], [13], and humans [14], [15]. Various types of sensors, including pressure sensors [6], [7], temperature sensors [16]–[18], speed sensors, accelerometers [19], [20], light sensors [21]–[23], cameras [24]–[26], acoustic sensors [27]–[29], magnetometers [30]–[32], electrodes [33]–[35], GPS devices [11], [36], [37], and conductivity sensors [38], have been employed in biologging studies, allowing the collection of diverse physiological and environmental data, as summarized in Table 1.1 [39]. By measuring these parameters, the natural behavior of many animals in the wild can be revealed. In addition, this approach enables quantitative investigation of behavioral metrics, such as stroke effort [40] and energy

Table 1.1 Sensors used in conventional [39].

| Sensor        | Measured Parameter                    | Information obtained                                                                |
|---------------|---------------------------------------|-------------------------------------------------------------------------------------|
| Pressure      | Depth (Water depth)                   | Diving depth, dive duration                                                         |
| Temperature   | Environmental temperature             | Water temperature, body temperature, stomach temperature (feeding timing)           |
| Accelerometer | Acceleration                          | Body motion, posture, stroke effort, behavioral state classification                |
| Speed         | Relative waterflow velocity           | Swimming speed, burst speed, cruising speed, locomotor performance                  |
| Light         | Ambient light intensity               | Illumination level, day length, sunrise-/sunset timing, horizontal position         |
| Camera        | Still image/video                     | Environmental context, prey information, foraging behavior, habitat use             |
| Acoustic      | Audible/ultrasonic signals, position  | Vocalization, sound-source localization, ambient soundscape characterization        |
| Magnetometer  | Geomagnetic field                     | Orientation, heading, turning behavior                                              |
| Electrode     | Bioelectric potential (EMG, ECG, EEG) | Muscle activity (EMG), heart rate variability (ECG), neural activity patterns (EEG) |
| GPS           | Geographic position                   | Location, migration route, movement path                                            |
| Conductivity  | Electrical conductivity               | Environmental salinity concentration                                                |

expenditure [41], that are difficult to assess solely through visual observation. As a result, this method has attracted considerable attention in biomechanics and related fields.

Among the many applications of biologging, its importance has been particularly evident in the study of marine animals, which are especially difficult to observe directly in their natural habitats. Consequently, biologging techniques have been extensively applied to marine organisms such as seals, penguins, and sea turtles to investigate their diving, swimming, and foraging behaviors [42].



### 1.2.2 Biologging research of marine animals

In marine animal biologging, a wide range of parameters has been recorded using diverse sensors, providing insight into various aspects of animal ecology. These applications range from documenting foraging behavior with cameras [26], [43] to monitoring underwater soundscapes with a hydrophone [29]. Although the ecology of marine animals remains only partially understood due to the difficulty of direct observation, recent advances in biologging have enabled quantitative analyses of behavior and gradually revealed their remarkable swimming capabilities.

For example, sea turtles have been shown to migrate across the Pacific Ocean [44], [45]. These outstanding swimming performances are thought to be achieved by efficiently using ocean currents, which allow animals to minimize energy expenditure during movement. Indeed, loggerhead turtles around Japan have been observed traveling along the Kuroshio Current [46]–[48], indicating that many marine animals effectively utilize oceanic flows to optimize swimming efficiency [49].

To quantitatively evaluate such swimming performance, it is essential to examine the relationship between the flipper strokes, representing energy expenditure, and the relative waterflow speed, defined as the animal's speed relative to the surrounding water (Fig. 1.1). Understanding this relationship is of great significance in the fields of biomechanics, fluid dynamics, behavioral science, and ecology.

### 1.2.3 Relative waterflow speed measurement in conventional biologging

In biologging studies, the most common approaches for detecting flipper strokes use

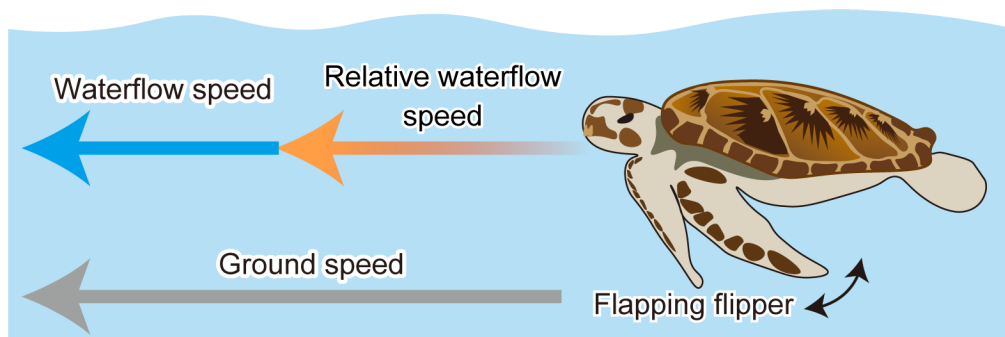


Fig. 1.1 Swimming of a marine animal and flapping flipper.

accelerometers and camera loggers. Aquatic animals such as sea turtles and penguins generate thrust by oscillating their flippers or hind limbs in a plane roughly perpendicular to their direction of travel, producing lift that is converted into forward propulsion. These movements are periodic in nature, and flipper strokes can be quantified by analyzing the cyclic acceleration signals recorded by an accelerometer attached to the animal's body trunk [20]. Another well-established approach uses camera loggers attached to the animal so the flippers remain within the field of view. By analyzing the recorded video footage, flipper strokes can be directly observed and quantified [50]. These approaches have been widely applied to various marine species, and they are now considered established and reliable methods for measuring flipper movements in biologging research.

Several methods have been developed to measure the relative waterflow speed of aquatic animals, including those based on acceleration and vertical velocity [51], methods for attaching the waterflow sensor to animals (fluid-flow noise analysis [52], [53], and miniaturized propeller (screw) sensors [54]).

The approach using acceleration and vertical speed estimates the swimming speed from the body pitch angle, which is calculated from the accelerometer outputs, and from the vertical speed derived from pressure data. This method yields an Earth-referenced speed estimate by reconstructing the animal's motion from depth changes and body pitch angle. Accordingly, the estimate can be interpreted as the relative waterflow speed, assuming that the surrounding current is negligible. In practice, the method has primarily been applied to deep-diving species, such as whales, which ascend and descend at steep angles. Because it captures only the vertical component of motion, it is unsuitable for species such as sea turtles that primarily swim in the horizontal plane.

To measure swimming speed components other than the vertical direction, a flow sensor must be attached to the animal. The method based on fluid-flow noise employs an acoustic sensor to record the sound generated by the surrounding waterflow and estimates the relative waterflow speed using an empirical correlation between the acoustic signal and flow speed. Although this approach does not require moving parts, it involves complex calculations and suffers from low measurement reliability and accuracy.

The propeller-type method estimates the relative waterflow speed from the rotational speed of a miniature propeller attached to the animal. Because it does not require

complex calculations and can be implemented in a compact data logger, this method has been applied to many animal species and is regarded as the most widely used approach for measuring relative waterflow speed in aquatic animals. On the other hand, its performance depends strongly on the mechanical precision of the rotating components. Because it relies on moving parts, degradation due to biofouling, marine debris, and corrosion is inevitable, making long-term measurements difficult. Furthermore, the propeller does not rotate at low swimming speeds, and its temporal response is limited by mechanical inertia, resulting in poor time resolution.

Using these methods, relative waterflow speed in marine animals has been measured, and swimming speed measurements in previous biologging studies have primarily focused on evaluating average swimming speed under steady swimming conditions. The methods described above that directly estimate relative waterflow speed, including propeller loggers and approaches based on fluid noise, generally calculate speed from either the average propeller rotation rate or spectral characteristics over a fixed time window. As a result, the obtained speed information is inherently time-averaged, making it difficult to capture instantaneous speed fluctuations with high temporal resolution. Furthermore, because propeller-based sensors have moving parts, they are easily affected by biofouling and marine debris intrusion, which hinder rotation and limit long-term, stable, continuous measurements. Because of these characteristics, swimming speed analyses in conventional biologging studies have tended to focus on time-averaged, quasi-steady speed components when viewed at the temporal scale.

In contrast, the actual swimming behavior of marine animals is not composed solely of such quasi-steady states. Speed variations occur over a wide range of time scales, from short-time-scale unsteady motions such as acceleration and deceleration associated with individual flipper strokes, to long-time-scale sustained swimming observed during movements such as migration. These motions are expected to contain essential information for understanding the swimming capabilities of marine animals. Therefore, it is important to obtain relative waterflow speed measurements that can consistently capture speed variation over a wide range of time scales, from short-time-scale fluctuations to long-time-scale variations.

In addition, marine animals exhibit complex and multidimensional movements,

including turning maneuvers [55], [56]. Such motions differ from simple forward swimming and represent unsteady, multidimensional swimming that involves changes in heading and lateral movement. Many biologging-based biomechanics studies have focused primarily on stable forward swimming. Nevertheless, the ability to change movement trajectory is closely associated with behavior such as foraging, predator avoidance, and obstacle avoidance, and therefore plays an important role in the survival strategies of marine animals [56].

These multidimensional swimming motions have been analyzed using motion-tracking methods based on fixed underwater cameras [56] or by reconstructing swimming trajectories using a combination of a single-axis propeller-type waterflow sensor, magnetometers, and inertia sensors [43], [55]. Camera-based approaches are difficult to apply in natural field environments. Moreover, methods relying on single-axis waterflow sensors can introduce errors during turning maneuvers, for example, due to sideslip angles, which cause mismatches between the measured velocity component and the actual direction of movement. Therefore, to evaluate such multidimensional swimming behavior, their relative waterflow velocity should be expressed as a multidimensional vector rather than a single scalar value. To analyze such swimming behavior in greater detail, it is important to measure the relative waterflow velocity in multiple dimensions, capturing both its magnitude and directional components.

In summary, existing methods for measuring relative waterflow velocity are limited in temporal resolution and robustness for long-term measurements, largely due to time-averaging procedures and the presence of moving parts. In addition, these approaches are insufficient for evaluating multidimensional swimming behaviors, such as turning maneuvers, in which velocity should be treated as a vector rather than a scalar. Consequently, there is a strong need for a waterflow sensor capable of high time resolution, long-term, and multidimensional measurements of relative waterflow velocity in marine animals. This doctoral thesis focuses in particular on high temporal resolution and multidimensional measurements.

#### 1.2.4 Conventional waterflow sensors

In addition to the measurement methods described in the previous section, several other types of flow sensors are commonly used for waterflow sensing, including hot-wire,

Table 1.2 Summary of the characteristic features of representative flow sensors

| Sensor                   | Propeller | Micro-<br>phone | Hot wire | Doppler | Electro-<br>magnetic | Pitot  |
|--------------------------|-----------|-----------------|----------|---------|----------------------|--------|
| Weight                   | light     | light           | light    | heavy   | heavy                | light  |
| Size                     | small     | small           | small    | large   | medium               | small  |
| Power consumption        | low       | low             | medium   | high    | high                 | low    |
| Measurement accuracy     | low       | low             | high     | high    | high                 | high   |
| Temporal response        | slow      | slow            | fast     | slow    | slow                 | fast   |
| Operational stability    | low       | high            | low      | high    | medium               | low    |
| Computational complexity | simple    | complex         | moderate | complex | complex              | simple |

Doppler, electromagnetic flowmeters, and Pitot tube. The characteristics of these waterflow sensors are summarized in Table 1.2.

The hot-wire flow sensor measures flow velocity based on the rate of heat transfer from a heated wire to the surrounding fluid, which depends on the fluid velocity. Variations in the electrical resistance of the wire, caused by temperature changes, are used to determine the flow speed [57], [58]. These sensors offer high responsiveness and can accurately measure fluctuating flow conditions. Because the wire must be continuously heated, the system consumes substantial electrical power, limiting its suitability for biologging applications where energy is limited.

The Doppler-type flow sensor determines flow velocity from the frequency shift of ultrasonic waves reflected by suspended particles or bubbles in water. For example, the Acoustic Doppler Current Profiler (ADCP) [59], [60] can measure three-dimensional flow velocity components. Its large size and heavy weight make it difficult to mount on animals, and its operation can generate acoustic signals that may disturb the surrounding marine environment [61], [62].

The electromagnetic flow sensor measures flow velocity by detecting the electromotive force induced when a conductive fluid passes through a magnetic field [63], [64]. This sensor provides stable measurements for conductive fluids and can also measure two-phase flows such as air–water mixtures [65]. Because it requires a hollow flow channel, it is susceptible to clogging and biofouling by suspended particles or marine organisms. In addition, generating the magnetic field requires continuous power consumption, which limits the sensor’s long-term usability in animal-borne applications.

### --- 1.3 Proposed method for measuring relative waterflow velocity ---

#### 1.3.1 Design concept of the Pitot-type waterflow sensor

Conventional methods and sensors for measuring relative waterflow velocity are unsuitable for application to marine animals under natural conditions, as described above.

When directly measuring the relative waterflow velocity of marine animals using a flow sensor, the device must accurately detect flow velocities of several meters per second and withstand the hydrostatic pressures of several megapascals encountered during deep dives. In addition, the sensor must be lightweight, structurally resistant to biofouling and suspended particles. Furthermore, to capture the fine-scale fluctuations associated with flipper strokes, a high temporal response is required.

To meet these demanding requirements, this study employs the Pitot-tube principle to measure the relative waterflow velocity of marine animals, as summarized in Table 1.2. The Pitot tube determines flow velocity by detecting the pressure generated by fluid flow using an internal pressure-sensing element. Because this method does not rely on mechanical moving parts, it is free from inertial effects and provides measurements with a high temporal response [66], [67].

However, marine animals such as sea turtles and penguins are air-breathing species that repeatedly surface and dive. Under such conditions, a conventional Pitot tube can allow air bubbles to enter through its opening during surfacing, thereby disturbing the internal pressure and degrading measurement accuracy [66], [68]. In addition, suspended particles and biofouling organisms in the water may also enter the tube, further hindering accurate pressure

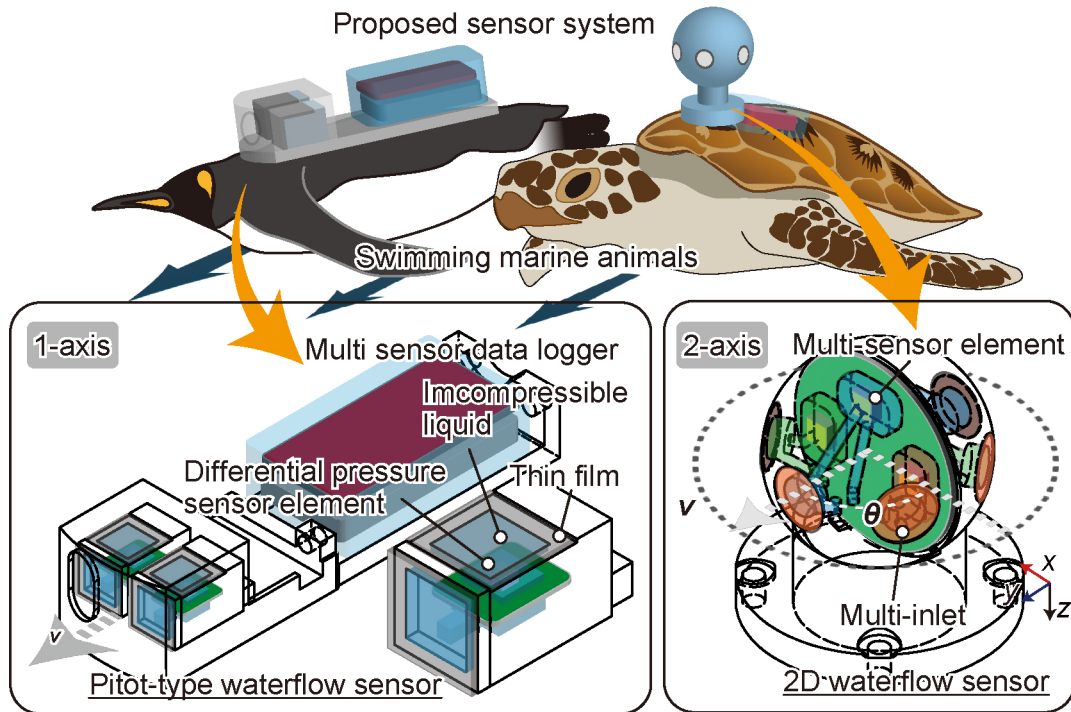


Fig. 1.2 Overview of the two types of proposed waterflow sensor systems.

measurement.

To overcome this issue, the present study proposes a one-axis Pitot-type waterflow sensor in which the Pitot tube is filled with an incompressible liquid and its inlet is sealed with a thin film (Fig. 1.2). The membrane prevents the intrusion of air bubbles and suspended materials, while the incompressible liquid inside the tube transmits external pressure to the internal sensor element. This design not only ensures accurate pressure transmission but also protects the sensing element from structural damage caused by hydrostatic pressure, enabling stable operation even during deep dives. Consequently, the proposed configuration enables reliable measurement of the animal's forward velocity in its natural underwater environment.

### 1.3.2 Extension to a two-dimensional waterflow sensor

Although the structure described in the previous section enables high-accuracy, high-temporal-resolution, and excellent-stability measurements, it can only measure a scalar quantity. This limitation arises because a conventional Pitot tube inherently measures only

the scalar component of flow velocity.

Recent studies have therefore focused on extending the Pitot-tube concept to detect not only the magnitude but also the direction of flow by increasing the number of inlets. Such approaches have been explored in both air and water, leading to the development of Pitot probes with diverse geometries. For airflow measurements, configurations such as five-hole hemispherical [69] and conical [70] probes, as well as cylindrical probes with three [71] or six [72] inlets and spherical probes with four inlets [73], have been investigated. For waterflow measurements, similar designs have been proposed, including hemispherical probes with five inlets [74] and cobra-type probes with three inlets [75].

These enhanced sensors estimate both flow speed and direction by comparing differential pressures across multiple inlets distributed across the probe surface. However, accurately detecting both parameters remains challenging because non-monotonic pressure gradients arise from flow separation and Kármán vortex shedding. In recent years, such complex nonlinear relationships have increasingly been addressed by integrating pressure sensors with machine learning techniques. In particular, highly accurate measurements of flow velocity and direction have been demonstrated by combining differential pressure sensors with polynomial regression models or neural networks (NNs) [76]–[79]. Thus, by increasing the number of inlets and sensing elements, Pitot-type waterflow sensors offer greater extensibility for multi-axis measurements, which is difficult to achieve with propeller-based waterflow sensors.

To demonstrate the extensibility of Pitot-type waterflow sensors to multi-axis measurements, this study focuses on two-dimensional swimming behavior among multidimensional swimming modes and proposes a closed multi-inlet two-dimensional (2D) waterflow vector sensor that is capable of capturing 2D swimming movements such as circling (Fig. 1.2). This sensor is equipped with multiple pairs of inlets on the surface of its spherical housing, and differential-pressure sensor elements corresponding to each inlet pair are embedded within the sensor. Furthermore, unlike conventional Pitot tubes with open inlets, each inlet of this sensor is sealed with a film. The tubes connecting the inlet to the internal differential pressure sensor element are filled with an incompressible liquid to ensure that the pressure applied to the inlet is transmitted to the internal sensor elements. As mentioned previously, the sealed design effectively prevents marine debris clogging and air



bubble intrusion. This makes the sensor suitable for marine biologging applications. In our previous study, we developed a 2D waterflow sensor that integrated a closed multi-inlet structure, two differential pressure elements, and polynomial regression [80]. However, the sensor had low accuracy because the number of explanatory variables was small. Moreover, the non-monotonic pressure distribution around the sensor could not be easily represented by polynomial regression. Therefore, we increased the number of sensor elements to three and employed a Neural Network (NN) that could better address complex nonlinear relationships than polynomial regression [77]. The speed and angle of the horizontal waterflow are predicted from the outputs of these differential pressure sensor elements using an NN-based regression model.

### 1.3.3 Overview of the waterflow sensor system

The objective of this study is to develop waterflow sensor systems capable of accurately measuring the relative waterflow velocity of sea turtles under natural underwater conditions. In particular, this doctoral thesis focuses on waterflow velocity sensors capable of measuring the relative waterflow speed of marine animals with high temporal resolution and multi-axis capability. Based on the Pitot principle, both a single-axis and a two-axis (2D) sensor are designed, developed, and experimentally validated.

The one-axis sensor incorporates the thin-film inlet and is filled with an incompressible liquid, preventing the intrusion of air bubbles and suspended particles and enabling reliable measurement of the forward (scalar) velocity component. The two-axis sensor extends this principle by increasing the number of inlet–sensor element pairs distributed over the sensor housing. By applying a neural network (NN) model to the differential pressure signals obtained from these multiple elements, the sensor can estimate both the magnitude and direction of the two-dimensional waterflow velocity. Through the development of this two-axis waterflow sensor, the high extensibility of the Pitot-type waterflow sensor to multi-axis measurements is demonstrated.

Furthermore, the developed one-axis flow sensor is integrated into a multi-sensor data logger to enable stand-alone underwater operation. This system is attached to a wild loggerhead turtle together with a conventional propeller logger, and comparative biologging experiments are conducted in natural marine environments to evaluate its performance under

natural conditions, including suspended particles and biofouling. The high temporal resolution of the sensor enables the detection of rapid flow fluctuations, such as velocity variations induced by flipper strokes, which conventional sensors have been unable to capture. These capabilities are experimentally demonstrated through field measurements presented in this study.

In summary, the main objectives of this doctoral thesis can be summarized into three points. First, the effectiveness of high temporal resolution waterflow measurements is demonstrated through biologging experiments using the single-axis Pitot-type waterflow sensor. Second, the measurement performance of the proposed sensor is quantitatively evaluated by comparing it with a conventional propeller logger. Third, the multi-axis capability of waterflow velocity measurement is demonstrated through the design and development of the two-axis Pitot-type waterflow sensor.

## 1.4 Significance of this study

---

The distinctive feature of this study lies in its development of novel sensors, designed from new principles to measure the relative waterflow velocity of marine animals. Rather than relying on existing technologies, this study introduces an entirely original system specifically created to address this long-standing challenge.

By directly measuring an animal's relative waterflow velocity, this approach allows a quantitative assessment of how marine animals exploit ocean currents, thereby providing new insights into their exceptional swimming performance. Moreover, by achieving multi-dimensional velocity measurements, the proposed method enables detailed analyses of complex swimming behaviors such as turning movements. In addition, the high temporal resolution enables the capture of short-time scale waterflow variations, including intra-stroke dynamics within individual flipper beats. Both types of measurements have been difficult to capture with existing techniques. Because relative waterflow velocity is also essential for estimating energy expenditure and reconstructing 3D swimming paths using dead-reckoning, the developed sensor system offers broad applicability beyond kinematic analysis.

In recent years, biologging studies have demonstrated that environmental fields surrounding animals can be inferred from behavioral data [18], [81]–[83], opening new

possibilities for extracting environmental information from behavioral data. By integrating the proposed sensor system with other biologging instruments, it becomes possible to obtain *in situ* measurements of ocean current velocities across a wide range of locations. Such data could serve as ground-truth observations for ocean data assimilation, thereby improving the accuracy of meteorological and oceanographic forecasts.

Furthermore, the proposed system represents a new waterflow-sensing platform capable of withstanding the harsh environmental conditions of underwater applications. Owing to its robustness, compact design, high temporal resolution, and multi-axis measurement capability, it can also be applied to a wide range of engineering domains, including underwater drone control, ocean observation buoys, and other marine sensing platforms. Accordingly, this research has the potential to make a significant impact not only in marine biology but also in ocean engineering, environmental monitoring, and advanced fluid-sensing technologies.

## 1.5 Thesis structure ---

This dissertation is organized as follows.

### **Chapter 1 General Introduction**

This chapter presents the objectives of this study and summarized the research background, relevant previous studies, and existing measurement approaches. It also introduced an overview of the proposed sensor system and discussed its distinctive features, originality, and significance.

### **Chapter 2 Principle, Design, and Fabrication of the Pitot-type waterflow sensor**

This chapter describes the principle, design, and fabrication of the one-axis Pitot-type waterflow sensor. First, the swimming characteristics of loggerhead turtles are analyzed to determine the sensor requirements. Next, the measurement principle of the waterflow sensor is established, and a physical model of the sensor is formulated. Based on the defined principle and design requirements, the waterflow sensor is then designed and prototyped accordingly.

### **Chapter 3 Fundamental Characteristics of the Pitot-Type Waterflow sensor**

This chapter presents an evaluation of the fundamental characteristics of the Pitot-type waterflow sensor. First, differential pressure is applied to the sensor, and the experimental results are compared with the predictions of the proposed physical model. Next, external disturbances such as water temperature and acceleration are introduced to verify that the proposed structure effectively reduces their influence on the sensor output. Finally, the sensor is exposed to a controlled waterflow, and an empirical equation for converting the sensor output to flow velocity is derived.

### **Chapter 4 Multi-Inlet Two-Dimensional Waterflow Vector Sensor**

This chapter presents the principle, design, and fundamental evaluation of the two-axis flow sensor. First, the physical model of the sensor is introduced, and the parameters governing the differential pressure distribution generated around the sensor are analyzed. Based on this theoretical model, a neural network (NN) is constructed to estimate waterflow speed and direction. A prototype sensor is subsequently fabricated, and water tunnel experiments are conducted under controlled waterflow speed and directions. The resulting data are then used to train the NN model, demonstrating that the fabricated sensor can accurately measure both flow speed and flow direction.

### **Chapter 5 Field and Experimental Validation of the Developed Waterflow Sensor System**

This chapter presents field measurements conducted using the Pitot-type waterflow sensor integrated into the biologging system. First, an aquarium experiment is performed to verify the correspondence between the sensor outputs and the swimming behavior captured in video recordings. Next, a calibration experiment is conducted using a motorized fishing rod on which both the proposed Pitot-type sensor and a conventional propeller logger are mounted. The outputs of the two sensors are compared to evaluate the accuracy of the proposed system. Finally, the complete sensor system is attached to a wild loggerhead turtle, and a biologging experiment is performed in a natural marine environment. The results demonstrate that the developed sensor system successfully measures the relative waterflow

velocity of marine animals under field conditions.

## **Chapter 6 Concluding Remarks**

This chapter summarizes the main findings of this study and discusses the conclusions and prospects.

## CHAPTER 2.

# Principle, Design, and Fabrication of the Pitot-type Waterflow Sensor

### 2.1 Introduction

---

In this chapter, the principles, design, and fabrication of the proposed Pitot-type waterflow sensor are described. First, based on the swimming characteristics of the target species, the loggerhead turtle (*Caretta caretta*), the expected flow conditions and environmental variations that may influence the sensor are identified, and the corresponding design requirements are defined. Next, the principle of waterflow speed measurement and the design process derived from these requirements are explained. Particular attention is given to sensitivity to dynamic pressure, disturbances caused by environmental factors such as temperature changes and acceleration, and the frequency characteristics associated with turtle flipper strokes. Finally, the fabrication of the sensor is presented in accordance with the design.

### 2.2 Swimming of the loggerhead turtle

---

#### 2.2.1 Flipper-based locomotion of the loggerhead turtle

In this study, the loggerhead turtle (*Caretta caretta*) was selected as the target

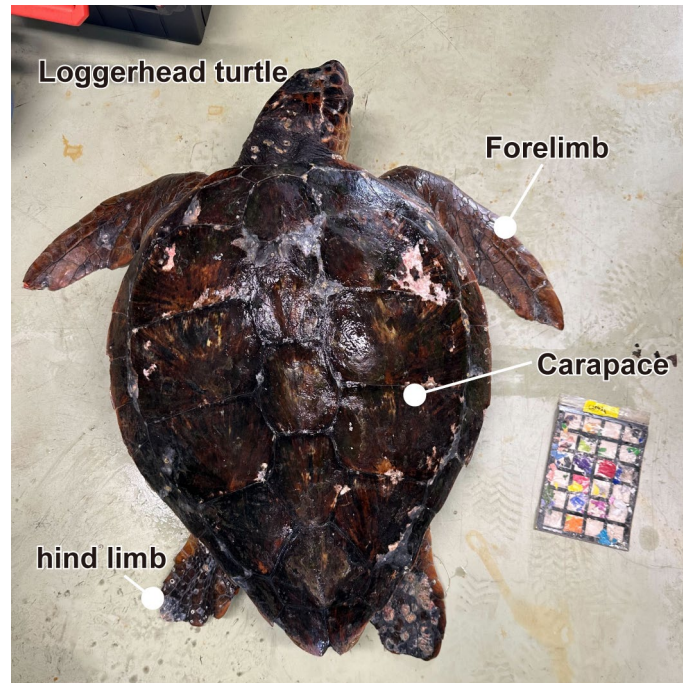


Fig. 2.1 Photograph of a loggerhead turtle (*Caretta caretta*)

species (Fig. 2.1). Sea turtles have a large, rigid carapace, and many biologging studies have been conducted on populations inhabiting the coastal waters of Japan. This feature makes sensor attachment comparatively easier than in other marine animals. Along the coast of Otsuchi, Iwate Prefecture, relatively large subadult loggerhead turtles are frequently captured in set-net fisheries [48]. Unlike adult females, which remain nearshore during the reproductive season and have been extensively studied, these subadults display diverse swimming behaviors. For these reasons, the Sanriku coastal area was selected as the experimental field, and loggerhead sea turtles incidentally captured along the Sanriku coast were considered the most suitable species as the target animal.

Loggerhead turtles swim by flapping their forelimbs in an up-and-down motion. By finely adjusting the angle of attack, the flippers convert lift into forward thrust, while the hind limbs are used primarily for posture control and steering. In sea turtle swimming, substantial thrust is generated primarily during the downstroke, whereas the upstroke contributes little to thrust generation [84] and is thought to be executed passively [85].

Depending on the situation, turtles alternate between active stroking and gliding, during which the flippers remain stationary. Stroking provides superior maneuverability and acceleration, whereas gliding represents an energy-efficient mode of locomotion. Loggerhead turtles adjust the balance between these two modes in response to oceanic conditions and behavioral objectives.

### 2.2.2 Sensor system requirements

The fundamental biological characteristics of target animals, loggerhead turtles along the Sanriku coast, and the corresponding sensor system requirements are summarized in Table 2.1. The sensor system needed to be sufficiently compact so as not to interfere with the animal's swimming [86]. Attaching tags to animals increases hydrodynamic drag and potentially raises energy expenditure. In bird tagging studies, increased weight and drag from tags may reduce the return rate of tagged birds [87]. To reduce these effects, the 5% rule has long been applied, recommending that tag mass be limited to less than 5% of the bird's body mass. This concept has also been widely adopted in tagging studies of terrestrial and aquatic animals. According to a quantitative bycatch survey conducted in the Sanriku region, the mean body mass of 152 loggerhead sea turtles incidentally captured in set nets between 2005 and 2010 was  $55.5 \pm 13.5$  kg (mean  $\pm$  SD) [48]. In this study, loggerhead sea turtles with body sizes commonly observed in the bycatch records from Otsuchi, corresponding to individuals around or above the mean body mass, were selected as target animals. Based on

Table 2.1 Characteristics of loggerhead turtles and sensor requirements

| Characteristics of loggerhead turtles |                    | Sensor requirement                |                   |
|---------------------------------------|--------------------|-----------------------------------|-------------------|
| Mean body mass [30]                   | $55.5 \pm 13.5$ kg | System mass                       | 2.8 kg            |
| Mean SCLn-t [30]                      | $70.8 \pm 6.4$ cm  | Frontal area                      | $20 \text{ cm}^2$ |
| Maximum diving depth [30]             | 340 m              | Allowable pressure                | 3.4 MPa           |
| Cruising speed [74]                   | 0.50 m/s           | Measurement range                 | 0–2.0 m/s         |
|                                       |                    | Resolution<br>(at cruising speed) | 0.01 m/s          |
| Flapping frequency[74]                | 0.20–0.36 Hz       | Response time                     | < 50 ms           |



this criterion, the allowable sensor system mass was set to approximately 5% of 55.5 kg, corresponding to about 2.8 kg, as a sensor system requirement.

For marine animals, the effect of tag mass is generally reduced by buoyancy, and the increase in overall hydrodynamic drag has a greater impact on swimming performance than tag mass itself [88], [89]. The effect of tag-induced drag on sea turtle swimming can be estimated from a tag shape (squared or tear-drop shaped), its frontal area (FA), and turtles' straight carapace length (SCL) [90]. According to the bycatch survey along the Sanriku coast, the mean straight carapace length notch to tip (SCLn-t) was  $70.8 \pm 6.4$  cm (mean  $\pm$  SD) [48]. Based on this result, the loggerhead turtles used in this study are planned to be selected to have an SCL of approximately 70 cm or longer. A practical framework for estimating the increase in tag-induced drag has been proposed by Jones *et al.* [90]. Following this approach, an SCL of 70 cm was assumed for the instrumented loggerhead turtle. Under this assumption, the frontal area of the attached tag required to limit the increase in drag force to within 10% of the baseline value was estimated to be 20 cm<sup>2</sup>.

In this study, biologging measurements are planned to be conducted using an auto-releasing system [91]–[93], which may introduce additional drag beyond that estimated for the sensor system alone. However, the present evaluation focuses specifically on the hydrodynamic impact of the sensor system itself, independent of the release system. The measurement duration is assumed to be on the order of several hours. Even if the total drag were to exceed the estimated value, it has been calculated that attaching an animal-borne tag that increases drag by up to 100% for three days would result in less than a 1% increase in the annual energy budget for sea turtles [94]. There is also report showing that even when a tag that increased drag by as much as 40% was attached to a sea turtle, the effect on the measured cruising swimming speed was small [95]. Compared with these reported cases, restricting the sensor frontal area to 20 cm<sup>2</sup> or less and limiting the measurement duration to several hours are expected to have a small effect on the instrumented turtles' overall energetic cost.

The Sanriku coastal region is an important foraging area for loggerhead sea turtles. In this region, loggerhead turtles do not exhibit a strong seasonal pattern in diving behavior and dive throughout the year. For this species, dives deeper than 340 m have been recorded, representing the deepest dives reported to date [48]. Therefore, in this study, the expected

maximum depth applied to the proposed sensor system was assumed to be 340 m, corresponding to a hydrostatic pressure of approximately 3.4 MPa.

Sea turtles exhibit slower cruising speeds than aquatic birds and mammals [95], [96]. The optimal swimming speed of sea turtles that minimizes the energy cost per unit time has been theoretically predicted to be in the range of 0.19–0.32 m/s, and measured cruising speeds of 0.27–0.50 m/s are generally consistent with this prediction [95]. Accordingly, sea turtles are expected to swim at speeds within this range under normal conditions. However, when turtles experience prolonged stress, they have been reported to swim at higher speeds than their typical cruising speeds immediately after release. In addition, aquatic animals generally exhibit a wide range of swimming speeds and stroke frequencies during both descent and ascent due to their buoyancy [97]. Furthermore, swimming animals for purposes other than locomotion do not necessarily swim at their cruising speed [98].

In this study, the cruising speed of sea turtles was assumed to be 0.5 m/s. To ensure the sensor system robustly captures occasional high-speed events, the measurement range was set to 0–2.0 m/s. This range corresponds to a four-fold margin relative to the assumed cruising speed and was adopted as a design margin. Because the proposed sensor is based on the Pitot-tube principle, its speed resolution depends on the magnitude of the measured waterflow speed. The sensor's speed resolution requirement was defined at cruising speed. The target speed resolution was set to 0.01 m/s at the cruising speed of 0.5 m/s, which is finer than the typical resolution of approximately 0.05 m/s reported for a conventional propeller logger (PD3GT, Little Leonardo Corporation, Tokyo, Japan).

Sea turtles swim by flapping their flippers, and the stroke frequency is theoretically expected to be proportional to the flipper reciprocation speed multiplied by  $m_b^{-1/3}$ , where  $m_b$  denotes the body mass of the turtle. In loggerhead turtles incidentally captured along the Sanriku coast, stroke frequency was described by  $0.491 \times m_b^{-0.131}$  and ranged from 0.20 to 0.36 Hz in biologging experiments [95]. Because the flipper stroke generates periodic thrust, the waterflow speed experienced by the sensor is not constant but is modulated at the stroke frequency and its higher harmonics. To accurately capture these temporal variations in waterflow speed, the sensor response time must be sufficiently shorter than the characteristic time scale of the stroke-induced waterflow fluctuations. Although the fundamental stroke frequency is on the order of 0.4 Hz, the resulting waterflow signal is not purely sinusoidal

and may contain higher-frequency components arising from rapid acceleration and deceleration within each stroke. Accordingly, a sampling rate of 20 Hz, approximately 50 times the fundamental stroke frequency, was adopted. This requirement translates to a sensor response time of 50 ms or less.

These requirements regarding measurement range, pressure resistance, and response time defined the design specifications of the sensor system.

## 2.3 Proposed system structure

### 2.3.1 Sensor system structure

The structure of the proposed sensor system is illustrated in Fig. 2.2 (a). The system comprises two Pitot-type flow sensors, a multi-sensor data logger, a battery, and a sensor case. All components were waterproofed and secured within a 3D-printed housing. The Pitot-type flow sensors directly measure the waterflow speed generated by the turtle's swimming, and the logger records these measurements together with data from the embedded inertial (Accelerometer and gyroscope), magnetometer, pressure, and temperature sensors. When attached to the carapace of a loggerhead turtle, the system enables simultaneous measurement of relative water speed, locomotion, and environmental conditions.

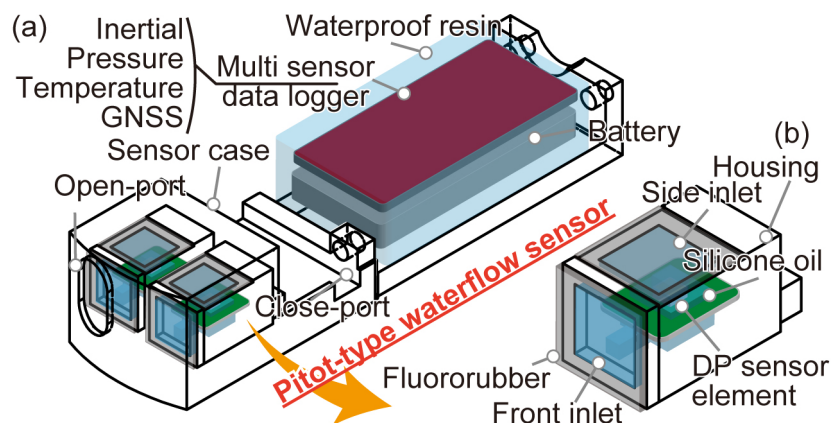


Fig. 2.2 (a) Schematic of the waterflow sensor system. (b) Structure of the Pitot-type waterflow sensor.

### 2.3.2 Pitot-type waterflow sensor structure

The structure of the Pitot-type waterflow sensor is shown in Fig. 2.2 (b). The sensor has a rectangular-like configuration with two inlets: a front (dynamic) inlet and a side (static) inlet. Although Pitot-type waterflow sensors with non-rectangular geometries were also developed, the fundamental principle is independent of the housing shape. Therefore, in the following section on design and principle, the sensor is assumed to have a rectangular shape housing for simplicity. A differential pressure sensor element is embedded inside the housing, and the pipelines connecting the ports to the sensor element are filled with an incompressible liquid, specifically silicone oil. A MEMS (Micro Electro Mechanical Systems) membrane-type differential pressure sensor was used as the differential pressure sensor element. As a result, the sensing element is much smaller than the inlet film. In addition, silicone oil was selected as the incompressible liquid because it is electrically insulated, non-volatile, and environmentally safe in the event of accidental leakage under natural conditions. Each inlet is covered with a thin film. Conventional Pitot tubes consist of open inlets. For proper operation, the tube must be filled with measured liquid without entrapped air bubbles, which requires careful and time-consuming preparation. In addition, when conventional Pitot tubes are used in harsh field environments with suspended particles or biofouling, clogging can occur within the tube, resulting in measurement failure.

In contrast, the proposed sensor incorporates a membrane at the inlet that prevents air bubbles and suspended particles from entering the interior. Simply attaching a membrane to the inlet would result in membrane failure under hydrostatic pressure. Therefore, the pipeline within the sensor is filled with an incompressible liquid that undergoes negligible volume change under pressure. The sealed incompressible fluid enhances the sensor's pressure resistance. As a result, the proposed sensor structure enables simple measurements with minimal operation and is suitable for deployment in field environments. This structural design makes the proposed Pitot-type waterflow sensor well-suited for biologging applications.

## 2.4 Principle of waterflow detection

---

The principle of flow speed detection by the proposed Pitot-type sensor is illustrated

in Fig. 2.3. The sensor consists of a rectangular housing with film-covered inlets located at the front and on the upper surface. The channels connecting these inlets to the internal differential pressure (DP) sensing element are filled with an incompressible liquid. The sensor operates on a similar principle as a conventional Pitot tube, in which flow speed is converted into pressure.

When waterflow impinges on the sensor, the front inlet receives both the dynamic pressure of the flow and the static pressure of the water. In contrast, the side inlet is subjected to static pressure and negative dynamic pressure induced by the sensor's geometry [99], [100]. As a result, a pressure difference is generated between the front and side inlets. This pressure difference is transmitted through the incompressible liquid to the membrane of the differential pressure sensing element, thereby allowing the sensor to detect flow speed. The dynamic pressure  $\Delta P$  generated by a flow with speed  $U$  can be expressed, according to Bernoulli's theorem, as

$$\Delta P = \frac{1}{2} \rho U^2, \quad (2.1)$$

where  $\rho$  is the fluid density. Thus, the relationship between the differential pressure measured by the proposed flow sensor and the flow speed is expected to follow a form similar to Eq. (2.1) such as  $\Delta P = a\rho U^2/2$ . Here,  $a$  is a dimensionless coefficient that accounts for the sensor geometry, because the side inlet can experience negative dynamic pressure and static pressure.

The physical model of the sensor differs substantially depending on whether the internal fluid is assumed to be incompressible or compressible. Filling the sensor interior with the incompressible liquid provides several performance advantages. To clarify the effects of the internal fluid properties, both incompressible and compressible models of the internal fluid are considered and discussed in Sections 2.5 and 2.6. By comparing these two

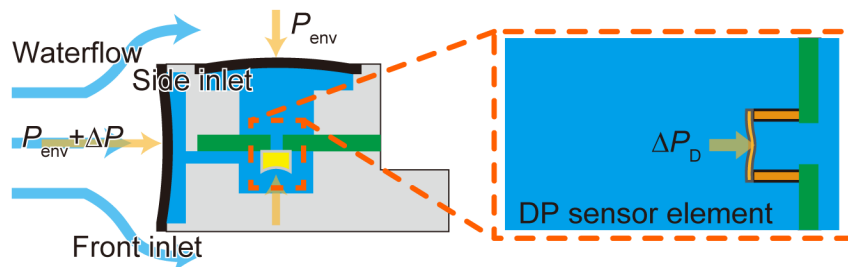


Fig. 2.3 Waterflow detection principle of the Pitot-type waterflow sensor

models, the advantages and necessity of using the incompressible liquid in the proposed sensor are theoretically demonstrated.

## 2.5 Effects of Reynolds number

---

The proposed Pitot-type waterflow sensor estimate the waterflow speed by utilizing the pressure increase (dynamic pressure) generated near the stagnation point at the sensor's front inlet, following  $\Delta P \propto \rho U^2$ . For Bernoulli's theorem to be valid, viscous effects in the flow field near the sensor front should be sufficiently small compared with inertial effects. Here, the normal stress exerted by the external fluid on the thin membrane at the sensor front is decomposed into an inertia-induced pressure scale (dynamic pressure) and a viscous stress scale. The required condition is then derived through an order-of-magnitude analysis.

Near the stagnation point at the sensor front, the flow decelerates from a speed  $U$  to zero. Accordingly, the representative scale of the dynamic pressure can be estimated as

$$\sigma_p \sim \frac{1}{2} \rho U^2. \quad (2.2)$$

For a Newtonian fluid, the viscous stress is proportional to the dynamic viscosity  $\mu$  and the velocity gradient  $\partial u / \partial x$ . In the vicinity of the stagnation point, if the characteristic length scale over which the velocity changes by  $O(U)$  is denoted by  $L_s$ , the velocity gradient can be estimated as  $\partial u / \partial x \sim U / L_s$ . Accordingly, the representative scale of the viscous stress is given by

$$\sigma_\mu \sim \mu \frac{U}{L_s}. \quad (2.3)$$

When the sensor geometry considered in this study is approximated as a rectangular prism (bluff body) facing the oncoming flow, the characteristic length scale over which the velocity recovers in the vicinity of the stagnation point is on the order of the representative body dimension. This representative length can be taken as the frontal width of the sensor, denoted by  $D$ . Accordingly, the characteristic length scale is expressed as

$$L_s \sim D. \quad (2.4)$$

To explicitly state the condition under which the viscous contribution is sufficiently small compared with the dynamic pressure, the ratio of the two stresses is evaluated as

$$\frac{\sigma_\mu}{\sigma_p} \sim \frac{\mu U / L_s}{\frac{1}{2} \rho U^2} = \frac{2\mu}{\rho U L_s} = \frac{2}{Re_{L_s}}. \quad (2.5)$$

Here,

$$Re_{L_s} = \frac{\rho U L_s}{\mu} \quad (2.6)$$

is the Reynolds number based on the characteristic length scale  $L_s$ . If the requirement is defined such that the systematic error due to viscosity (viscous contribution) is limited to a value no greater than  $\varepsilon$ ,

$$\frac{\sigma_\mu}{\sigma_p} \leq \varepsilon \quad (2.7)$$

then, from the above relation, this condition leads to

$$\frac{2}{Re_{L_s}} \leq \varepsilon \Rightarrow Re_{L_s} \geq \frac{2}{\varepsilon} \quad (2.8)$$

This inequality specifies the minimum Reynolds number required for viscous effects to be sufficiently small compared with the dynamic pressure. Here, by setting  $\varepsilon=0.05$ , allowing a viscous contribution of no more than 5%, the above condition becomes

$$Re_{L_s} \geq 40. \quad (2.9)$$

Furthermore, using the rectangular-bluff-body approximation, the characteristic length scale  $L_s$  can be taken as  $L_s \sim D$ . The minimum representative width  $D_{\min}$  required to ensure that the Bernoulli-type quadratic relationship does not break down at the minimum target flow speed  $U_{\min}$  can be expressed as

$$D_{\min} = \frac{Re_{\min} \mu}{\rho U_{\min}} = \frac{40\mu}{\rho U_{\min}}. \quad (2.10)$$

This expression provides a design criterion linking the minimum measurable flow speed to the sensor's characteristic frontal dimension. Here, the minimum target speed is set to a value near the cruising speed,  $U_{\min} = 0.50$  m/s. Using typical seawater properties,  $\rho \approx 1025$  kg/m<sup>3</sup> and  $\mu \approx 1.0 \times 10^{-3}$  Pa·s, the minimum representative width  $D_{\min}$  is estimated as

$$D_{\min} = \frac{40\mu}{\rho U_{\min}} \approx \frac{40 \times 1.0 \times 10^{-3}}{1025 \times 0.50} \approx 7.8 \times 10^{-5} \text{ m} \approx 0.08 \text{ mm}. \quad (2.11)$$

Thus,  $D_{\min}$  is on the order of  $10^{-4}$  m. This value is sufficiently small compared with the practical fabrication scale of the sensor. Furthermore, because Bernoulli's theorem holds

more accurately as the Reynolds number increases, viscous effects in the external flow do not constitute a primary limitation when the sensor dimension  $D$  is sufficiently larger than  $D_{\min}$ . Accordingly, the design space for the sensor dimension  $D$  can be conceptually expressed as

$$D_{\min} \ll D < D_{\text{animal}} \quad (2.12)$$

where  $D_{\text{animal}}$  denotes the upper bound imposed by animal-related sensor system requirement, such as frontal area. The sensor dimensions considered in this study are much larger than the minimum characteristic length  $D_{\min}$ , whereas the practical upper limit of the design is governed by the increase in hydrodynamic drag associated with animal-borne deployment. Therefore, for the speed range and sensor dimensions examined in this study, the minimum size constraint based on the Reynolds number, from the standpoint of the validity of the Bernoulli's theorem, is sufficiently relaxed. As a result, the primary design guideline is determined by requirements imposed by the animal to which the sensor is attached.

## 2.6 Effects of fluid compression on sensor response

---

### 2.6.1 Comparison of Membrane and Incompressible Fluid Deformation under Dynamic Pressure

Although the proposed sensor is filled with an incompressible liquid, such fluids undergo slight compression when subjected to pressure. To compare the compression of the internal fluid with the deformation of the membrane caused by dynamic and hydrostatic pressures, a simplified cylindrical chamber is considered, as illustrated in Fig. 2.4. The chamber is separated from the exterior by a membrane and filled with incompressible liquid. The chamber volume is denoted by  $V$ , the internal pressure by  $P_c$ , the membrane deformation by  $\Delta S$ , and the radial and vertical displacements from the membrane center by  $r$  and  $z$ , respectively.

When a membrane with radius  $a$  and thickness  $h$  is subjected to a pressure  $P$ , the deformation  $w$  of the membrane at a radial position  $r$  within an infinitesimal region is given by



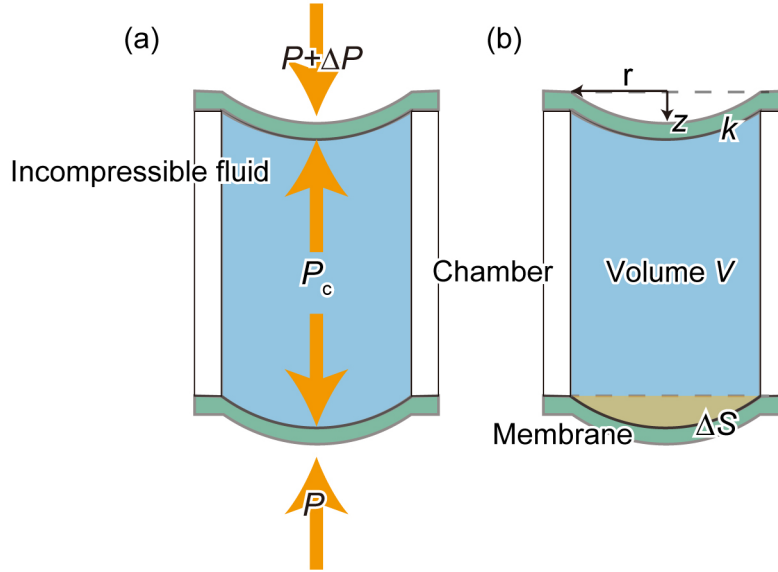


Fig. 2.4 Schematic of a chamber sealed by membranes on both sides, filled with incompressible fluid, and subjected to dynamic pressure.

$$w = w_0 \left( 1 - \frac{r^2}{a^2} \right)^2 \quad (2.13)$$

$$w_0 = \frac{Pa^4}{64D} \quad (2.14)$$

$$D = \frac{Eh^3}{12(1-\nu^2)} \quad (2.15)$$

Here,  $w_0$  denotes the displacement at the membrane center, and  $D$  is the flexural rigidity, a constant determined by the material properties and geometry of the membrane [101]. From Eq. (2.13), when pressure  $P$  is applied to the membrane, the total membrane deformation  $\Delta S$  is expressed as follows:

$$\Delta S = \pi \int_0^a r^2 dw \quad (2.16)$$

$$dw = \frac{Pa^4}{64D} \left( \frac{4r(r^2 - a^2)}{a^4} \right) dr \quad (2.17)$$

$$\Delta S = \pi \int_0^a r^2 \frac{Pa^4}{64D} \left( \frac{4r(r^2 - a^2)}{a^4} \right) dr = \frac{a^6 P \pi}{192D} = \frac{a^2}{3} \pi w_0. \quad (2.18)$$

From Eq. (2.18), the relationship between the central displacement of the membrane,  $\Delta z$ , and the applied pressure  $P$  can be expressed as

$$P = k\Delta Z, \quad (2.19)$$

$$k = \frac{64D}{a^4}. \quad (2.20)$$

which takes the form of an equivalent spring constant.

The relationship between pressure and the compressibility of the incompressible liquid (silicone oil) used in this study is shown in Fig. 2.5 [102]. Silicone oil exhibits a linear decrease in volume with increasing pressure up to approximately 20 MPa. Within this linear region, the change in chamber volume of the incompressible liquid,  $\Delta V$ , can be expressed as

$$\Delta V = \beta \Delta PV, \quad (2.21)$$

where the compressibility  $\beta$  depends on the type of fluid and the temperature. From the slope of the graph in Fig. 2.5, the compressibility of the silicone oil used in this study was calculated to be  $1.191 \times 10^{-4}$  at 25 °C. The compressibility of water is  $0.45 \times 10^{-9}$ , and silicone oil is more compressible than water. However, because of its additional advantages, including electrical insulation, non-volatility, and environmental safety, silicone oil was selected as the

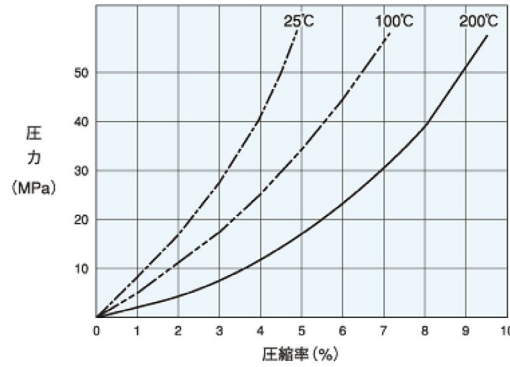


Fig. 2.5 Relationship between pressure and compressibility of the silicone oil used in this study (Shin-Etsu Silicone [102]).

Table 2.2 Deformation of the membrane and incompressible liquid under dynamic pressure (waterflow speed 2.0 m/s).

|                                                                |                                    |
|----------------------------------------------------------------|------------------------------------|
| Membrane deformation, $\Delta S$                               | $1.35 \times 10^{-8} \text{ m}^3$  |
| Incompressible liquid deformation (silicone oil), $\Delta V_c$ | $2.38 \times 10^{-11} \text{ m}^3$ |

incompressible liquid in this study. To compare the compression of silicone oil with membrane deformation under pressure, the variables of the defined chamber were set as

$$\begin{cases} V = 1.0 \times 10^{-5} \text{ m}^3 \\ r = 10 \text{ mm} \\ h = 1 \text{ mm} \end{cases} \quad (2.22)$$

And the Young's modulus  $E$  and Poisson's ratio  $\nu$  of the membrane were assumed to be close to those of the silicone rubber used in the actual sensor, namely

$$\begin{cases} E = 2.6 \text{ MPa} \\ \nu = 0.499 \end{cases} \quad (2.23)$$

When a flow speed of 2.0 m/s is applied to this chamber, the membrane deformation  $\Delta S$  due to dynamic pressure and the compression  $\Delta V_c$  of the silicone oil can be obtained from Eqs. (2.1), (2.18), and (2.21). The results are summarized in Table 2.2. The compression of the incompressible fluid was found to be more than 500 times smaller than the membrane deformation, indicating that membrane deformation is the dominant effect.

## 2.6.2 Comparison of compression between incompressible liquid and compressible gas

Next, the magnitude of the volumetric change due to compression is compared between an incompressible liquid and a compressible gas. As illustrated in Fig. 2.6, consider a chamber filled with either an incompressible liquid or a compressible gas subjected to an external pressure  $P$ . For the incompressible liquid, the volumetric change follows Eq. (2.21), whereas for the compressible gas, the relationship is governed by Boyle's law,

$$PV = \text{const.} \quad (2.24)$$

When a pressure of 1 MPa, equivalent to a depth of 100 m, is applied to a chamber with a volume of  $V=1.0 \times 10^{-5} \text{ m}^3$ , the volumetric changes  $\Delta V_c$  of silicone oil (incompressible liquid) and air (compressible gas) are obtained as summarized in Table 2.3. The change in silicone oil is more than 300,000 times smaller than that of air, indicating that the deformation of the compressible gas is overwhelmingly larger. Thus, the volumetric deformation of the incompressible liquid (silicone oil) is negligible compared with that of the membrane or compressible gas. Therefore, in this study, the incompressible liquid was assumed to remain undeformed, and its volume was treated as constant.

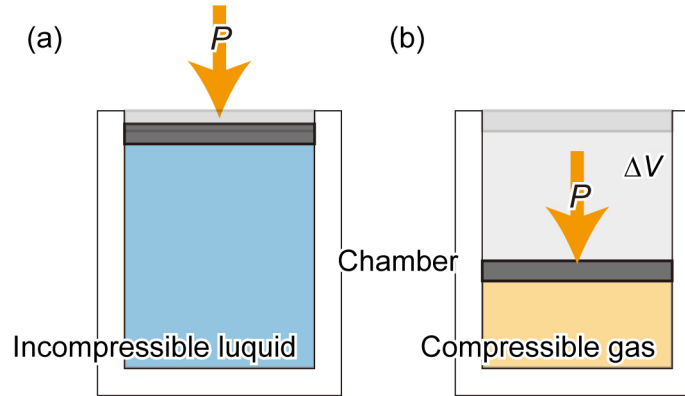


Fig. 2.6 (a) Deformation of an incompressible liquid and (b) deformation of a compressible gas under the same applied pressure.

Table 2.3 Comparison of volumetric deformation between an incompressible liquid and a compressible gas under applied pressure.

|                                                   |                                    |
|---------------------------------------------------|------------------------------------|
| Silicone oil (incompressible liquid) $\Delta V_c$ | $2.38 \times 10^{-11} \text{ m}^3$ |
| Air (compressible gas) $\Delta V_c$               | $0.909 \times 10^{-5} \text{ m}^3$ |

## 2.7 Effects of hydrostatic pressure on sensor response

The pressures applied to each membrane when the sensor is subjected to a hydrostatic pressure  $\Delta P_E$  are discussed below. As shown in Fig. 2.7, the sensor is approximated by a simplified cylindrical model with one dynamic inlet and one static inlet. For simplicity, the volume of front and side housing are both denoted as  $V$  and assumed to be equal. Under normal conditions, atmospheric pressure  $P$  is applied to both the top and bottom inlets.

As noted earlier, the physical model of the sensor differs substantially depending on whether the internal fluid is an incompressible liquid or a compressible gas. Therefore, the governing principles were derived for both cases, with the chamber filled either with incompressible liquid or with compressible gas.

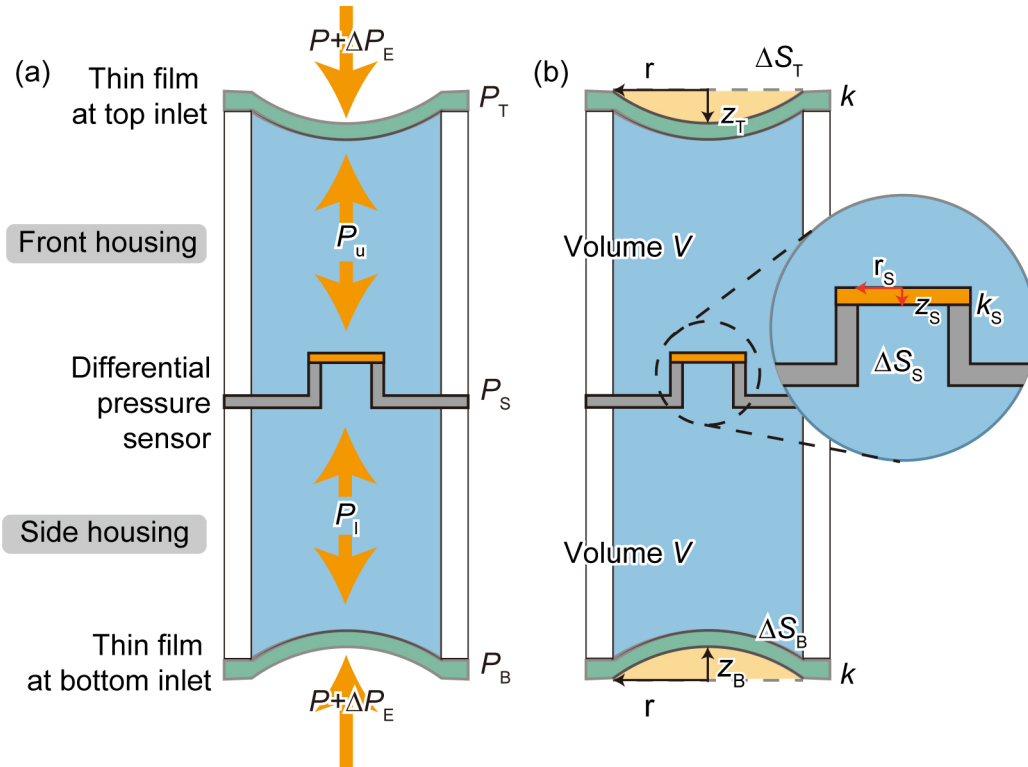


Fig. 2.7 Schematic diagram of a simplified cylindrical sensor with one dynamic inlet and one static inlet. (a) Pressure distribution around the sensor when static pressure is applied to the dynamic and static inlets, and (b) definition of membrane deformation.

### 2.7.1 Effect of hydrostatic pressure in the case with a compressible gas

The pressures applied to the membranes of the top inlet, bottom inlet, and sensing element can be expressed as

$$\begin{cases} P_T = (P + \Delta P_e) - (P + \Delta P_u) = \Delta P_e - \Delta P_u \\ P_S = (P + \Delta P_u) - (P + \Delta P_l) = \Delta P_u - \Delta P_l \\ P_B = (P + \Delta P_e) - (P + \Delta P_l) = \Delta P_e - \Delta P_l \end{cases} \quad (2.25)$$

Accordingly, from Eq. (2.7), the membrane deformations at the top inlet, bottom inlet, and sensing element are given by

$$\begin{cases} \Delta S_T = A_1 \cdot (\Delta P_e - \Delta P_u) \\ \Delta S_S = A_2 \cdot (\Delta P_u - \Delta P_l) \\ \Delta S_B = A_1 \cdot (\Delta P_e - \Delta P_l) \end{cases} \quad (2.26)$$

$$A_1 = \frac{1}{3} \cdot \frac{r^2}{k}, A_2 = \frac{1}{3} \cdot \frac{r_s^2}{k_s}$$

Since the chamber inside the sensor satisfies the Boyle's law described in Eq. (2.24), the relationship between the volumes of the front housing and the side housing can be expressed as

$$\begin{cases} PV = (P + \Delta P_u)(V + \Delta V_u) \\ PV = (P + \Delta P_l)(V + \Delta V_l) \end{cases} \quad (2.27)$$

Expanding Eq. (2.27) yields the following relationships:

$$\begin{cases} PV = PV + P\Delta V_u + \Delta P_u V + \Delta P_u \Delta V_u \\ PV = PV + P\Delta V_l + \Delta P_l V + \Delta P_l \Delta V_l \end{cases} \quad (2.28)$$

$$\begin{cases} \Delta V_u = -\frac{\Delta P_u}{P} V \\ \Delta V_l = -\frac{\Delta P_l}{P} V \end{cases} \quad (2.29)$$

The volume change of the front housing and side housing are also related to the membrane deformation as

$$\begin{cases} \Delta V_u = \Delta S_T - \Delta S_S \\ \Delta V_l = \Delta S_S - \Delta S_B \end{cases} \quad (2.30)$$

By substituting Eq. (2.29) into Eq. (2.30), the following relationships are obtained:

$$\begin{cases} \Delta P_u = \frac{P}{V} (\Delta S_S - \Delta S_T) \\ \Delta P_l = \frac{P}{V} (\Delta S_B - \Delta S_S) \end{cases} \quad (2.31)$$

Finally, substituting Eq. (2.26) into Eq. (2.31) gives

$$\begin{cases} \Delta P_u = \frac{P}{V} (A_1 \cdot (\Delta P_e - \Delta P_u) - A_2 \cdot (\Delta P_u - \Delta P_l)) \\ \Delta P_l = \frac{P}{V} (A_1 \cdot (\Delta P_e - \Delta P_l) - A_2 \cdot (\Delta P_u - \Delta P_l)) \end{cases} \quad (2.32)$$

By solving Eq. (2.32), the pressures inside each chamber can be determined.

$$\begin{cases} \Delta P_u = \frac{A_1 P}{A_1 P + V} \Delta P_e \\ \Delta P_l = \frac{A_1 P}{A_1 P + V} \Delta P_e \end{cases} \quad (2.33)$$

The equations for each chamber can be expressed as shown in Eq. (2.33). Since the pressure applied to the sensing membrane is the difference between the pressures in the two chambers, it becomes

$$\Delta P_S = \Delta P_u - \Delta P_l = 0 \quad (2.34)$$

which cancels out to zero. From Eq. (2.35), the pressures applied to the top and bottom inlets are expressed as

$$\begin{cases} P_T = \Delta P_e - \Delta P_u = \left(1 - \frac{A_1 P}{A_1 P + V}\right) \Delta P_e \\ P_B = \Delta P_e - \Delta P_l = \left(1 - \frac{A_1 P}{A_1 P + V}\right) \Delta P_e \end{cases} \quad (2.35)$$

Thus, even when hydrostatic pressure is applied, the differential pressure acting on the sensing element becomes zero, and the sensor does not respond to hydrostatic pressure.

Although no pressure is applied to the membrane of the sensing element, the membranes at the top and bottom inlets are subjected to the pressures given in Eq. (2.35). For example, consider a membrane at the sensor inlets with radius  $r = 1$  mm, thickness  $h = 0.5$  mm, Young's modulus  $E = 2.6$  MPa, and Poisson's ratio  $\nu = 0.499$ . When a pressure of 100 kPa is applied, Eq. (2.14) indicates that the membrane deflects by  $z = 0.294$  m. Such a large deformation would not normally occur in a practical membrane, indicating that the theoretical model considerably overestimates the actual displacement.

It should be noted that Eq. (2.13), which underlies the above principle, is valid only within the range of small membrane deformations. For cases involving large deflections as described above, the following expression applies [101].

$$w_0 = \frac{P a^4}{64D} \frac{1}{1 + 0.488 \frac{w_0^2}{h^2}} \quad (2.36)$$

The above equation accounts not only for the local (infinitesimal) deformation but also for the effect of the central displacement on membrane stiffness: as the membrane deflects further, additional deformation becomes increasingly difficult. Assuming, as before,  $w_0 = 0.294$  m, we obtain

$$\frac{w_0^2}{h^2} = \frac{0.294^2}{0.5 \times 10^{-3}} \quad (2.37)$$

By substituting Eq. (2.26) into Eq. (2.25), the expression can be approximated as follows.

$$w_0 = 0.00347 \frac{P a^4}{64D} \quad (2.38)$$

This allows the displacement of the membrane under a high applied pressure of 100 kPa to

be described. However, because the membrane undergoes large deformation, in the case of a model filled with a compressible fluid such as air, there is a potential risk of sensor damage.

### 2.7.2 Effect of hydrostatic pressure in the case with an incompressible liquid

When the chamber inside the sensor is filled with an incompressible liquid, the internal fluid does not deform under compression. Since the chamber volume remains constant, from Eqs (2.36) and (2.37), the following relationship holds:

$$\frac{1}{3}r^2 \frac{(\Delta P_e - \Delta P_u)}{k} = \frac{1}{3}r_s^2 \frac{(\Delta P_u - \Delta P_l)}{k_s} = \frac{1}{3}r^2 \frac{(\Delta P_e - \Delta P_l)}{k} \quad (2.39)$$

In the present sensor, a MEMS-based membrane-type differential pressure sensing element is used as the sensor element. The membrane of this element is much smaller than those of the inlets, and therefore the membrane size can be expressed as

$$r_s \ll r \quad (2.40)$$

which leads to

$$\frac{r_s^2}{r^2} \rightarrow 0 \quad (2.41)$$

Accordingly, the pressure components can be approximated as

$$\begin{cases} \Delta P_e \approx \Delta P_u \\ \Delta P_e \approx \Delta P_l \end{cases} \quad (2.42)$$

and the pressure applied to the sensing element becomes

$$\Delta P_s = \Delta P_u - \Delta P_l = 0 \quad (2.43)$$

Thus, as in the case with a compressible gas, the sensing element does not detect hydrostatic pressure. Furthermore, the pressures applied to the membranes of the inlets are given by

$$\begin{cases} P_T = \Delta P_e - \Delta P_u = 0 \\ P_B = \Delta P_e - \Delta P_l = 0 \end{cases} \quad (2.44)$$

Therefore, when the chamber is filled with an incompressible liquid, the pressure differences across the membranes also become zero, suggesting that the sensor will not be damaged even under high hydrostatic pressure.

By matching the chamber volume and the size of the membrane on the inlet, the effect of hydrostatic pressure on the sensor output can be theoretically cancelled, regardless



of whether the internal fluid is compressible or incompressible. However, when a compressible fluid is used inside the sensor, hydrostatic pressure induces deformation of the inlet membrane, which may lead to mechanical damage or failure. In contrast, when an incompressible liquid is used as the internal fluid, the effect of hydrostatic pressure on the membrane can be effectively canceled. As a result, use of the incompressible liquid inside the sensor greatly improves the pressure resistance of the sensor.

### 2.7.3 Case considering the compression of an incompressible liquid

In the previous section, the sensor's response to hydrostatic pressure was theoretically derived under the assumption that the incompressible liquid inside the sensor is perfectly incompressible. However, in an actual sensor, the liquid undergoes slight compression under pressure, and the sensor housing also experiences minor deformation. In addition, the sensor may deform under pressure for several reasons, including elastic deformation of the housing, volumetric change of internal oil, deformation of adhesive, and the presence of residual air trapped within the oil. As a result, phenomena that differ slightly from the theoretical model described earlier may occur. In this section, these effects are theoretically derived and analyzed in detail. As in the previous section, the following definitions are adopted. The external hydrostatic pressure is denoted as  $\Delta P_E$ , which is assumed to act equally on both the upper and bottom surfaces of the sensor. The internal pressures on the front and side chambers are denoted as  $\Delta P_u$  and  $\Delta P_l$ , respectively. Accordingly, the differential pressure applied to the pressure sensor is defined as

$$\Delta P_s = \Delta P_u - \Delta P_l \quad (2.45)$$

The bulk compressibility of the incompressible fluid sealed inside the sensor is defined as  $\beta$ , where the change in fluid volume is expressed as:

$$\Delta V_{\text{fluid}} = -\beta V \Delta P. \quad (2.46)$$

In this model, the sensor housing also deforms slightly under hydrostatic pressure. Therefore, the total deformation caused by water pressure, including both the housing and the membrane, is defined using volumetric compliance  $C$ . When the differential pressure between the exterior and interior  $\Delta P_E - \Delta P_l$  is applied, the geometrical volume changes by:

$$\Delta V_{\text{geom},i} = C_i(\Delta P_E - \Delta P_i). \quad (2.47)$$

where an increase in volume is taken as positive. The coefficient  $C_i$  is a constant determined by the material properties and geometry of the membrane and sensor housing, corresponding to the term  $A$  in Equation (2.26). The volumetric compliance combining the front housing and top inlet is defined as  $C_u$  and that combining the side housing and bottom inlet is defined as  $C_l$ . The compliance of the differential pressure sensor membrane is defined as  $C_s$ .

When hydrostatic pressure is applied to the sensor housing, the total volume change inside the front and side housings should theoretically be zero. In other words, the sum of the geometrical volume change of the housing  $\Delta V_{\text{geom}}$  (including the deformation of the housing and inlet membranes), the contribution of the sensor membrane  $\Delta V_{\text{dp}}$ , and the compression of the internal fluid  $\Delta V_{\text{fluid}}$  satisfies the following relationship:

$$\Delta V_{\text{geom}} + \Delta V_{\text{dp}} + \Delta V_{\text{fluid}} = 0. \quad (2.48)$$

In the front housing, the following relationship holds:

$$C_u(\Delta P_E - \Delta P_u) + C_s(\Delta P_u - \Delta P_l) - \beta V_u \Delta P_u = 0. \quad (2.49)$$

In the side housing, the following relationship holds:

$$C_l(\Delta P_E - \Delta P_l) - C_s(\Delta P_u - \Delta P_l) - \beta V_l \Delta P_l = 0. \quad (2.50)$$

Thus, the following simultaneous equations hold:

$$\begin{cases} J_u \Delta P_u + C_s \Delta P_l = \Delta P_E C_u \\ C_s \Delta P_u + J_l \Delta P_l = \Delta P_E C_l \end{cases}. \quad (2.51)$$

where  $J_u$  and  $J_l$  are defined as

$$J_u = C_u + \beta V_u - C_s, \quad J_l = C_l + \beta V_l - C_s. \quad (2.52)$$

By solving these simultaneous equations,  $\Delta P_u$  and  $\Delta P_l$  can be expressed as follows:

$$\Delta P_u = \frac{(C_u J_l - C_l C_s)}{(J_u J_l - C_s^2)} \Delta P_E \quad (2.53)$$

$$\Delta P_l = \frac{(C_l J_u - C_u C_s)}{(J_u J_l - C_s^2)} \Delta P_E \quad (2.54)$$

The pressure detected by the differential pressure sensor is given by Equation (2.45). Substituting the above expressions into this equation yields the following:

$$\Delta P_S = \frac{\beta(C_u V_l - C_l V_u)}{(J_u J_l - C_s^2)} \Delta P_E \quad (2.55)$$

In summary, the sensor's response to hydrostatic pressure can be expressed by the above equation. If the compliances of the housings and the volumes of the enclosed fluid are perfectly identical, the sensor can completely cancel out the effect of hydrostatic pressure. However, in practice, achieving perfect symmetry between these parameters is difficult. Therefore, the sensor output is expected to vary proportionally to a constant determined by the housing compliances, the enclosed fluid volume, the fluid compressibility, and the compliance of the differential pressure sensing element. Even if hydrostatic pressure is not perfectly canceled, the effect of hydrostatic pressure can be compensated by calculating the constant, and its influence can be substantially reduced through sensor design. By adopting the differential pressure configuration and using the incompressible internal liquid, the proposed sensor effectively suppresses the influence of hydrostatic pressure while remaining sensitive to the dynamic pressure generated by waterflow. Because the dynamic pressure is much smaller than the ambient hydrostatic pressure, this capability is particularly important for underwater waterflow sensing applications.

## 2.8 Effect of dynamic pressure due to waterflow on sensor response

The pressures acting on each membrane under the dynamic pressure  $\Delta P$  induced by waterflow are discussed below. Figure 2.8 shows the definition of pressure and deformation when flow is applied to a simplified cylindrical model of the waterflow sensor with one top inlet and one bottom inlet. As in the previous section, the volumes of the front housing and side housing are both denoted as  $V$  and assumed to be equal. Under normal conditions, an atmospheric pressure  $P$  is applied to both the top and bottom inlets. The membranes of the top and bottom inlets are assumed to be made of the same material, with identical thickness and dimensions. The physical model of the sensor varies significantly depending on whether the internal fluid is compressible or incompressible. Therefore, the principles were derived separately for two cases: one in which the chamber is filled with a compressible gas, and one in which it is filled with an incompressible liquid. By deriving models for both compressible and incompressible internal fluids, the advantages of using the incompressible liquid within

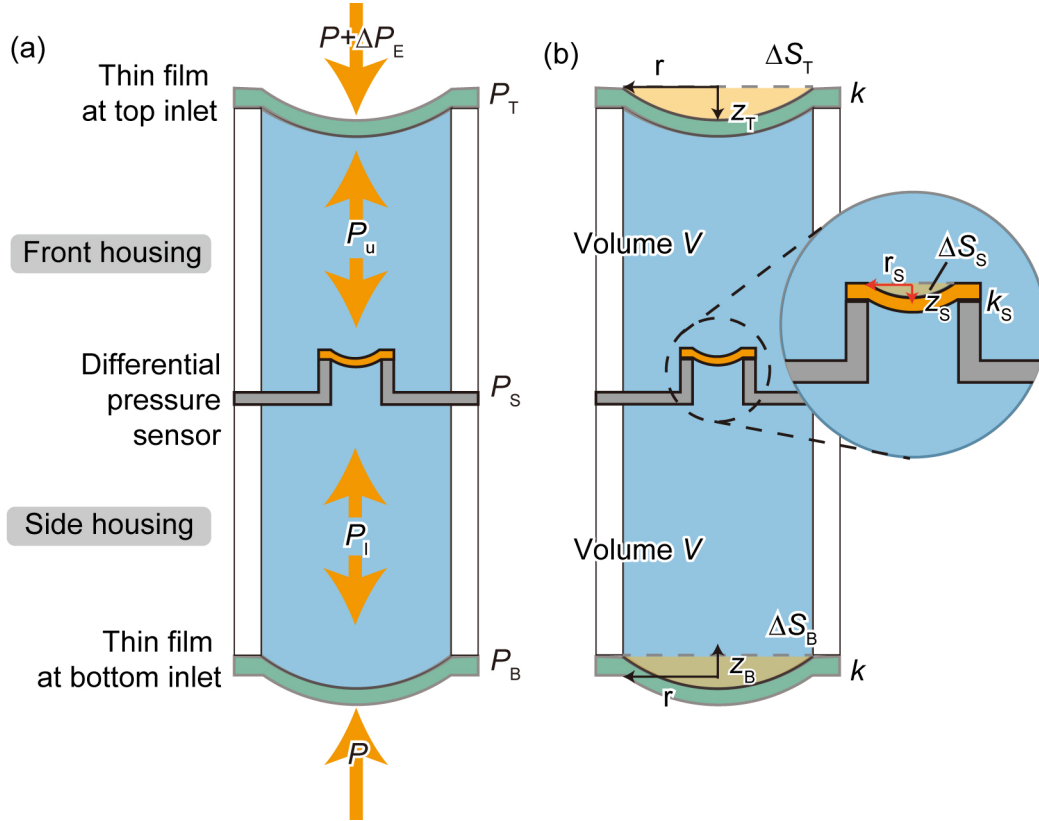


Fig. 2.8 Schematic of the waterflow sensor simplified as a cylindrical model. (a) Pressure distribution around the sensor under dynamic pressure induced by waterflow, and (b) definition of membrane deformation.

the sensor are demonstrated theoretically.

### 2.8.1 Effect of dynamic pressure in the case with a compressible gas

When a waterflow is applied to the sensor and the resulting dynamic pressure  $\Delta P$  acts on the top inlet, the chamber volume and the internal pressure vary as expressed in Eq. (2.26). The pressures applied to the membranes of the top inlet, bottom inlet, and sensing element can be written as

$$\begin{cases} P_T = (P + \Delta P) - (P + \Delta P_u) = \Delta P - \Delta P_u \\ P_S = (P + \Delta P_u) - (P + \Delta P_l) = \Delta P_u - \Delta P_l \\ P_B = (P + \Delta P_l) - P = \Delta P_l \end{cases} \quad (2.56)$$

From Eq. (2.27), the membrane deformations are expressed as

$$\begin{cases} \Delta S_T = A_1 \cdot (\Delta P - \Delta P_u) \\ \Delta S_S = A_2 \cdot (\Delta P_u - \Delta P_l) \\ \Delta S_B = A_1 \cdot \Delta P_l \\ A_1 = \frac{1}{3} \cdot \frac{r^2}{k}, A_2 = \frac{1}{3} \cdot \frac{r_s^2}{k_s} \end{cases} \quad (2.57)$$

Since the Boyle's law applies to each chamber of the sensor, Eq. (2.31) gives

$$\begin{cases} \Delta P_u = \frac{P}{V} (A_2 \cdot (\Delta P_u - \Delta P_l) - A_1 \cdot (\Delta P - \Delta P_u)) \\ \Delta P_l = \frac{P}{V} (A_1 \cdot \Delta P_l - A_2 \cdot (\Delta P_u - \Delta P_l)) \end{cases} \quad (2.58)$$

Since  $\Delta P_S$  is the difference between  $\Delta P_u$  and  $\Delta P_l$ ,

$$\Delta P_S = \Delta P_u - \Delta P_l = \frac{A_1 \cdot P}{(2 \cdot A_2 + A_1) \cdot P - V} \cdot \Delta P \quad (2.59)$$

represents the pressure acting on the sensing element. Eq. (2.59) indicates that  $\Delta P_S$  is influenced by the constant  $A$ , which characterizes the membrane. Thus, the sensitivity of the sensor varies depending on the material properties and thickness of the membranes.

## 2.8.2 Effect of dynamic pressure in the case with an incompressible liquid

When the waterflow sensor is filled with an incompressible liquid, the chamber volume remains constant, and consequently the deformations of all membranes must be the same. From Eq. (2.19), the membrane volume change can be expressed as

$$\Delta S = \frac{1}{3} r^2 \Delta Z = \frac{1}{3} r^2 \frac{\Delta P}{k} \quad (2.60)$$

Because the sensor is filled with an incompressible liquid, the deformations of the membranes at the top inlet, bottom inlet, and sensing element satisfy the relationship

$$\Delta S_T = \Delta S_S = \Delta S_B \quad (2.61)$$

Substituting Eq. (2.26) into Eq. (2.61) yields

$$\frac{1}{3} r^2 \frac{(\Delta P - \Delta P_u)}{k} = \frac{1}{3} r_s^2 \frac{(\Delta P_u - \Delta P_l)}{k_s} = \frac{1}{3} r^2 \frac{\Delta P_l}{k} \quad (2.62)$$

As mentioned earlier, the differential pressure sensing element used in this study is a MEMS device, and the membrane of the sensing element is much smaller than those of the inlets. Therefore,

$$r_s \ll r \quad (2.63)$$

$$\frac{r_s^2}{r^2} \rightarrow 0 \quad (2.64)$$

which leads to

$$\begin{cases} \Delta P_l \approx 0 \\ \Delta P \approx \Delta P_u \end{cases} \quad (2.65)$$

Substituting these relationships into Eq. (2.40), the pressure applied to the sensing element is obtained as

$$\Delta P_s \approx \Delta P \quad (2.66)$$

Thus, when the chamber is filled with an incompressible liquid and the inlet membranes are made sufficiently larger than that of the differential pressure sensing element, the pressure  $\Delta P$ s applied to the sensing element becomes equal to the pressure  $\Delta P$  at the top inlet. As a result, the sensor can measure waterflow speed without being influenced by the membrane properties, thereby preserving the intrinsic sensitivity of the sensing element.

The proposed sensor adopts the sensor package that incorporates membrane and oil. In general, for sensor packages employing membrane and oil, the sensor sensitivity is strongly influenced by the package structure. Therefore, the package and sensor element need to be jointly optimized. In contrast, the proposed structure employs a MEMS differential pressure element as the sensing element, while the inlet membrane is relatively large and connected to the sensing element through the oil-filled pipeline. Owing to this configuration, the overall sensor sensitivity is governed primarily by the characteristics of the sensing element rather than the package structure. Hence, the proposed design offers high flexibility, enabling the sensitivity and measurable waterflow speed range to be easily adjusted by changing sensing element without modifying the overall sensor structure.

## 2.9 Effect of temperature change

---

The proposed sensor exhibits drift in response to temperature variations due to the thermal expansion and contraction of the internal oil and the sensor housing. In this section, the effects of such temperature-induced drift are modeled, and design guidelines required to

mitigate these effects are derived. Temperature drift can be modeled as an apparent differential pressure generated at the differential pressure sensor element when the volume-balance condition between the two chambers is not perfectly maintained. This imbalance arises from thermal expansion of the internal liquid (silicone oil), thermal expansion and elastic deformation of the housing and membranes, and the finite compressibility of the internal liquid. In this section, a model similar to that shown in Fig. 2.7 is employed. In the previous section, the front and side housing and the membranes attached to their inlets were assumed to have identical volumes and properties. Here, these components are instead allowed to have different volumes and membrane characteristics. Under static conditions with no flow input (dynamic pressure input  $\Delta P=0$ ) and constant external pressure ( $\Delta P_E=0$ ), the differential pressure drift induced by a temperature change  $\Delta T$  is formulated by extending the compliance-based framework introduced in Section 2.7.3.

The volume change due to compression of the internal liquid is described by Eq. (2.46). In addition, the geometric volume changes arising from elastic deformation of the housing and the membrane are defined using Eq. (2.47). In addition, a volume balance condition expressed by Eq. (2.48) was imposed, requiring that the sum of the geometric volume change, the deformation of the differential pressure sensor diaphragm, and the volume change due to liquid compression be zero. To account for temperature variation, an additional term representing the volume change due to thermal expansion is introduced. For a temperature change of  $\Delta T$ , the volume change associated with the free thermal expansion of the internal fluid (silicone oil) in chamber  $i$  is given by

$$\Delta V_{T,\text{fluid},i} = \alpha_f V_i \Delta T \quad (2.67)$$

where  $\alpha_f$  is the volumetric thermal expansion coefficient of the internal fluid and  $V_i$  is the nominal internal volume of chamber ( $i = u$  (upper),  $l$  (lower)). Meanwhile, thermal expansion of the housing and the membrane also changes the geometric volume of the chamber itself. This effect can be represented using an effective volumetric thermal expansion coefficient  $\alpha_{g,i}$  as

$$\Delta V_{T,\text{geom},i} = \alpha_{g,i} V_i \Delta T. \quad (2.68)$$

After a temperature change, each chamber remains a closed system. The admissible volume change is therefore determined by how the excess volume generated by thermal expansion is

accommodated through liquid compression associated with an internal pressure change (Eq. (2.46)) and through geometric deformation of the chamber and membranes (Eq. (2.47)). Accordingly, extending the volume balance condition in Eq. (2.48) to include thermal effects yields, for each chamber,

$$\Delta V_{\text{geom},i} + \Delta V_{\text{dp},i} + \Delta V_{\text{fluid},i} + \Delta V_{T,\text{fluid},i} - \Delta V_{T,\text{geom},i} = 0. \quad (2.69)$$

Here, the additional terms explicitly account for the thermal expansion of the internal fluid and the chamber geometry. Here,  $\Delta V_{\text{geom},i}$  and  $\Delta V_{\text{fluid},i}$  are defined in the same manner as in the previous section as

$$\Delta V_{\text{geom},i} = C_i(0 - \Delta P_i) = -C_i\Delta P_i, \quad \Delta V_{\text{fluid},i} = -\beta V_i\Delta P_i \quad (2.70)$$

where, in this section, the external pressure difference is set to  $\Delta P_E = 0$ . In addition, the volume change of the differential pressure sensor diaphragm is introduced using the same sign convention as in Eqs. (2.49) and (2.50). Specifically, the diaphragm-induced volume change is expressed as  $+C_s(\Delta P_u - \Delta P_l)$  for the upper chamber, and  $-C_s(\Delta P_u - \Delta P_l)$  for the lower chamber. Using the above relations, the governing equation for the upper chamber (front housing) is obtained as

$$-C_u\Delta P_u + C_s(\Delta P_u - \Delta P_l) - \beta V_u\Delta P_u + (\alpha_f - \alpha_{g,u})V_u\Delta T = 0, \quad (2.71)$$

and for the lower chamber (side housing),

$$-C_l\Delta P_l - C_s(\Delta P_u - \Delta P_l) - \beta V_l\Delta P_l + (\alpha_f - \alpha_{g,l})V_l\Delta T = 0. \quad (2.72)$$

These two equations describe the pressure balance in the front and side housings under a temperature change  $\Delta T$ . Here,  $C_u$  and  $C_l$  denote the volumetric compliances that include both housing deformation and inlet membrane deformation for the front and side housings, respectively. When the radius and thickness of the top and bottom inlet membranes differ, these compliances are generally not equal. In particular, the volumetric compliance of a circular thin membrane is determined as a function of the membrane radius and thickness based on the membrane deformation theory introduced in the previous section (Eqs. (2.13)–(2.18)). Consequently, the geometric properties of the membranes contribute to the temperature-induced pressure drift through their influence on  $C_u$  and  $C_l$ . The apparent differential pressure detected by the differential pressure sensor is defined as



$$\Delta P_s = \Delta P_u - \Delta P_l \quad (2.73)$$

which follows the same definition as Eq. (2.45). For notational simplicity, following Eq. (2.52), the following quantities are defined:

$$J_u = C_u + \beta V_u - C_s, \quad J_l = C_l + \beta V_l - C_s. \quad (2.74)$$

Using these definitions, Eqs. (2.71) and (2.72) can be rewritten as the following system of linear simultaneous equations:

$$J_u \Delta P_u + C_s \Delta P_l = (\alpha_f - \alpha_{g,u}) V_u \Delta T \quad (2.75)$$

$$C_s \Delta P_u + J_l \Delta P_l = (\alpha_f - \alpha_{g,l}) V_l \Delta T \quad (2.76)$$

These equations describe the coupled pressure responses of the front and side housings under a temperature change  $\Delta T$ . Solving Eqs. (2.75) and (2.76) and substituting the solutions into Eq. (2.73), the differential-pressure drift induced by a temperature change can be written as

$$\Delta P_s = \frac{(\alpha_f - \alpha_{g,u}) V_u (J_l + C_s) - (\alpha_f - \alpha_{g,l}) V_l (J_u + C_s)}{J_u J_l - C_s^2} \Delta T \quad (2.77)$$

That is, to first order, the temperature drift is proportional to the temperature change  $\Delta T$ , and the proportionality coefficient is determined by the chamber volumes ( $V_u$  and  $V_l$ ), the volume compliances ( $C_u$ ,  $C_l$ , and  $C_s$ ), the liquid compressibility  $\beta$ , and the thermal expansion mismatch ( $\alpha_f - \alpha_{g,u}$  and  $\alpha_f - \alpha_{g,l}$ ).

From Eq. (2.77), if the sensor is perfectly symmetric such that

$$V_u = V_l, \quad C_u = C_l, \quad \alpha_{g,u} = \alpha_{g,l}, \quad (2.78)$$

the two terms in the numerator cancel each other, yielding  $\Delta P_s \approx 0$ . Consequently, the temperature drift is theoretically canceled. However, in practice, perfect symmetry is difficult to achieve because of manufacturing tolerances, the presence of adhesive layers, variations in the amount of encapsulated oil, nonuniform membrane thickness, and small differences in the elastic properties of the housing. Consequently, the proportionality coefficient in Eq. (2.77) is identified experimentally and used as a correction factor for temperature compensation in this study. On the other hand, Eq. (2.77) provides a basis for deriving design guidelines to reduce the temperature drift.

In this study, a soft and easily deformable rubber membrane is used for the inlet. As a result, the deformation of the housing body due to pressure is considered to be relatively small. Accordingly, for the previously defined relations

$$C_u = C_{\text{housing},u} + C_T \text{ and } C_l = C_{\text{housing},l} + C_B, \quad (2.79)$$

the following assumptions are introduced:

$$C_{\text{housing},u} \ll C_T \text{ and } C_{\text{housing},l} \ll C_B. \quad (2.80)$$

Under these assumptions, the chamber-side compliances can be approximated by the inlet membrane compliances, yielding

$$C_u \approx C_T \text{ and } C_l \approx C_B \quad (2.81)$$

Here,  $C_T$  denotes the volume compliance of the top inlet membrane, and  $C_B$  denotes the volume compliance of the bottom inlet membrane. The volume change  $\Delta S$  induced by the pressure difference  $P$  acting on the membrane is given by Eqs. (2.13)–(2.18). Therefore, the volume compliance of the membrane, defined as  $C_{\text{mem}} \equiv \Delta S / P$ , is given by

$$C_{\text{mem}} = \frac{\pi a^6}{192D} = \frac{\pi(1 - \nu^2) a^6}{16E h^3}. \quad (2.82)$$

This expression explicitly shows that the membrane compliance is proportional to  $a^6$  and inversely proportional to  $h^3$ . Accordingly, for the top inlet membrane (with radius  $a_T$ , thickness  $h_T$ , and material properties  $E_T$  and  $\nu_T$ ) and the bottom inlet membrane (with  $a_B$ ,  $h_B$ ,  $E_B$ , and  $\nu_B$ ), the following relations are obtained:

$$C_T = \frac{\pi(1 - \nu_T^2) a_T^6}{16E_T h_T^3}, \quad C_B = \frac{\pi(1 - \nu_B^2) a_B^6}{16E_B h_B^3}. \quad (2.83)$$

By substituting Eqs. (2.81) and (2.83) into Eq. (2.77) and rearranging, the temperature drift can be expressed as a function of the chamber volumes ( $V_u$  and  $V_l$ ) and the membrane compliances ( $C_T$  and  $C_B$ ). In addition, this study employs a MEMS differential pressure sensing element. Because the MEMS element is extremely small, its compliance is assumed to be negligible compared with that of the inlet membranes. Under this assumption, the relations can be approximated as

$$J_u \approx C_T + \beta V_u, \quad J_l \approx C_B + \beta V_l. \quad (2.84)$$

In this case, Eq. (2.77) can be approximated as

$$\Delta P_s \approx \left[ \frac{(\alpha_f - \alpha_{g,u})V_u}{C_T + \beta V_u} - \frac{(\alpha_f - \alpha_{g,l})V_l}{C_B + \beta V_l} \right] \Delta T. \quad (2.85)$$

By further substituting Eq. (2.83),  $\Delta P_s$  can be written explicitly in terms of the membrane radius and thickness as

$$\Delta P_s \approx \left[ \frac{(\alpha_f - \alpha_{g,u})V_u}{\frac{\pi(1 - \nu_T^2) a_T^6}{16E_T h_T^3} + \beta V_u} - \frac{(\alpha_f - \alpha_{g,l})V_l}{\frac{\pi(1 - \nu_B^2) a_B^6}{16E_B h_B^3} + \beta V_l} \right] \Delta T \quad (2.86)$$

This formulation makes it possible to directly interpret, from the equation, how the membrane dimensions ( $a$  and  $h$ ) influence the temperature drift. Each fractional term in this equation can be interpreted as the excess volume generated by a temperature change  $(\alpha_f - \alpha_{g,i})V_i\Delta T$ , divided by the volume compliance that can absorb this excess volume through a pressure change  $C_{\text{mem}} + \beta V_i$ . Accordingly, the following design guidelines can be derived.

The membrane compliance increases in proportion to  $a^6$ . Therefore, increasing  $a_T$  or  $a_B$  enlarges the denominator of each fractional term, thereby reducing the magnitude of each contribution to  $\Delta P_s$ . In other words, increasing the membrane radius is effective in reducing temperature drift. Similarly, because the membrane compliance is inversely proportional to  $h^3$ , decreasing the membrane thickness  $h_T$  or  $h_B$  increases  $C_T$  and  $C_B$ . This increase enlarges the denominator in Eq. (2.86) and consequently reduces the temperature drift. Thus, reducing the membrane thickness is also effective for suppressing temperature drift. Because  $V_u$  and  $V_l$  appear explicitly in the numerator of Eq. (2.86), the excess volume generated by a temperature change increases in proportion to the chamber volume. Therefore, in a design regime where the membrane compliance is dominant ( $C_{\text{mem}} \gg \beta V$ ),

$$\frac{(\alpha_f - \alpha_{g,i})V_i}{C_{\text{mem},i} + \beta V_i} \approx \frac{(\alpha_f - \alpha_{g,i})V_i}{C_{\text{mem},i}} \propto V_i. \quad (2.87)$$

This result clearly indicates that reducing the encapsulated volume is effective for lowering the temperature drift.

Because the temperature drift is observed as differential pressure, it is canceled when the responses of the front housing and the side housing are matched. In summary, the design guidelines for the proposed sensor are as follows. The front-housing side and the side-housing side should be made as symmetric as possible. In addition, the inlet membranes should be

designed to be large in radius and thin in thickness, and the volume of the encapsulated incompressible fluid should be minimized. Following these design steps is effective for suppressing the temperature drift.

## 2.10 Disturbances compensation

---

Thus far, the responses of the sensor to waterflow and hydrostatic pressure have been discussed. In addition to pressure variations caused by flow and hydrostatic pressure, the sensor system is also subject to disturbances arising from temperature changes, acceleration, and other environmental factors. The sensor exhibits temperature dependent responses because temperature change induces mechanical deformation of the sensor structure, thermal expansion and contraction of the internal oil, and deformation of the sensing element itself. When the sensor is subjected to vibration or acceleration, inertial forces acting on the internal fluid can also generate sensor responses, resulting in sensitivity to vibration induced disturbances. Furthermore, although Section 2.6 demonstrated that hydrostatic pressure is theoretically canceled, in practice the sensor housing undergoes strain under hydrostatic loading. As a result, the sensor does not achieve perfect cancellation and still responds to hydrostatic pressure. Therefore, the sensor system requires a mechanism capable of compensating for these disturbances.

Fig. 2.9 presents an overview of the sensor system. The system is equipped with two Pitot-type waterflow sensors: Pitot<sub>det</sub> (detection) for flow measurement and Pitot<sub>com</sub> (compensation) for disturbance compensation. Both sensors are housed in a case with separate compartments, and an open port is provided only at the front of Pitot<sub>det</sub>. Consequently, flow is applied only to Pitot<sub>det</sub>, while Pitot<sub>com</sub> is shielded from direct flow. Pitot<sub>det</sub> is therefore subjected to pressure variations from both flow and external disturbances, whereas Pitot<sub>com</sub> responds only to disturbances. The pressures applied to Pitot<sub>det</sub> and Pitot<sub>com</sub> can be expressed as:

$$\begin{aligned}\Delta P_{\text{Pitot}_{\text{det}}} &= \Delta P_{\text{flow}} + \Delta P_{\text{dis}} \\ \Delta P_{\text{Pitot}_{\text{com}}} &= \Delta P_{\text{dis}}\end{aligned}\tag{2.88}$$

By subtracting the two, the relationship becomes

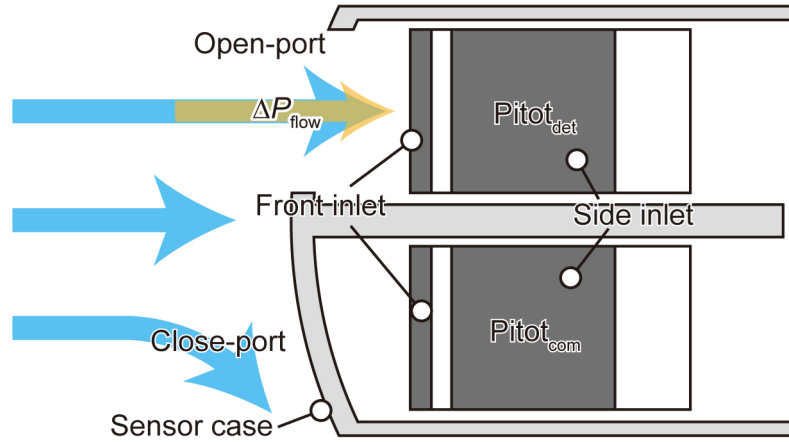


Fig. 2.9 Conceptual diagram of disturbance compensation in the waterflow sensor system (top view).

$$\Delta P_{Pitot_{det}} - \Delta P_{Pitot_{com}} = \Delta P_{flow} \quad (2.89)$$

In summary, by taking the differential output of the two Pitot-types waterflow sensors in the system, the effects of external disturbances can be reduced, enabling the sensor system to measure the flow accurately.

Unlike a conventional Pitot tube, the proposed sensor's inlet is covered with a membrane to prevent the intrusion of air bubbles and suspended particles. In addition, by employing the differential pressure element, the sensor can measure waterflow speed while effectively suppressing the influence of hydrostatic pressure. Furthermore, by combining the two Pitot-types waterflow sensors within the sensor case in which only one side has the open port, the influence of external disturbances can be further reduced. Previous study have demonstrated ocean current speed measurement using Pitot tube by employing two pressure sensors to compensate for external disturbances [66] Although this approach is effective for fixed and stationary waterflow sensors, it is difficult to apply animal-borne measurements, in which the sensor moves over wide areas and repeatedly crosses the sea surface. Under such conditions, air bubbles and suspended particles can strongly interfere with flow measurements.

In contrast, the proposed sensor system integrates the membrane covered inlets, the oil-filled internal pipeline, the sensor case with the large open port, the two Pitot-types

waterflow sensors. This configuration enables a new sensor system that can be mounted on freely moving marine animals while maintaining robust waterflow measurements under these challenging field conditions. The next chapter describes the fabrication process of the sensor system based on these structures and principles.

## 2.11 Development of the Pitot-type waterflow sensor

---

### 2.11.1 Design of the pitot-type waterflow sensor

As shown in Fig. 2.2, the Pitot-type waterflow sensor was designed with a rectangular body to facilitate fabrication and installation within the sensor case. In addition, for measurements conducted without the sensor case, streamlined housing was also designed to reduce hydrodynamic drag. The sensor has two types of inlets: a top inlet and a side inlet. A differential pressure sensing element is embedded between the housings, and the internal pipelines are filled with an incompressible liquid. Each inlet is covered with a thin film to prevent bubbles and suspended particles in seawater from entering the sensor. The incompressible liquid enclosed within the pipelines also ensures high pressure resistance. As noted earlier, because the inlet membranes are sufficiently larger than that of the differential pressure sensing element, the pressure measured by the element corresponds to the differential pressure between the inlets. Consequently, the sensor can measure waterflow speed without being influenced by the membrane properties. In this study, two types of Pitot-type waterflow sensors were developed:

- Sensor P (Package MEMS sensor type):** a Pitot-type waterflow sensor built using a commercially available packaged MEMS differential pressure (DP) sensor. To improve sensor reliability, a commercially packaged pressure sensor was employed.

Sensor P was developed in two housing configurations:

- **Sensor P-R (rectangular housing type):** designed for ease of fabrication and installation.
- **Sensor P-S (streamlined housing type):** designed to reduce hydrodynamic drag.

- Sensor D (MEMS sensor die type):** a Pitot-type waterflow sensor built using a MEMS DP sensor die, combined with a custom-designed substrate and additional components. By fabricating an internal differential pressure sensor board using a commercially available

differential pressure sensing element, the board can be optimized for the proposed waterflow sensor structure. This approach enables both high sensitivity and sensor miniaturization. The details of each design are described below.

The dimensions of the housing of Sensor P and Sensor D are shown in Fig. 2.10. Each housing consists of an upper part and a lower part. The housings were fabricated using a stereolithography 3D printer (Form 4 or Form 3, Formlabs Inc., Somerville, MA, USA). The front and side inlets of Sensor P-R have circular openings with a diameter of 15 mm. In Sensor P-S, the front inlet has an inner diameter of 10 mm, while each side inlet has an inner diameter of 8.91 mm. These dimensions were designed so that the total deformation of the

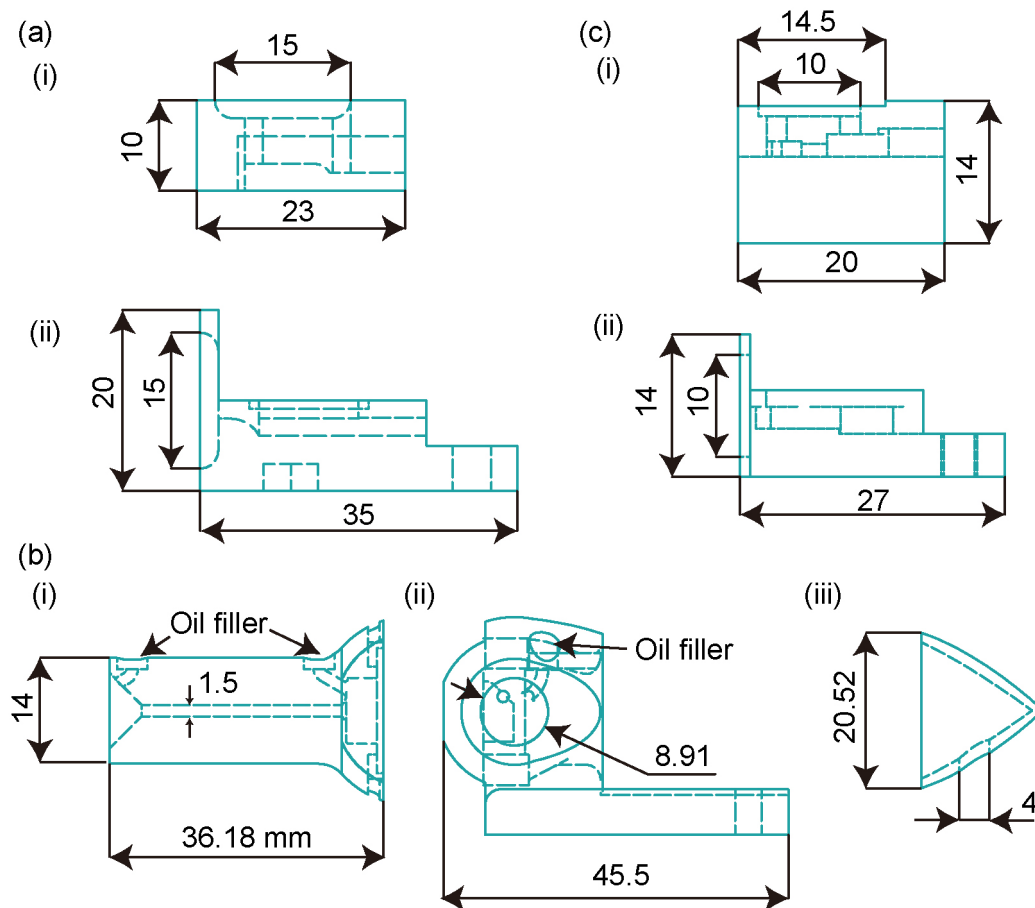


Fig. 2.10 Dimensions of the housings of the Pitot-type waterflow sensors. (a) Sensor P-R (packaged MEMS sensor type): (i) upper part and (ii) lower part. (b) Sensor P-S: (i) upper part, (ii) lower part, and (iii) cover part. (c) Sensor D (MEMS sensor die type): (i) upper part and (ii) lower part.

two-front inlets equals that of a single front inlet under the same applied pressure. In contrast, the inlets of Sensor D are square shaped with a side length of 10 mm. In addition, each housing is equipped with an oil inlet to allow filling with incompressible liquid. The incompressible liquid inside the sensor expands and contracts with temperature, producing pressure differences within the internal chambers.

Although an incompressible liquid (silicone oil) is sealed inside the sensor, it undergoes slight thermal expansion and contraction in response to temperature changes. This thermal volume change can induce a pressure imbalance between the upper and lower chambers, resulting in an offset in the differential pressure sensor output. In oil-filled differential pressure measurement systems, such temperature-induced drift is often a dominant source of output variation. Accordingly, minimizing temperature sensitivity was identified as a key design objective of this study. Specifically, to minimize the absolute volume change induced by temperature variations, the internal flow paths were designed with small diameters to reduce the volume of the enclosed liquid as much as possible. In addition, to increase the volumetric compliance of the inlet membrane and allow temperature-induced volume mismatch to be absorbed through elastic deformation, the inlet openings were designed to be as large as practically feasible. Larger openings lead to more compliant membranes, alleviating pressure changes caused by the thermal expansion of the enclosed liquid through membrane deformation and thereby suppressing temperature-induced drift.

These design considerations are also consistent with the selection of the rectangular sensor housing. The proposed sensor requires two types of inlets, namely a front inlet and a side inlet. From the standpoint of reducing temperature sensitivity, it is desirable for these inlets to have as large an opening area as possible. A rectangular housing provides flat surfaces for mounting inlets, allowing the inlet diameter or opening area to be maximized within a constrained overall sensor size. Moreover, to minimize the influence of environmental disturbances, such as temperature changes and hydrostatic pressure, it is advantageous to design the two chambers as symmetric as possible in terms of both volume and membrane properties. The simple geometry of a rectangular housing facilitates the realization of such symmetry. In addition, because disturbance conditions encountered in real marine environments, including temperature fluctuations, hydrostatic pressure, and changes in body orientation, cannot be predicted perfectly, maintaining a simple structural design is



beneficial for systematic factor separation, modeling, and the identification and calibration of residual drift. For these reasons, the Sensor D and Sensor P-R were designed with simple housing geometries. On the other hand, from a hydrodynamic perspective, streamlined shapes are generally preferable for suppressing flow separation and reducing drag. In environments where external disturbances such as temperature fluctuations and hydrostatic pressure variations are limited, for example, in controlled settings such as aquariums, hydrodynamic performance can be prioritized over structural simplicity. For such applications, a streamlined housing, designated as the Sensor P-S, was also designed.

The frontal area of Sensor P-R was approximately 400 mm<sup>2</sup>, that of Sensor P-S was approximately 550 mm<sup>2</sup>, and that of Sensor D was approximately 200 mm<sup>2</sup>. All frontal area were designed to be below the required frontal area limit, thereby minimizing hydrodynamic drag.

### 2.11.2 Design of the sensor circuit

For the internal sensing element of Sensor P, a commercially available MEMS DP sensor (ELVR-L30D-F1RJ-NI5F, Amphenol All Sensors Corporation, Morgan Hill, CA, USA), was employed. This sensor incorporates a MEMS diaphragm-type differential pressure sensing element, and internal signal processing converts the measured pressure into a 15-bit digital voltage value, which is output in I<sup>2</sup>C format.

In Sensor D, instead of employing a packaged pressure sensor, further miniaturization was pursued by using a commercially available MEMS sensor die (L1C-10K-RT, Merit Sensor Inc., South Jordan, UT, USA). A dedicated circuit was designed to convert the output of the sensor die into a voltage signal for measurement. The circuit diagram of the ADC (analog-to-digital converter) board used with the differential pressure sensor is shown in Fig. 2.11. The pressure sensor die is configured as a Wheatstone bridge. By supplying the bridge with a low-noise power source and measuring its output with the ADC, the analog signal from the sensor die is converted into a digital signal that can be output via I<sup>2</sup>C. Because no amplifier is employed in this circuit, the output voltage is very small (typically only a few tens of millivolts). However, the use of a 24-bit high-resolution ADC enables accurate measurement of this low-level signal. Avoiding the use of an amplifier not only eliminates amplifier-induced noise but also allows the circuit board size to be reduced. The components

used in this study are shown in Table 2.4. The sensor die was attached to the sensor board using epoxy adhesive, and the electrical connections were made by wire bonding. Furthermore, to enable monitoring of temperature variations within the sensor pipeline for compensation purposes, a temperature sensor (LM73CIMKX-1, Texas Instruments Inc.) was mounted on the backside of the pressure sensor die. The ADC used in the present circuit board was designed so that it's I<sup>2</sup>C address can be modified by changing the wiring configuration. In this implementation, the board was structured to allow two selectable I<sup>2</sup>C addresses.

2.11.3 Fabrication process of the sensor

The assembly procedure of the sensors is illustrated in Fig. 2.12. The overall assembly process was essentially the same for both sensor P and sensor D. The sensor housings were divided into upper and lower parts and fabricated using a stereolithography

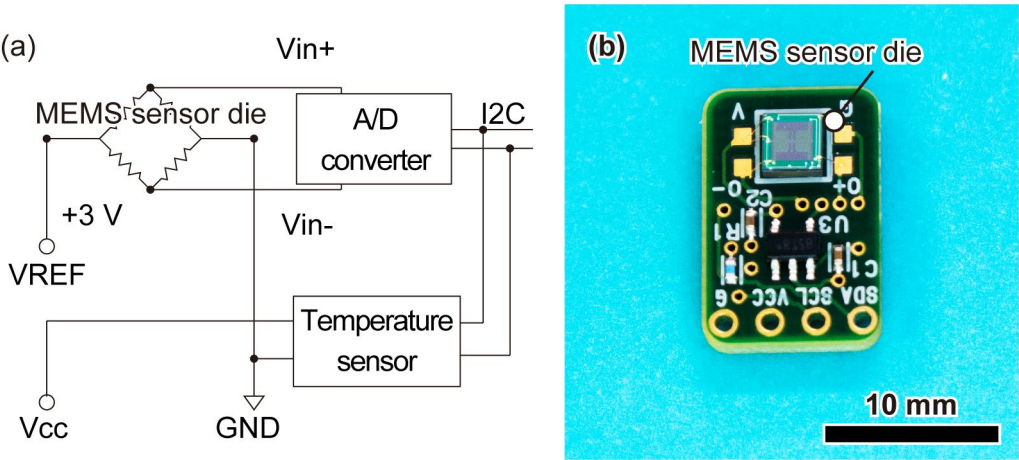


Fig. 2.11 (a) Circuit diagram of the differential pressure sensor ADC board, and (b) photograph of the fabricated board.

Table 2.4 Components used for the ADC board.

| Components used    |                                        |
|--------------------|----------------------------------------|
| MEMS sensor die    | L1C-10K-RT, Merit Sensor Inc.          |
| Vref               | LM4120IM5-3.0, Texas Instruments Inc.  |
| A/D converter      | ADS122C04IRTER, Texas Instruments Inc. |
| Temperature sensor | LM73CIMKX-1, Texas Instruments Inc.    |

(SLA) 3D printer (Form 4 or Form 3, Formlabs Inc., Somerville, MA, USA). Since SLA-printed structures contain residual volatile substances immediately after printing, post-curing was performed using a Form Cure unit at 50 °C for 6 hours to ensure complete hardening. After printing, fine irregularities caused by support structures remained on the housing surface. To achieve a smooth finish, the surfaces were polished using waterproof sandpaper and a polishing compound. Fluoro-rubber sheets with a thickness of 5 mm (Fluoro-rubber (FKM) sheet, Akitsu Co., Ltd., Tokyo, Japan) were attached to each inlet using an adhesive (Cemedine PPX, Cemedine Co., Ltd., Tokyo, Japan). In this study, sensor P employed a packaged MEMS differential pressure sensor (ELVR-L30D-F1RJ-NI5F, Amphenol All Sensors Corporation, Morgan Hill, CA, USA ), whereas sensor D utilized the custom-designed circuit board described in Section 2.9.2. For sensor P, the protective cover of the commercial sensor package was removed using an ultrasonic cutter to expose the internal sensing element as shown in Fig. 2.13. For sensor D, the bare MEMS sensor die was attached to the fabricated circuit board using epoxy adhesive (Quick 5, Konishi Co., Ltd., Osaka, Japan), and electrical connections were made via wire bonding. Finally, for both sensor P and sensor D, the electrical wiring was soldered, and the sensor boards were bonded between the upper and lower housings using the epoxy adhesive.

After assembly, silicone oil (HIVAC F-4, Shin-Etsu Chemical Co., Ltd., Tokyo, Japan) was filled inside the sensor through the oil inlet located at the rear of the housing as the incompressible liquid. Silicone oil was selected because it is a non-volatile liquid, which prevents evaporation inside the sensor. In addition, it is non-corrosive to electronic components, environmentally safe even in the event of accidental leakage, and has sufficiently low vapor pressure to allow subsequent vapor deposition processes. To remove microbubbles trapped in the oil, degassing was first carried out for several days using a vacuum desiccator. Since the vacuum level of the desiccator was insufficient, a higher-vacuum degassing process was subsequently performed for approximately one day using the degassing unit of the parylene deposition system. After degassing, the oil filler was cleaned with ethanol, and the entire sensor was coated with a parylene film. The coating process was known as PoLD (Parylene on liquid deposition) [103], [104] and carried out under vacuum, during which vaporized parylene monomers condensed on the sensor surface to form a uniform thin film. Since the coating was deposited directly on the oil layer at the oil inlet, a

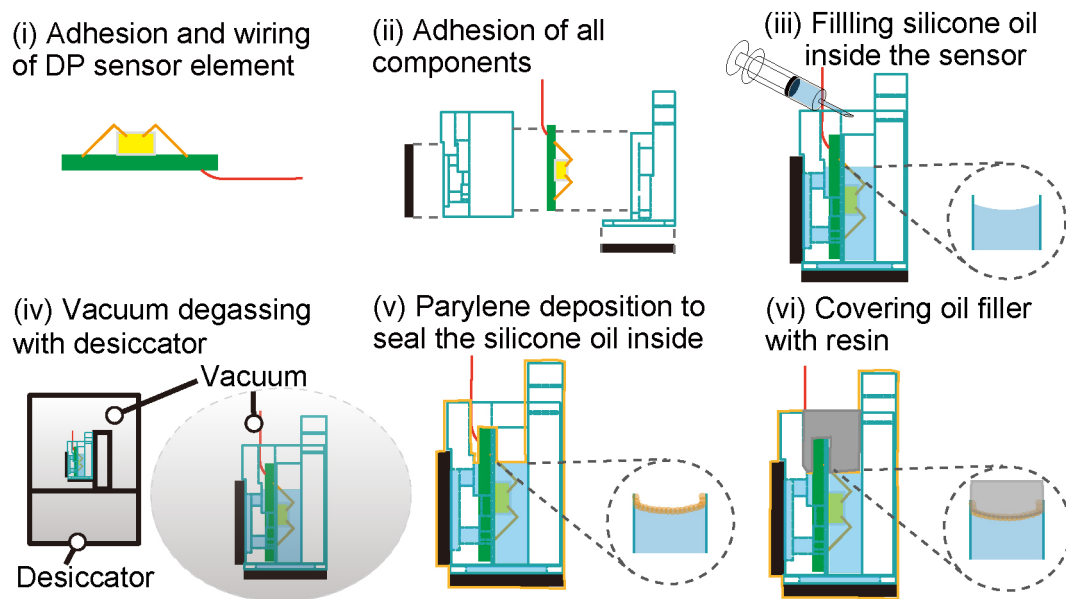


Fig. 2.12 Fabrication process of the Pitot-type waterflow sensor

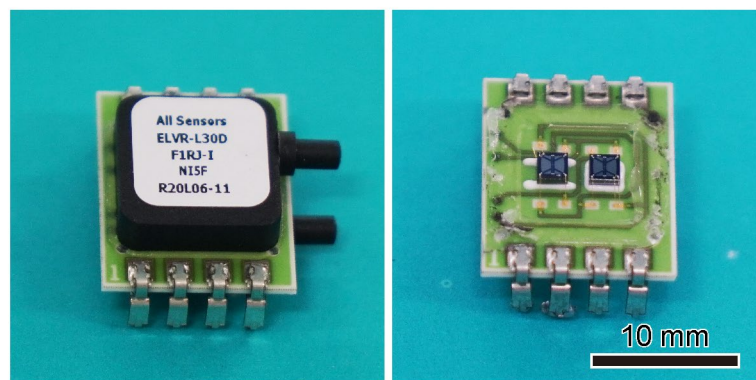


Fig. 2.13 Photograph of the commercial MEMS differential pressure sensor (ELVR-L30D-F1RJ-NI5F, Amphenol All Sensors).

parylene film was also formed over the oil itself, thereby enabling bubble-free sealing of the incompressible liquid inside the sensor. In this study, parylene C was deposited with a mass of 5 g, resulting in a film thickness of approximately 5  $\mu\text{m}$ . Finally, to prevent deformation of the parylene film covering the oil inlet, the inlet was reinforced by filling it with epoxy adhesive (ET-300, Devcon Japan Co., Ltd., Tokyo, Japan). Previous studies have also used membranes and oil to isolate and protect pressure sensors from the external environment

[105], [106]. In these studies, sealing the oil required specialized equipment such as laser welding, resistance seam welding, or vacuum brazing, which need large-scale fabrication facilities and dedicated equipment. However, in this study, the oil-sealing process was substantially simplified by employing parylene deposition, enabling bubble-free oil encapsulation to be achieved using laboratory-scale equipment. If air bubbles remain in the oil inside the sensor, the pressure response becomes nonlinear, and the sensor exhibits increased sensitivity to hydrostatic pressure. Consequently, residual air bubbles significantly degrade sensor performance. For this reason, developing an oil-sealing method that prevents the formation of residual air bubbles was critically important in this study. Pressure sensor packaging methods that employ oil and parylene have also been developed for implantable pressure sensor in biomedical applications [107]. In conventional designs, parylene is deposited directly onto an exposed surface. In contrast, the proposed sensor requires the oil to be filled into a relatively complex internal pipeline and subsequently sealed. If even small

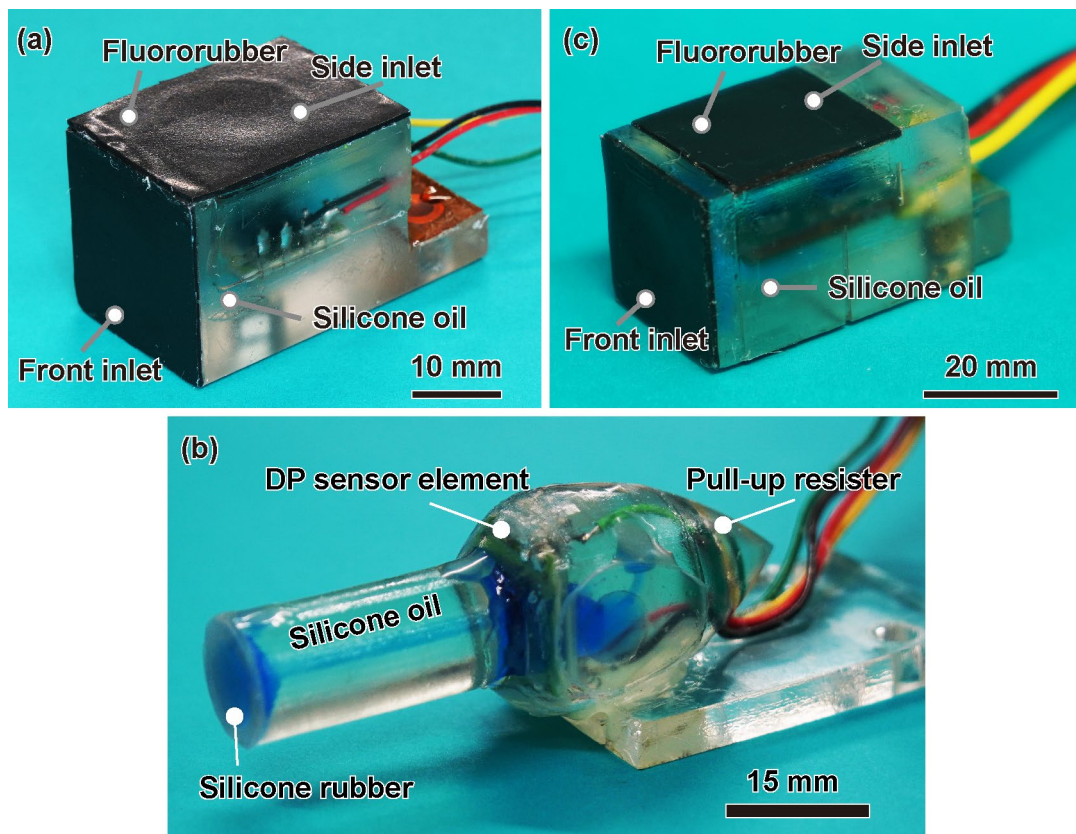


Fig. 2.14 Photographs of fabricated (a) sensor P-R, (b) sensor P-S and (c) sensor D.

air bubbles remain in the internal oil, they can rapidly expand under vacuum conditions during parylene deposition, leading to boiling-like behavior that inhibits proper formation of the parylene film. Therefore, long-term degassing and ethanol cleaning were performed prior to deposition to eliminate residual air bubbles as thoroughly as possible.

Although pressure sensors employing parylene membranes as pressure sensing area using PoLD have been reported, very few studies have applied this approach to seal oil within sensors that contain complex internal pipelines, as proposed sensor design. From a fabrication standpoint, the proposed sensor therefore adopts a distinctive manufacturing approach. Fig. 2.14 shows a photograph of the fabricated sensor. All components were waterproofed, and it was confirmed that no air bubbles remained inside the sensor.

#### 2.11.4 Bit-to-Voltage Conversion

The values measured by the waterflow sensors are output via I<sup>2</sup>C as digital bit values. The pressure sensor used in sensor P converts the measured pressure into a voltage signal, which is then represented as a 15-bit integer. Although the data are recorded in the logger as digital bits, the sensor operates at a 3.3 V logic level. Accordingly, the bit-based output from the sensor can be converted into the corresponding voltage  $V$  using the following equation:

$$V = \text{Output}(\text{bit}) \frac{3.3}{2^{15}} \quad (2.90)$$

For sensor D, the output from the ADC (ADS122C04, Texas Instruments Incorporated, Dallas, TX, USA) is represented as a signed 24-bit code in two's complement format. According to the datasheet, the full-scale differential input voltage range depends on the reference voltage  $V_{\text{ref}}$  and the programmable gain  $G$ . The relationship between the output (bit) and the sensor voltage output  $V$  is given by

$$V = \text{Output}(\text{bit}) \frac{V_{\text{ref}}}{2^{23} \cdot G} \quad (2.91)$$

In this study, the measurements were conducted with the reference voltage set to  $V_{\text{ref}} = 3.0 \text{ V}$ , and the gain set to  $G = 1$ .



## 2.12 Development of logging system

The Pitot-type waterflow sensor alone cannot perform measurement or data recording. Therefore, a dedicated logging system was developed to acquire data from both the Pitot sensor and additional sensors. In this study, two types of logging systems were designed and implemented.

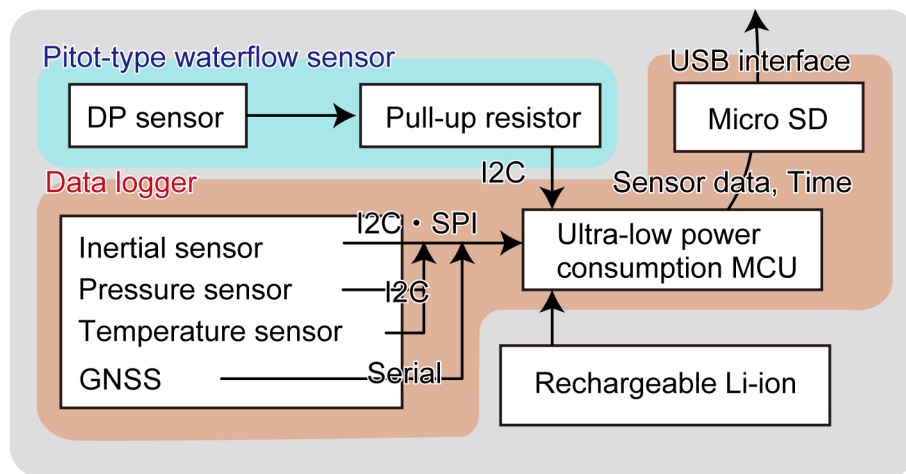


Fig. 2.15 Configuration of the Ninja Data logger

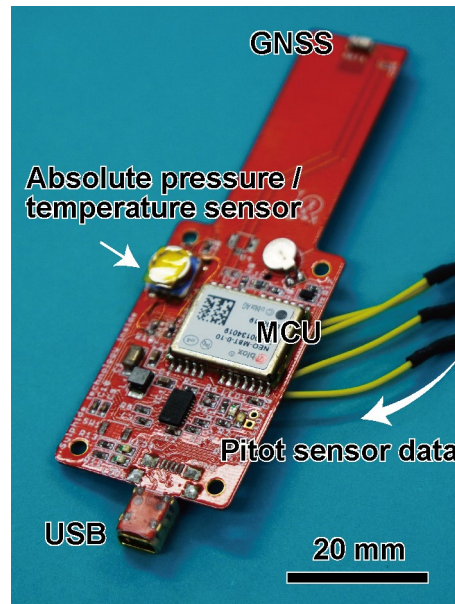


Fig. 2.16 Photograph of the Ninja data logger

### 2.12.1 Design of the Ninja data logger

The sensor system consists of a Pitot-type waterflow sensor, a data logger, and a battery. Fig. 2.15 shows configuration of the Ninja logger system. In this study, a customized version of the Ninja logger (Ninja Watari, Little Leonard Corp., Tokyo, Japan), originally developed for seabird biologging, was employed as the data logger (Fig. 2.16).

The logger incorporates multiple sensors in addition to the Pitot-type waterflow sensor, including a six-axis inertial measurement unit (IMU; three-axis accelerometer and three-axis gyroscope), a geomagnetic sensor, a waterproof absolute pressure and temperature sensor, and a GNSS receiver. All sensors are controlled at a 3.3 V voltage level by an ultra-low-power microcontroller unit (MCU: C8051F381-GQ, Silicon Laboratories, Inc., Austin, TX, USA). The MCU sends commands to each sensor and acquires their outputs. The Pitot-type waterflow sensor, the geomagnetic sensor, and the waterproof pressure–temperature sensor is controlled via I<sup>2</sup>C communication, while the six-axis accelerometer uses SPI communication and the GNSS module is operated through serial communication.

The sampling rates were as follows: Pitot-type waterflow sensor, 3.125 Hz; accelerometer, 100 Hz; geomagnetic sensor, 6 Hz; and GNSS, 5 Hz. All acquired data were recorded onto a microSD card together with synchronized GNSS time data. Although the MCU has sufficient computational capability to estimate turtle posture during deployment, in this study such processing was carried out externally on a PC. This design choice enabled

Table 2.5 Specifications and components of the Ninja logger

|                                 | Component used      | Sampling frequency | Communication interface |
|---------------------------------|---------------------|--------------------|-------------------------|
| Inertial sensor                 | TDK InvenSense      |                    |                         |
| Acceleration                    | MPU-9250            | 100 Hz             | SPI                     |
| Angular speed                   |                     | 100 Hz             | SPI                     |
| Magnetometer                    | TDK InvenSense      | 6 Hz               | I <sup>2</sup> C        |
|                                 | MPU-9250            |                    |                         |
| GNSS receiver                   | U-blox NEO-M8T      | 5 Hz               | Serial                  |
| Absolute pressure / temperature | TE MS5803-01BA      | 6 Hz               | I <sup>2</sup> C        |
| MCU                             | SiLabs C8051F381-GQ |                    |                         |
| Storage                         | Micro SD            |                    |                         |



the use of a low-power MCU, thereby extending the operational lifetime of the logger.

After measurements, the logger can be switched to an interface mode, allowing data to be retrieved via USB connection. The logger is powered by a rechargeable lithium-ion battery, which permits repeated use of the sensor system through recharging. The specifications of the logger used in this study are summarized in Table 2.5.

### 2.12.2 Fabrication of the Ninja data logger

The Ninja logger, the waterflow sensor, and the battery were soldered together, and the soldered joints were coated with epoxy adhesive for waterproofing. A lithium-ion rechargeable battery specifically designed for biologging applications (ATTACCATO. Limited Liability Company) was employed. This battery provides a specific energy of 288.6 Wh/kg, which is approximately 1.4 times greater than the typical value of 207 Wh/kg, thereby extending the operational lifetime of the logger.

After connection, functional tests were conducted with the sensor, and the logger and battery were placed in a 3D-printed mold. Resin was then cast into the mold to form a waterproof encapsulation (Fig. 2.17). The soldering of components to the Ninja logger and the molding process were carried out by Little Leonardo Corp. Because resin molding around the GNSS receiver would block satellite signals, the mold was designed with a hollow structure surrounding the receiver, leaving it exposed to ensure signal reception. The USB connector was protected by a metal cap, and the logger could be switched ON/OFF by inserting a dedicated pin into the USB port. The fabrication of the waterproof cap, the manufacturing of the data logger, and the waterproofing by resin molding were conducted by Little Leonardo Corp.

All measurement data from the waterflow sensor, the auxiliary sensors, and the

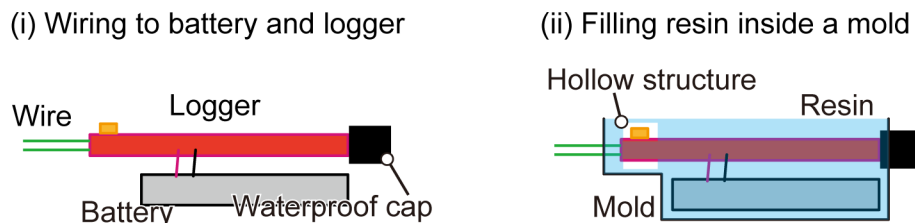


Fig. 2.17 Fabrication process of the Ninja logger

synchronized time information were stored on a microSD card using a proprietary file format with the extension “.dat.” These .dat files were subsequently converted into standard CSV format on an external PC, enabling sensor data analysis.

### 2.12.3 Design of high time resolution (HTR) logger

The Ninja logger introduced above was equipped with a GNSS module, which enabled time synchronization using satellite signals as well as the acquisition of positional information when the animal surfaced. However, the GNSS antenna consumed a considerable amount of power, accounting for a large fraction of the logger’s processing resources. As a result, it was difficult to achieve high time-resolution measurements of the Pitot tube and other sensor signals with this configuration. To address this limitation, an alternative logger without a GNSS module was developed, allowing the remaining sensors to be recorded at higher temporal resolution.

This logger was designed as the high time-resolution (HTR) logger. Fig. 2.18 shows the configuration of HTR logger. The HTR logger incorporates a nine-axis inertial measurement unit (IMU), consisting of a three-axis accelerometer and three-axis gyroscope for inertial sensing, together with a three-axis magnetometer for geomagnetic field measurement. In addition, the logger is equipped with an additional waterproof absolute pressure sensor and a temperature sensor. The system is controlled by a microcontroller unit (MCU; R5F56719DDFM, Renesas Electronics Corporation, Tokyo, Japan) operating at a voltage level of 1.8 V. The MCU manages the Pitot-type waterflow sensor, the temperature sensor integrated into the Pitot sensor, and all auxiliary sensors through serial communication interfaces (I<sup>2</sup>C and SPI). Table 2.6 shows the components used in the HTR logger. All sensors were sampled at 100 Hz. The MCU also incorporates a real-time clock (RTC), which maintains accurate timekeeping even when the logger is powered off. This design ensures that all sensor measurements are stored on a microSD card together with synchronized time information. The logger is equipped with both a USB-C connector and an SD card slot; inserting the SD card activates the power supply and initiates measurement.

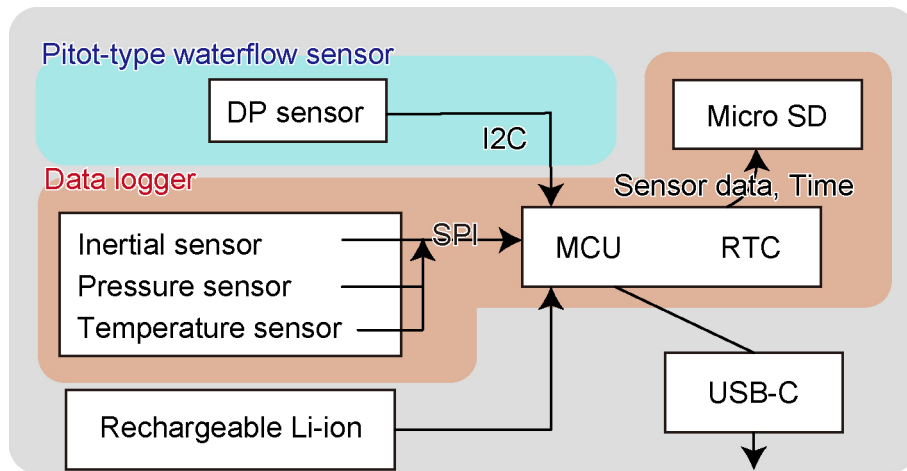


Fig. 2.18 Configuration of the HTR logger

Table 2.6 Specifications and components of the HTR logger

|                                 | Component used  | Sampling frequency | Communication interface |
|---------------------------------|-----------------|--------------------|-------------------------|
| Inertial sensor                 | TDK Invensense  |                    |                         |
| Acceleration                    | ICM-20948       | 100 Hz             |                         |
| Angular speed                   |                 | 100 Hz             | SPI                     |
| Magnetometer                    | TDK Invensense  | 100 Hz             | SPI                     |
|                                 | ICM-20948       |                    |                         |
| Absolute pressure / temperature | TE MS580330BA01 | 100 Hz             | SPI                     |
| MCU                             | RENESAS         |                    |                         |
|                                 | R5F56719DDFM    |                    |                         |
| Storage                         | Micro SD        |                    |                         |

#### 2.12.4 Fabrication of a waterproof case for the HTR logger

Figure 2.19 shows a photograph of the fabricated logger. The design and fabrication of these loggers were commissioned to Analog Signal Technology Inc. To enable operation of these loggers under seawater conditions, waterproofing and pressure-resistant processing were applied. The logger can be accessed from a PC via USB, allowing time to be written to the RTC and the battery capacity to be monitored. In addition, since the SD card functions as the measurement switch, both the USB connector and the SD card slot must remain accessible

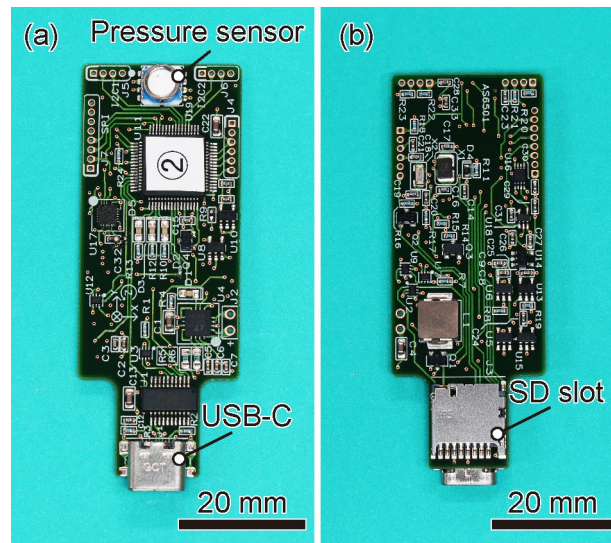


Fig. 2.19 Photograph of the HTR logger

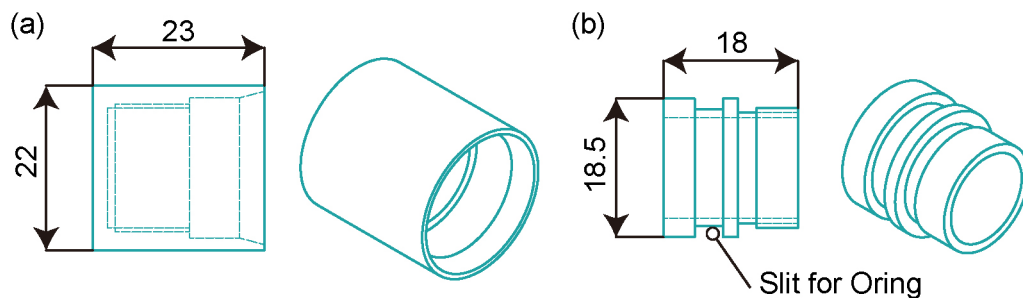


Fig. 2.20 Design and dimensions for the waterproof (a) cap and (b) neck.

even after waterproof processing. To achieve this, a waterproof cap was designed and fabricated to accommodate both the USB port and the SD card slot.

The design and dimensions of the waterproof cap are shown in Fig. 2.20. The cap is equipped with a slit for an O-ring, which provides waterproof sealing inside the cap. The material used was aluminum, and the cap was manufactured by mechanical machining. To prevent corrosion, the entire surface was subsequently treated with black anodization.

To further waterproof the logger, a logger case was fabricated by mechanical machining, as shown in Fig. 2.21. The case consists of four parts: the logger box, the cap stand, the substrate partition, and the lower partition. To prevent corrosion, all parts were

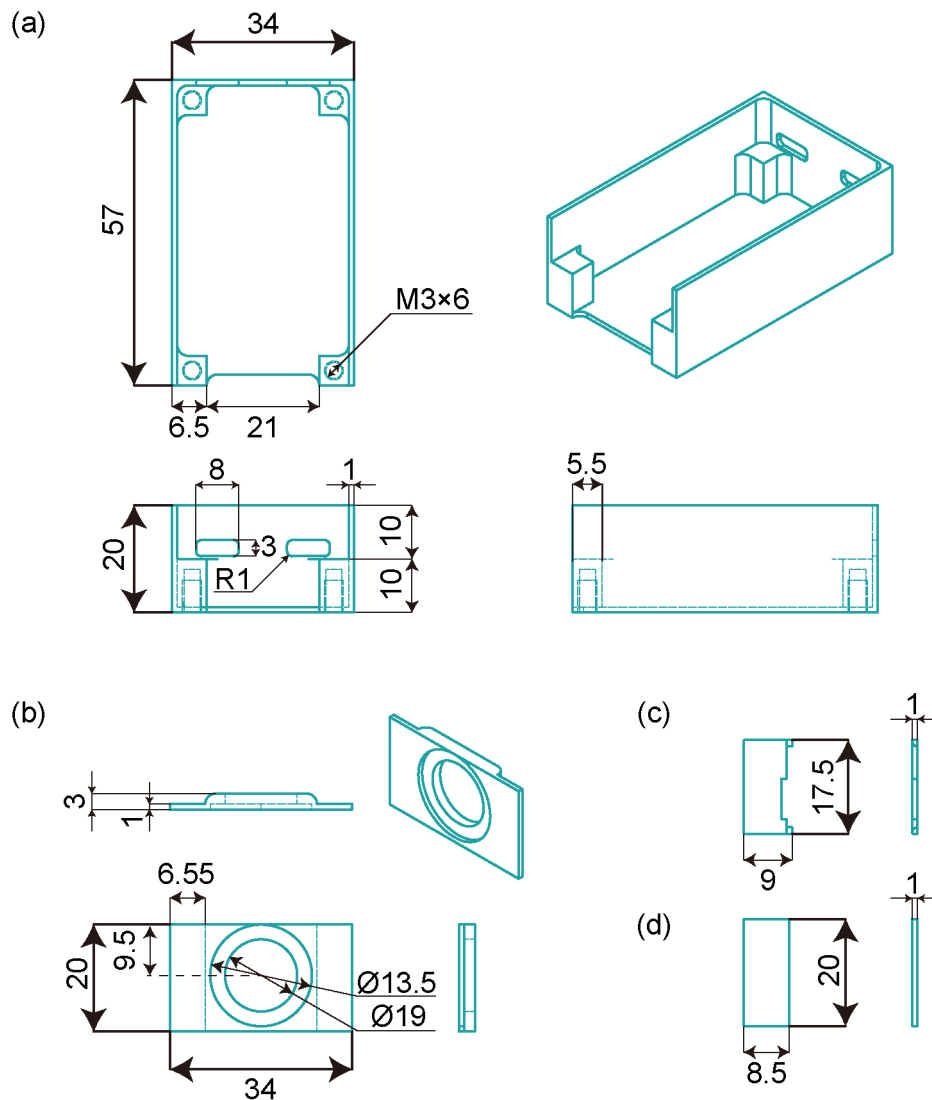


Fig. 2.21 Design and dimensions of logger case: (a) logger box, (b) cap stand, (c) substrate partition, and (d) lower partition.

treated with black anodization. By assembling the case together with the cap, logger board, and battery, the high time-resolution (HTR) logging system was completed.

The fabrication process of the logger is illustrated in Fig. 2.22. First, wiring was carried out for the HTR logger and the battery, using an LP903042 lithium-ion battery (EEMB Co., Ltd., Shenzhen, China). Subsequently, a partition was bonded to the logger board to cover the USB connector and SD card slot. The sensor case and cap were then

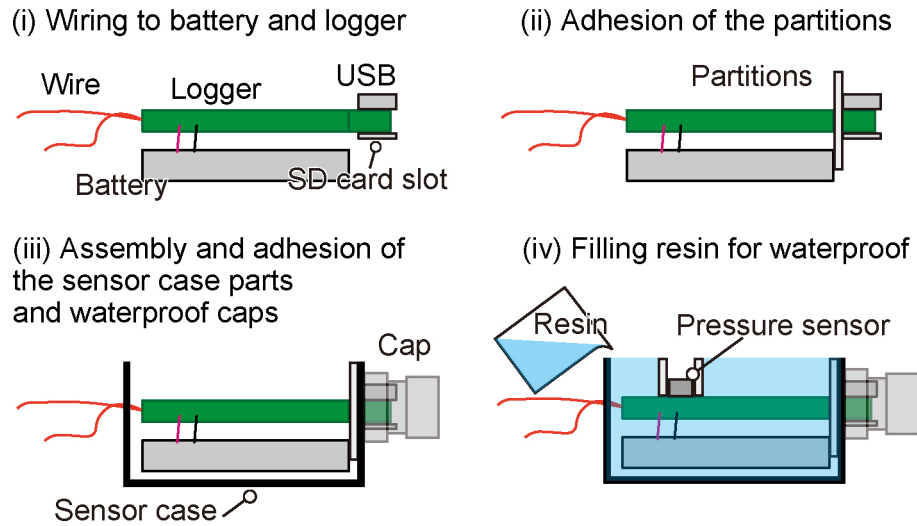


Fig. 2.22 Fabrication process of the HTR logger.

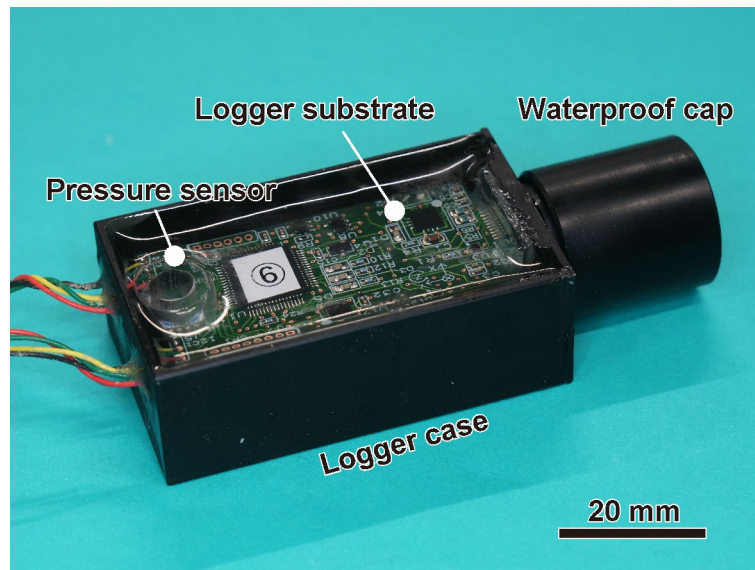


Fig. 2.23 Photograph of the fabricated HTR logger

assembled and bonded together. During this step, the logger was positioned as horizontally as possible, and a cylindrical barrier was attached around the pressure sensor. The combination of this barrier and the partition prevented the resin, which was later poured to encapsulate the entire sensor, from leaking into the regions surrounding the pressure sensor

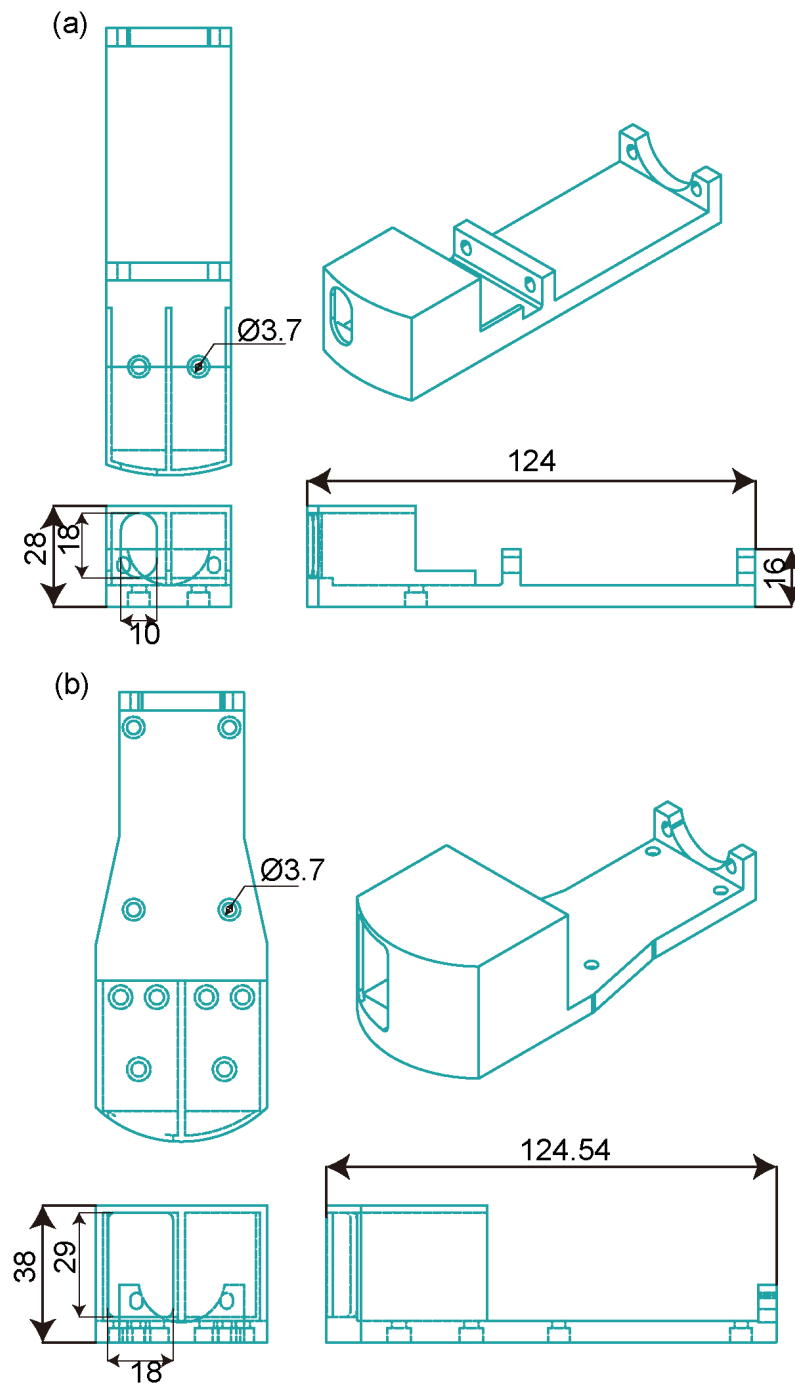


Fig. 2.24 Fabrication process of the HTR logger.

and the USB connector. Finally, the entire logger was encapsulated with resin (ET-300, Japan Devcon Inc.), which was allowed to cure for one day. Following these steps, the fabrication



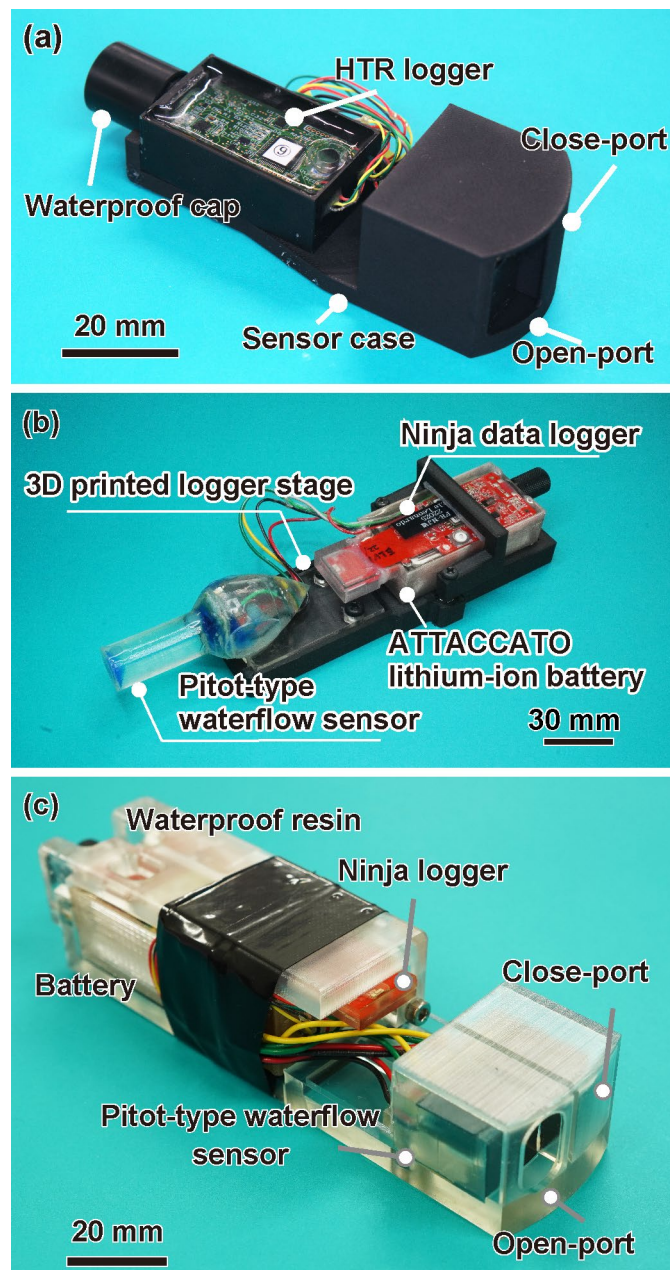


Fig. 2.25 Fabricated Pitot-type waterflow sensor system: (a) sensor P-R, (b) sensor P-S, and (c) sensor D.

of the logger was completed. Figure 2.23 shows fabricated HTR logger.



### 2.12.5 Design of the sensor case

To protect the sensors from external impacts and compensate for external disturbances, sensor P-R and sensor D were equipped with dedicated sensor cases. The fabrication of these sensor cases is described below, and their dimensions are shown in Fig. 2.24. These sensor cases were fabricated either by stereolithography (SLA) or by fused deposition modeling (FDM) 3D printing, depending on the required specifications. When higher mechanical strength was needed, the cases were produced using an FDM 3D printer (X1-Carbon, Bambu Lab (Shenzhen Tuozhu Technology Co., Ltd.), Shenzhen, China) with a carbon fiber-reinforced PLA filament (PLA-CF). The logger and sensors were connected by soldering, and the entire assembly was secured to the sensor case using screws. In this way, the sensor system was completed. A photograph of the fabricated system is shown in Fig. 2.25. For Sensor P-S, the sensor was mounted directly onto the case without any protective housing, leaving the sensing element exposed.

The total mass and frontal area of the Sensor P-R equipped with the HTR logger and sensor case was 159.1 g and 19 cm<sup>2</sup>, while the total mass and frontal area of the Sensor D equipped with the Ninja logger and sensor case was 125.8 g and 9.8 cm<sup>2</sup>.

## 2.13 Engineering novelty of the Pitot-type waterflow sensor

---

Conventional Pitot tubes require the internal tube to be completely filled with liquid, without entrapped air bubbles, which necessitates careful, time-consuming preparation. Moreover, in field environments, clogging from suspended particles or biofouling is common, leading to measurement failures. These limitations restrict the applicability of conventional Pitot tubes to biologging studies.

The proposed Pitot-type waterflow sensor incorporates the membrane-covered inlet that prevents the intrusion of air bubbles and suspended particles into the internal pipeline. From an engineering perspective, the use of the incompressible liquid (silicone oil) is essential for this configuration. Although the influence of hydrostatic pressure on the sensor output can, in theory, be canceled by appropriately balancing the chamber volume and membrane area, using a compressible fluid would induce membrane deformation under hydrostatic pressure, potentially leading to mechanical failure. To prevent this failure under

hydrostatic pressure, the internal pipeline is filled with an incompressible liquid. This oil-filled configuration suppresses membrane deformation induced by hydrostatic pressure and enhances pressure resistance, thereby enabling stable waterflow measurements in field environments with minimal operational complexity.

Another key novelty of the proposed sensor is the decoupling of sensor sensitivity from sensor structure. In conventional membrane-oil sensor package structure, sensitivity is strongly influenced by the package geometry, requiring joint optimization of the package and the sensing element. In contrast, the proposed design employs a MEMS differential pressure sensor element connected to the relatively large inlet membrane via an oil-filled pipeline. As a result, the sensor sensitivity is primarily determined by the sensing element rather than the package structure, enabling a measurable waterflow speed range. It enables a measurable waterflow speed range to be readily adjusted by changing the sensing element without redesigning the sensor package.

Furthermore, the proposed system integrates the two Pitot-type waterflow sensors within the sensor case, with only one side open. When combined with differential pressure measurement, this configuration effectively suppresses the influence of external disturbances. Unlike previous Pitot tubes, the proposed sensor system is specifically designed for animal-borne applications on freely moving marine animals, where the sensor repeatedly crosses the sea surface and is exposed to air bubbles and suspended particles.

From a fabrication standpoint, the proposed sensor adopts the simplified distinctive oil-sealing method based on parylene deposition. Whereas previous studies relied on specialized sealing processes such as welding or brazing, the proposed approach enables bubble-free oil encapsulation using laboratory-scale equipment. Because residual air bubbles critically degrade pressure response and tolerance to hydrostatic pressure, extensive degassing and cleaning were performed prior to parylene deposition. Applying this technique to seal oil within the sensor containing complex internal pipelines therefore represents a distinctive manufacturing approach.

In summary, the proposed Pitot-type waterflow sensor exhibits engineering novelty by combining the membrane-covered inlet, the oil-filled internal pipeline, the sensitivity design independent of the package structure, dual sensor structure enabling robust measurement under environmental disturbances, and the simplified fabrication process.

suitable for biologging applications.

## 2.14 Conclusion

---

In this chapter, the principles, design, and fabrication of a Pitot-type waterflow sensor for measuring the swimming speed of marine animals were presented. The swimming characteristics of the target species, sea turtle, were analyzed to derive the design requirements. From these considerations, the specifications were defined as follows: a system mass of 2.8 kg, a frontal area of 20 cm<sup>2</sup>, an allowable pressure of 3.4 MPa, a measurement range of 0–2.0 m/s, a resolution of 0.01 m/s, and a response time shorter than 50 ms.

The sensor was modeled as a simplified system composed of a membrane and a chamber, and its responses were theoretically examined under various conditions: when the internal fluid was assumed to be a compressible gas or an incompressible liquid, under dynamic pressure due to flow, and under disturbances such as temperature fluctuations or acceleration.

To meet the defined requirements, three types of sensors were designed, and two types of data loggers were developed: one equipped with GNSS for positional and timing information, and another designed for high time-resolution measurements. Both sensors and loggers were successfully fabricated.

These developments established the foundation for subsequent experimental evaluations. In the next chapter, the performance of the fabricated sensors is assessed through experiments to validate their capability for measuring the swimming speed of marine animals.

## CHAPTER 3.

# Fundamental Characteristics of the Pitot-Type Waterflow Sensor

### 3.1 Introduction

---

In this chapter, the fundamental characteristics of the developed Pitot-type waterflow sensor are presented. First, a pressure resistance test is conducted by applying hydrostatic pressure to evaluate the structural robustness of the sensor. Next, differential pressure is applied to the fabricated sensors to experimentally verify the validity of the theoretical model and to characterize the pressure response. From these results, the relationship between the applied differential pressure and the sensor output is derived. Subsequently, step pressure change is applied to evaluate the dynamic response of the sensor to pressure variations, and the effects of environmental disturbances such as water temperature and acceleration are also investigated. Finally, steady-flow experiments are carried out in a circulating water tunnel to apply constant flow velocities to the sensor. The obtained results are used to establish the relationship between the sensor output and flow velocity, demonstrating the capability of the developed Pitot-type waterflow sensor to accurately measure flow velocity.

## 3.2 Pressure resistance test

### 3.2.1 Experimental setup

The experimental setup is shown in Fig. 3.1. Loggerhead turtles around Sanriku coast dive sea throughout the year. The recorded deepest dive is 340 m [48]. Accordingly, the measurement system must have sufficient structural integrity to withstand the associated hydrostatic pressure of 3.4 MPa. To evaluate the pressure resistance of the sensor, the fabricated Pitot-type waterflow sensor (Sensor P-R) was immersed in water inside a pressure chamber commonly used for watch testing, and a hydrostatic pressure of 0.6 MPa was applied for 60 minutes. Ideally, a pressure of 3.4 MPa should be applied using a larger pressure application system. However, such high-pressure hydrostatic test equipment was not available in our laboratory, and conducting tests at this pressure using hand-made equipment at this pressure involves safety risks. Therefore, in this study, the pressure of 0.6 MPa was applied instead. Even within this pressure range, the test was sufficient to evaluate the

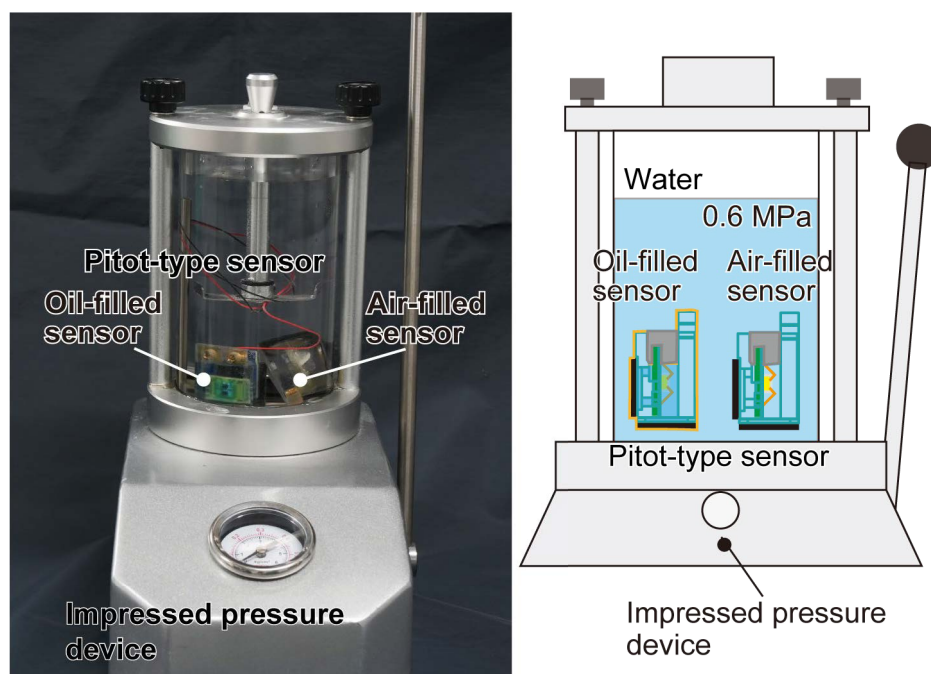


Fig. 3.1 Photograph and schematic diagram of the setup for the pressure-resistance experiment.

performance difference between using the compressible gas (air) and the incompressible liquid (silicone oil) as the internal fluid. This experiment therefore experimentally verifies the improvement in pressure resistance achieved by filling the sensor with oil. Two types of sensors were prepared: one filled with oil and the other filled with air. Pressure was subsequently applied to both sensors.

### 3.2.2 Experimental result

Figure 3.2 shows photographs of the waterflow sensor filled with air and oil after the pressure-resistance test. No cracks or loss of tension were observed in the membrane of both sensors after the pressure loading. However, the oil-filled sensor showed no noticeable change, whereas the air-filled sensor allowed water to leak inside the sensor chamber (pipeline).

Because the sensor's internal chamber volume was small, membrane deformation due to hydrostatic pressure was limited, preventing large deformation. As a result, the membrane itself suffered little damage under pressure. Instead, failure in the air-filled sensor occurred at the adhesive joint of the sensor housing, allowing water to enter the sensor. As shown in , water intrusion into the sensor chamber can be observed, resulting in the formation of air bubble inside the sensor. In contrast, the oil-filled sensor did not fail under pressure, as the incompressible oil effectively hydrostatic pressure-induced deformation. These results

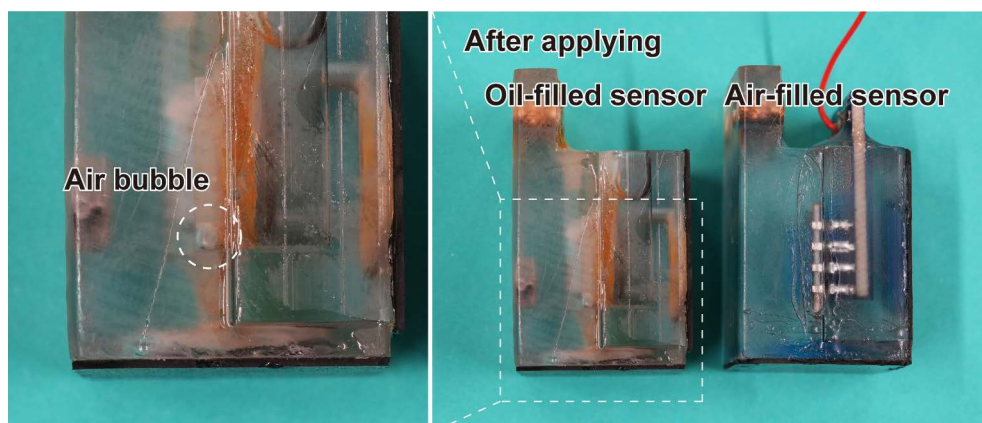


Fig. 3.2 Photographs of the Pitot-type waterflow sensor filled with air and oil after the pressure-resistance test.

confirmed that the structure with internally sealed oil provides sufficient pressure resistance. In addition, no degradation of the adhesive materials, such as dissolution or weakening, was observed on oil-filled sensor, indicating that the materials used in the sensor possess adequate resistance to hydrostatic pressure.

### 3.3 Calibration of the differential pressure

---

#### 3.3.1 Experimental setup

To evaluate the pressure response of the fabricated sensor system, the response to applied pressure at the top inlet of the sensor was examined. A differential pressure was applied to the fabricated sensor using a pressure calibrator (KAL200, Halstrup Walcher Inc.), and the corresponding output was recorded. The pressure calibrator was controlled by an externally connected PC, which switched the applied pressure at predetermined time intervals to impose differential pressure on the sensor.

In the case of Sensor P-S, a tube was fitted over the top inlet to connect the sensor to the pressure calibrator for applying differential pressure. For Sensor P-R and Sensor D, custom jigs were fabricated for each sensor to enable the application of differential pressure during testing. Figure 3.3 shows dimensions of fixing jigs for DP calibration experiment.

As shown in Fig. 3.4, the sensors were mounted on the pressure calibrator to apply differential pressure. For Sensor P-S, positive pressure was applied to the top inlet, whereas for Sensors A-R and B, negative pressure was applied to the side inlet using a custom fixture.

#### 3.3.2 Experimental evaluation of the influence of membrane thickness and internal fluid on sensor sensitivity for differential pressure

To evaluate the effect of membrane thickness on the pressure sensitivity of the Pitot-type sensor and to verify the validity of the theoretical model, experiments were conducted using the fabricated sensor (Sensor P-S). The response of the sensor to differential pressure (DP) was investigated. A silicone tube was used to connect the tip of the sensor

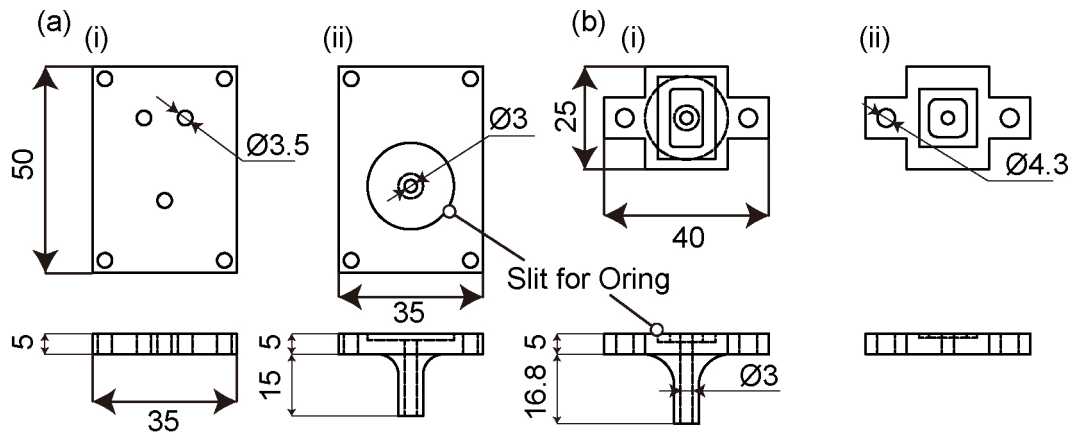


Fig. 3.3 Fixing jigs for (a) Sensor P-R: (i) upper part and (ii) bottom part, and (b) Sensor D: (i) upper part and (ii) bottom part.

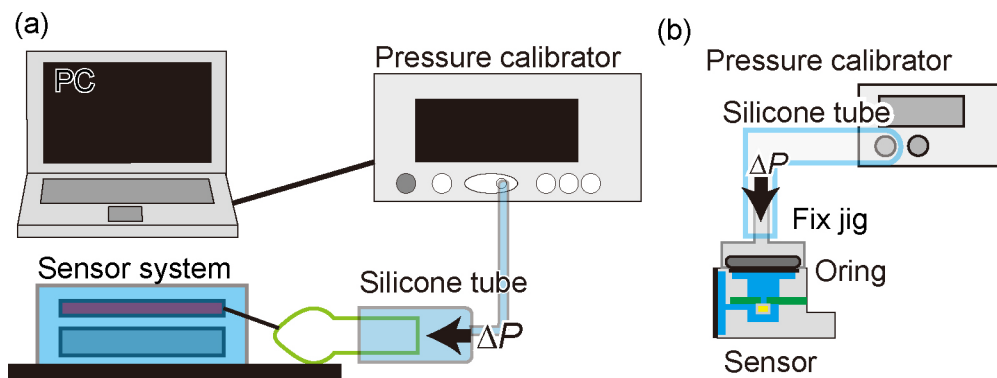


Fig. 3.4 Experimental setup for pressure calibration: (a) Sensor P-S and (b) Sensors P-R and D.

housing to a pressure calibrator (KAL200, Halstrup-Walcher GmbH, Kirchzarten, Germany), and DP was applied from 0 kPa to 5 kPa in 500 Pa increments. To examine the influence of the membrane and the internal fluid, eight types of sensors were fabricated: four with silicone membranes of different thicknesses (0.5, 1.0, 1.5, and 2.0 mm), each filled with either air or silicone oil. The flexural rigidities  $D$  of the membranes were experimentally determined by measuring the displacement of a single membrane subjected to pressure within the small-deformation region using a digital microscope (VHX-6000, Keyence Corporation, Osaka, Japan). The measured values are summarized in Table 3.1. For reference, the pressure calibration of the DP sensor (ELVR-L30D-F1RJ-NI5F, Amphenol All Sensors) was also



performed independently. During each pressure test, measurements were taken over a 50 s period, with no pressure applied from 0 to 25 s and the set pressure applied from 25 to 50 s. The difference between the average voltage during 10–15 s and that during 35–40 s was defined as the sensor output  $\Delta E$ . Figure 3.5 shows the response of each sensor when a DP of 5 kPa was applied. It was confirmed that the sensor output returned to its initial value after the pressure load was released. Figure 3.6 (a) presents the experimental results, showing that all sensor outputs increased linearly with applied pressure. The outputs of all sensors containing silicone oil were comparable to that of the reference DP sensor, whereas those containing air exhibited reduced outputs, less than 15% of the reference value. Fig. 3.6 (b) and Table 3.2 show the relationship between membrane thickness and sensitivity, where the slope of the fitted line was defined as the sensitivity. The theoretical sensitivities for air-filled membranes calculated from Eq. (2.59) are also plotted. In the calculation,  $A_2$  was neglected because the sensing element was sufficiently small compared with the membranes. Each  $A_1$  value was calculated from the measured  $D$  using Eqs. (2.7) and (2.46), as summarized in Table 3.1. Here,  $A_1$  and  $A_2$  represent the deformation per unit pressure applied to the

Table 3.1 Measured property of each membrane

| Film thickness                         | 0.5 mm | 1.0 mm | 1.5 mm | 2.0 mm |
|----------------------------------------|--------|--------|--------|--------|
| $D$ ( $10^{-4}$ Pa m <sup>3</sup> )    | 0.574  | 1.80   | 2.96   | 11.3   |
| $A_1$ ( $10^{-12}$ m <sup>3</sup> /Pa) | 10.6   | 3.41   | 2.06   | 0.54   |

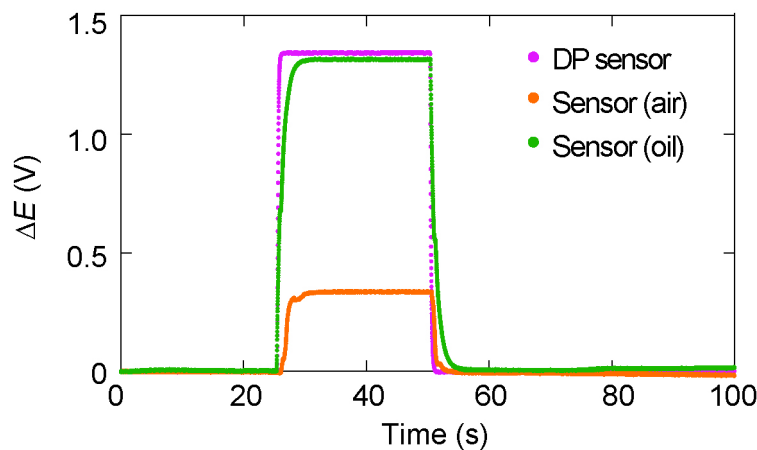


Fig. 3.5 Response of the sensor when pressure is applied.

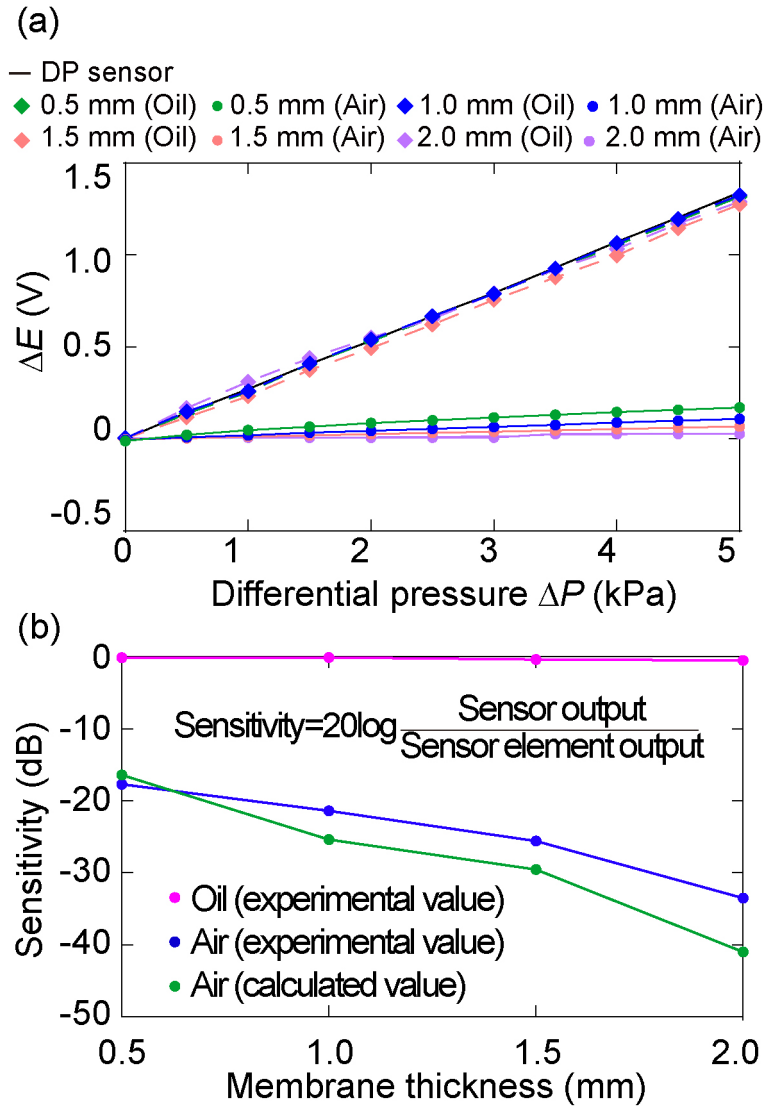


Fig. 3.6 (a) Experimental results of pressure calibration experiment obtained with membranes of differential thickness and with oil/air inside. (b) Relationship between film thickness and sensitivity with oil/air inside.

membranes attached to the sensor ports and to the sensing element, respectively, as defined in Eq. (2.46). These parameters characterize the pressure–deformation relationship of each membrane and are used to theoretically determine the overall pressure response of the sensor.

The values of  $A_1$  and  $V$  were determined based on the design of the tip-side housing. The sensitivity of the air-filled sensors decreased with increasing membrane thickness,

Table 3.2 Sensor sensitivity of each film thickness with oil/air inside

|                         | 0.5 mm   | 1.0 mm   | 1.5 mm   | 2.0 mm   |
|-------------------------|----------|----------|----------|----------|
| Oil                     | -0.11 dB | -0.09 dB | -0.37 dB | -0.50 dB |
| Air                     | -17.7 dB | -21.4 dB | -25.6 dB | -33.5 dB |
| Air (Theoretical value) | -16.4 dB | -25.4 dB | -29.5 dB | -41.0 dB |

indicating that the characteristics of the outer membrane influenced the overall sensitivity. The experimental results exhibited trends similar to those predicted by the theoretical model. The discrepancies between the experimental and theoretical values are attributed to the slight non-flatness of the membranes caused by bonding them to the Pitot-static tube housing. In contrast, the sensitivity of the sensors filled with silicone oil remained constant regardless of membrane thickness. The sensors maintained their sensitivity and responded consistently with the reference DP sensor. These results confirm that by filling the internal cavity with an incompressible liquid and using sufficiently large inlets, the dynamic pressure generated by waterflow can be detected without being affected by the mechanical properties of the outer membrane.

### 3.3.3 Calibration of sensor P-R

The pressure calibration of Sensors P-R and D was performed using the same procedure. The fix jig equipped with an O-ring was attached to the side inlet of each sensor, and a negative differential pressure was applied to the side inlet. Differential pressure was applied in increments of 500 Pa from -5 kPa to +5 kPa, and the corresponding sensor outputs were recorded. The sensor P-R outputs were measured by the HTR logger. The sampling rate was set to 100 Hz. Figure 3.7 shows the sensor P-R output  $\Delta E$ , during the pressure calibration experiment. The output  $\Delta E$  was calculated by averaging the data over 250–253 s with no applied pressure and setting the average to 0 V. In measuring sensor P-R, the sensor responded in a step-like manner to the applied differential pressure and returned to its original

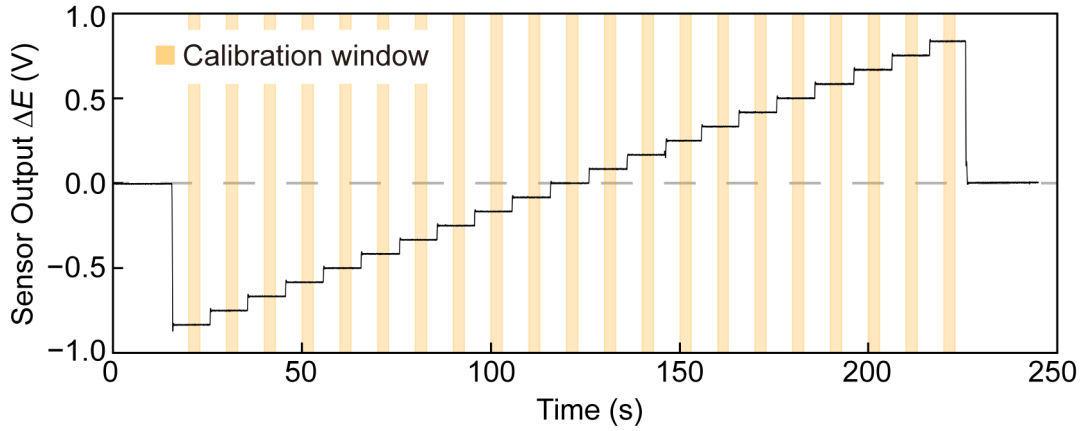


Fig. 3.7 Sensor P-R output during the pressure calibration experiment.

output without offset after the pressure was released, indicating low hysteresis.

Using the output data from the orange-shaded calibration window (300 samples, corresponding to 3 s of stable output at each applied differential pressure), the relationship between the sensor output  $\Delta E$  and the applied differential pressure  $\Delta P$  was obtained as shown in Fig. 3.8 (a). For each applied pressure, 300 samples were used. In total, 6300 samples were collected. These data were then used to obtain the fitting line using the least-squares method. The sensor responded linearly to the differential pressure. The relationships between the applied differential pressure  $\Delta P$  and the sensor output  $\Delta E$  of the sensor P-R were expressed as follows:

$$\Delta E = 0.167\Delta P. \quad (3.1)$$

The coefficient of determination  $R^2$  was 1.000, indicating that there is no measurable nonlinearity was present. Fig. 3.8 (b) shows the fitting line and the residuals of each experimental data point. The residuals remained within a narrow band around zero without systematic trends. Given the extremely high linearity and the low hysteresis, the sensor can calculate the applied differential pressure from the sensor output.

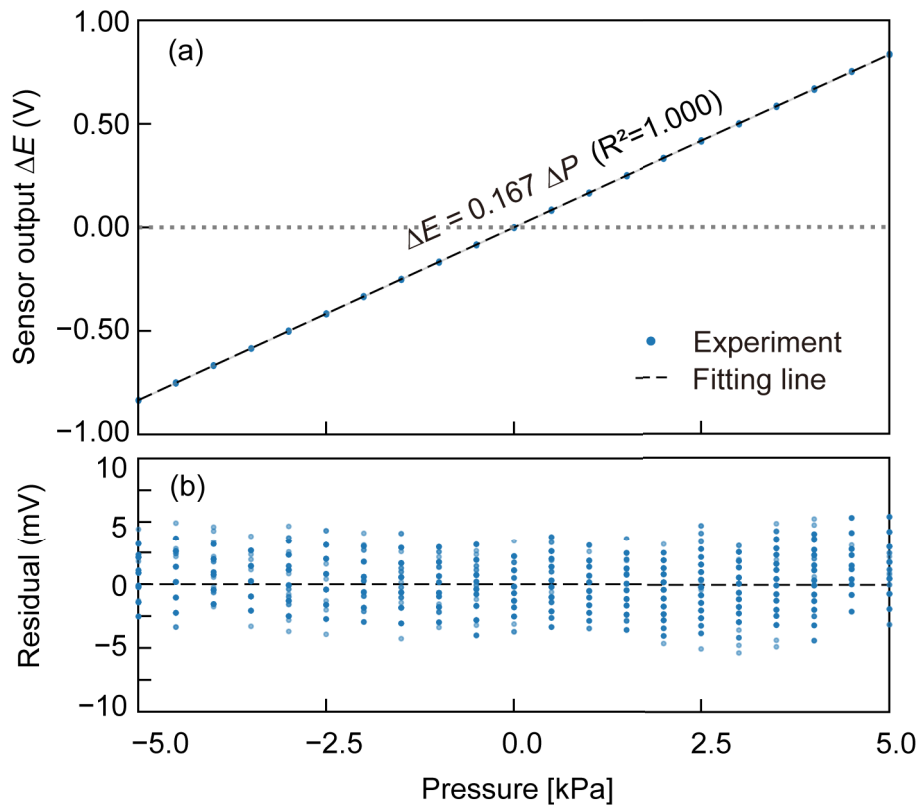


Fig. 3.8 (a) Relationship between applied differential pressure and sensor output of sensor P-R. (b) Residuals between the experimental data of the sensor P-R and the fitting line.

### 3.3.4 Calibration of sensor D

In the measurement with sensor D, experimental data were recorded using the Ninja data logger, which sampled the sensor output at 3.125 Hz. Differential pressure was also applied in increments of 500 Pa from -5 kPa to +5 kPa, and the corresponding sensor outputs were recorded. The sensor output  $\Delta E$  was calculated by averaging the 11 data points from 185.6 to 188.8 s under no applied pressure and setting this average to zero. Figure 3.9 shows the sensor D output  $\Delta E$  during the pressure calibration experiment. The sensor D showed a step-like change in output as the applied pressure was changed, similar to the sensor P-R. After the applied pressure was released, the output returned to zero without any offset, indicating negligible hysteresis.

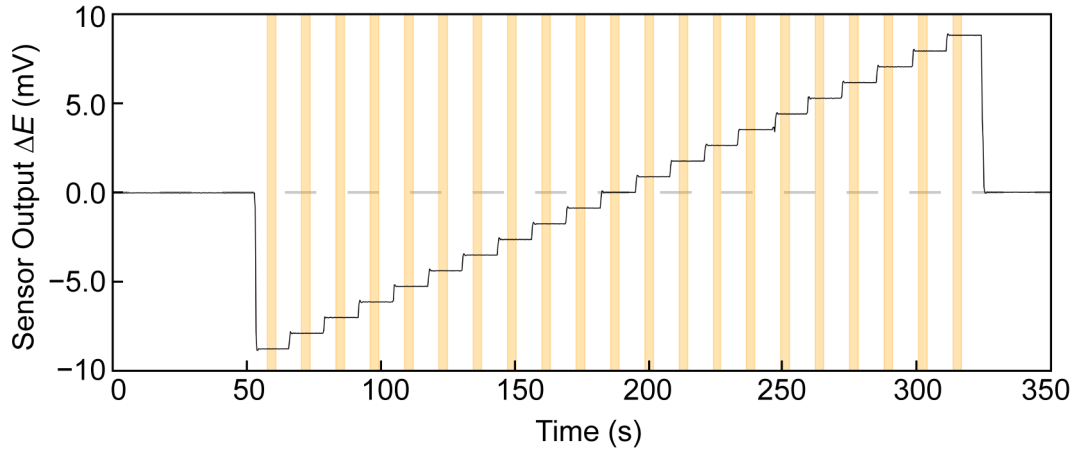


Fig. 3.9 Sensor D output during the pressure calibration experiment.

Using the output data from the orange-shaded calibration window (10 samples, corresponding to 3.2 s of stable output at each applied differential pressure), the relationship between the sensor output  $\Delta E$  and the applied differential pressure  $\Delta P$  was obtained as shown in Fig. 3.10 (a). For each applied pressure, 10 samples were used. In total, 210 samples were collected. These data were then used to obtain the fitting line using the least-squares method. The sensor D responded linearly to differential pressure and relationship between the sensor D output  $\Delta E$  and applied differential pressure is expressed as follows:

$$\Delta E = 1.76 \times 10^{-3} \Delta P. \quad (3.2)$$

The coefficient of determination  $R^2$  was 1.000, indicating that the linear relationship between differential pressure  $\Delta P$  and sensor output  $\Delta E$  was fully maintained. This result confirms that the entire range from  $-5$  kPa to  $5$  kPa lies within the sensor's linear operating region. Figure 3.10 (b) shows the fitting line and the residuals of each experimental data point. The residuals were randomly scattered without any systematic trend, and no bias associated with pressure magnitude was observed. This result indicates that nonlinearity errors are minimal and that the residuals primarily reflect random electrical noise and external disturbances.

For both sensor P-R and sensor D, the outputs responded linearly to the applied differential pressure, and the fitting line exhibited high coefficients of determination with residuals showing no systematic bias. These results indicate that the calibration equations

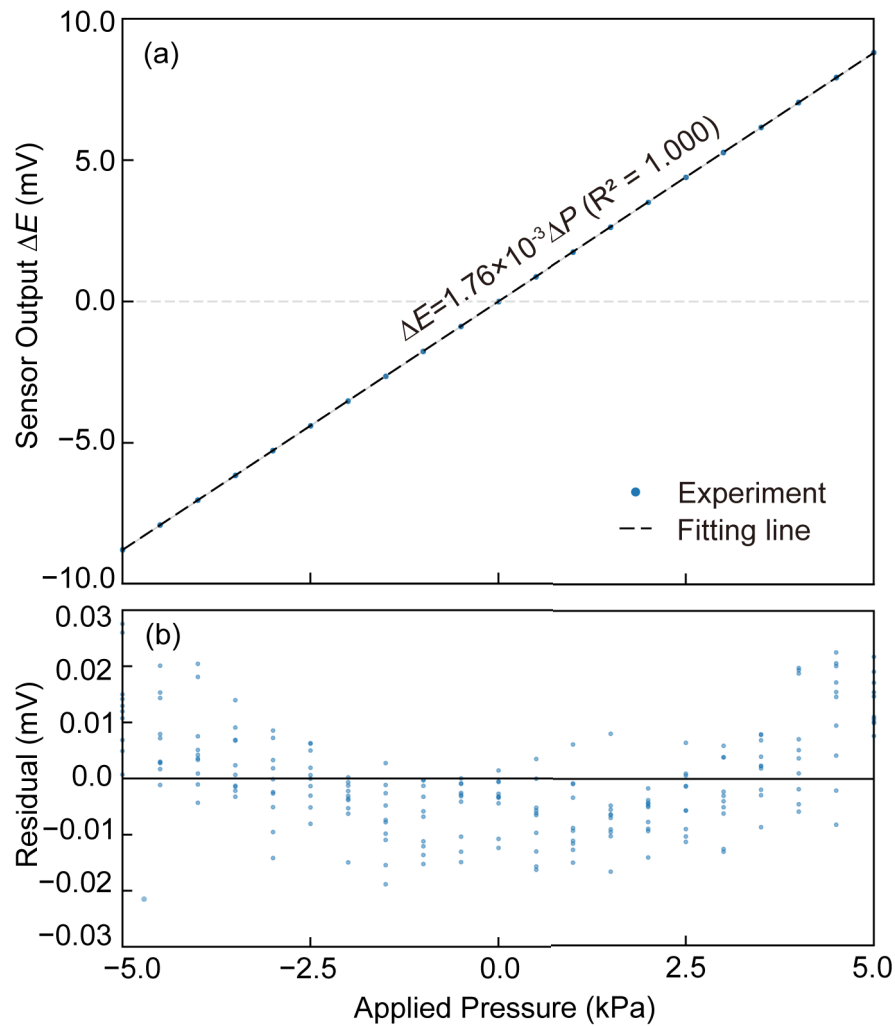


Fig. 3.10 (a) Relationship between applied differential pressure and sensor output of sensor P-R. (b) Residuals between the experimental data of the sensor P-R and the fitting line.

obtained from the experiments can be used to accurately calculate the differential pressure from the sensor outputs.

### 3.4 Dynamic response evaluation under step pressure input

#### 3.4.1 Experimental setup

The time responsivity of the sensor was evaluated using a step-pressure test. Figure 3.11 (a) shows a schematic diagram of the experimental setup. The sensor was connected in series with a solenoid valve, a 3D-printed chamber, a mechanical valve, and a pressure calibrator through silicone tubes. The chamber had a volume of 125 mL to ensure a stable internal pressure. The experiment was conducted using Sensor P-S, which provided an analog voltage output. The sensor signals were recorded using a scope recorder (DL850, Yokogawa Electric Corporation, Tokyo, Japan). Initially, a differential pressure (DP) of 2 kPa was applied to the chamber by closing the solenoid valve, after which the mechanical valve was

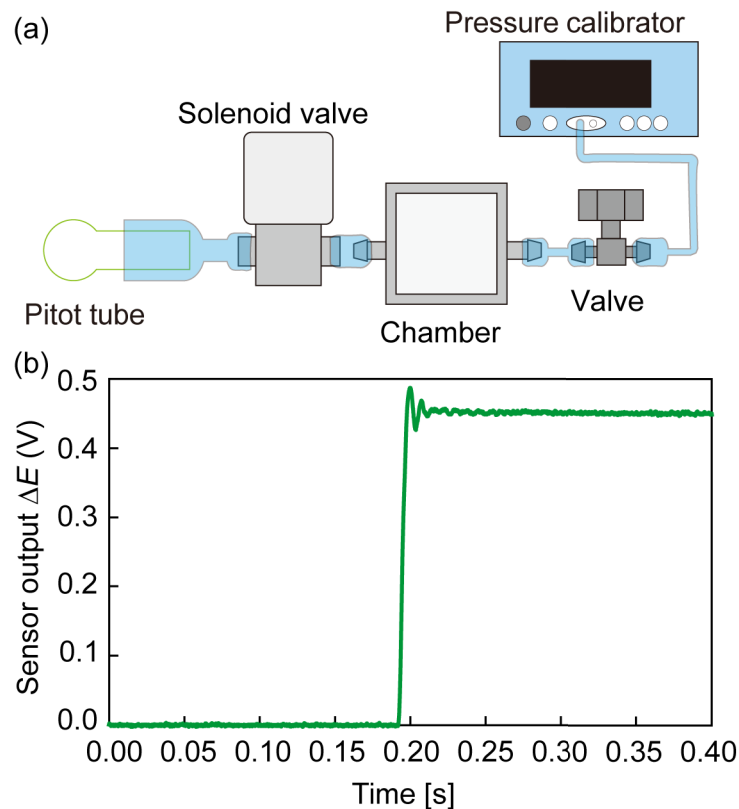


Fig. 3.11 (a) Schematic image of the experimental setup to evaluate the time responsivity. (b) The sensor response when pressure is applied with step response.



manually closed to isolate the system. Subsequently, the solenoid valve was opened, generating a step-like differential pressure change applied to the sensor.

### 3.4.2 Experimental result

Figure 3.11 (b) shows the sensor's output response to the applied step pressure. The sensor exhibited a step-like response, and a small overshoot appeared immediately after the step pressure was applied. This overshoot results from the combined mechanical dynamics of the sensor and the experimental setup. The sensor consists of the membrane and the oil-filled chamber, while the experimental setup includes the air-filled tube and chamber connected to the sensor. These elements likely produce the observed underdamped response. To evaluate the sensor's response speed, the output was normalized by setting the average value from 0–0.1 s (before pressure application) to 0 and the average value from 0.3–0.4 s (after the response settled) to 1. The normalized response is shown in Fig. 3.12. The temporal responsivity of the sensor was quantified using the 10–90% rise time. In the normalized output, the times  $t_{10}$  and  $t_{90}$ , which correspond to the output first reaching 0.1 and 0.9, were

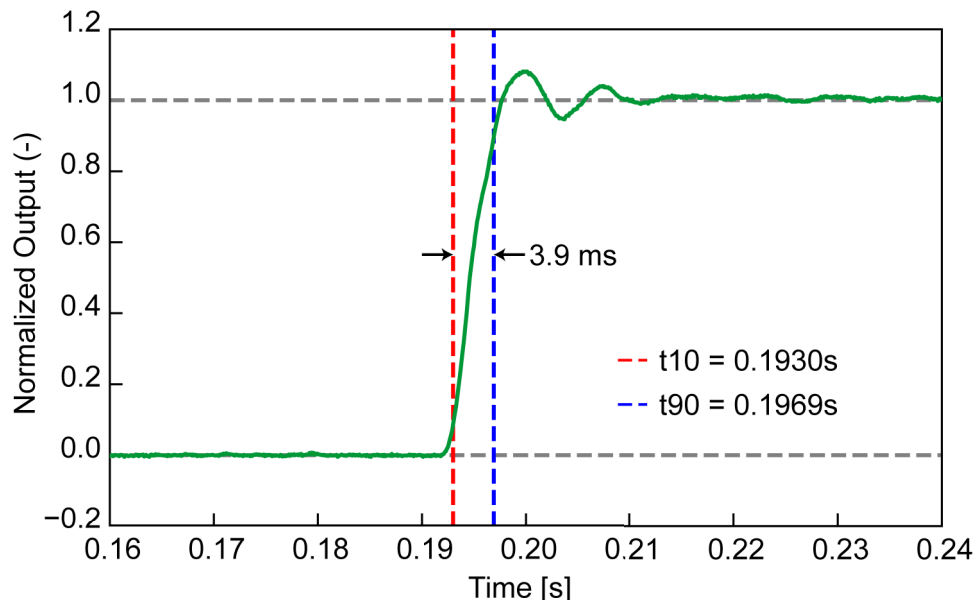


Fig. 3.12 Normalized pressure sensor output during when pressure is applied with step response.

extracted. The rise time  $t_r$  was defined as

$$t_r = t_{90} - t_{10}. \quad (3.3)$$

For the fabricated sensor,  $t_{10}$  and  $t_{90}$  were calculated as 0.1930 s and 0.1969 s, giving a 10–90% rise time of

$$t_r = 3.9 \text{ ms}. \quad (3.4)$$

The observed rise time of 3.9 ms includes the delay associated with the opening of the solenoid valve and the dynamics of the attached silicone tube and chamber. Therefore, this value should be interpreted as an upper bound on the sensor's temporal responsivity. The true responsivity of the sensor is expected to be equal to or faster than this value. A rise time of 3.9 ms indicates that the sensing system can respond to pressure variations occurring on millisecond timescales, corresponding to an equivalent time resolution on the order of several hundred hertz (approximately 250 Hz). This time scale is substantially faster than the characteristic behavioral frequencies of swimming sea turtles [95], such as flipper-stroke or body-motion frequencies. These results demonstrate that the developed sensor exhibits sufficiently high time resolution to capture rapid variations in waterflow and has the potential to be used to evaluate high-frequency behavior, such as speed fluctuations caused by animal movement.

### 3.5 Evaluation of temperature characteristics of the Pitot-type waterflow sensor

---

The proposed waterflow sensor developed in this study is completely filled and sealed with silicone oil. The sensor comprises two internal chambers, both containing the oil. However, because the two chambers have different volumes, a difference in volumetric expansion occurs when the temperature changes, resulting in a pressure imbalance between the chambers. Consequently, the baseline output voltage of the sensor varies with temperature, indicating the necessity of temperature compensation.

### 3.5.1 Experimental setup

To evaluate the temperature dependence of the fabricated waterflow sensor system, the sensor was submerged in water within a constant-temperature bath (LTB-400a, AS ONE Corp.), as shown in Fig. 3.13. To examine whether the use of two sensors can reduce the influence of temperature variation, the experiment was conducted with the logger connected to two sensors, each equipped with its own sensor case. The temperature varied from 5 °C to 25 °C in 5 °C increments, and the corresponding sensor outputs were recorded.

### 3.5.2 Experimental result of the sensor P-R

The experiments were conducted using two types of sensors: Sensor P-R and Sensor D. For each type, two sensors were connected to the data logger. The HTR logger was used for experiments with Sensor P-R, while the Ninja logger was employed for those with the Sensor D.

During the experiment with the Sensor P-R, the temperature of the thermostatic water tank was changed every 30 minutes. The resulting sensor P-R output is shown in Fig. 3.14. Both the  $Pitot_{det}$  and  $Pitot_{comp}$  responded to temperature change. For temperature effect evaluation, a 500-s stable segment (50000 samples) was extracted from each interval. Figure 3.15 (a) shows the relationship between the sensor output and the applied temperature. After extracting 50000 samples for each interval, the output at 5 °C was averaged, and the average was set as the zero baseline. All other samples were expressed as differential values  $\Delta E_{diff}$

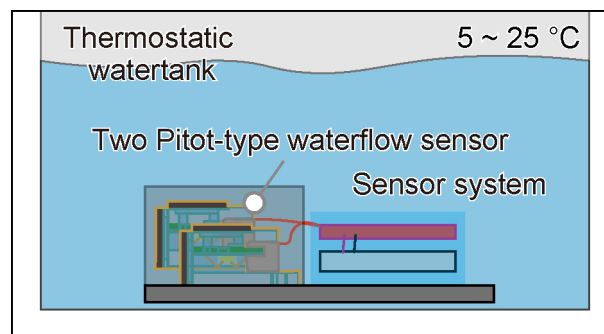


Fig. 3.13 Experimental setup of temperature calibration experiment.

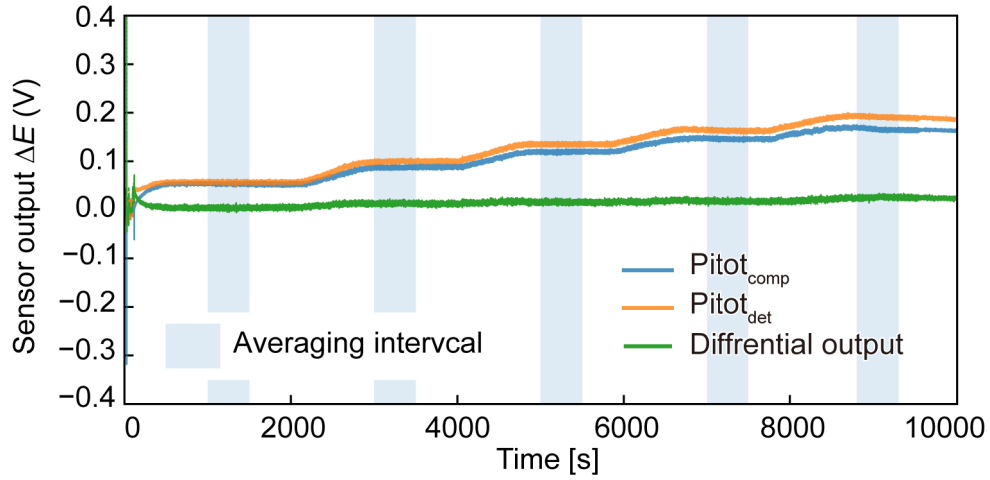


Fig. 3.14 Output of sensor P-R during the temperature calibration experiment.

relative to this baseline. Using all data points, a linear relationship between  $\Delta E_{\text{diff}}$  and the temperature difference  $\Delta T$  relative to 5 °C was obtained using the least-squares method. Both  $\text{Pitot}_{\text{comp}}$  and  $\text{Pitot}_{\text{det}}$  showed negative responses to temperature. The relationship between the  $\text{Pitot}_{\text{comp}}$  output and temperature is expressed as follows

$$\Delta E = -5.41 \times 10^{-3} \Delta T \quad (3.5)$$

The relationship between the  $\text{Pitot}_{\text{det}}$  output and temperature is given by

$$\Delta E = -6.40 \times 10^{-3} \Delta T, \quad (3.6)$$

and the relationship for differential output is given by

$$\Delta E = -0.997 \times 10^{-3} \Delta T. \quad (3.7)$$

The coefficient of determinations  $R^2$  for the fitting line of the  $\text{Pitot}_{\text{det}}$ ,  $\text{Pitot}_{\text{comp}}$ , and the differential output were 0.9817, 0.9854, and 0.7995, respectively. The high  $R^2$  values for  $\text{Pitot}_{\text{det}}$  and  $\text{Pitot}_{\text{comp}}$  indicate that the outputs of the individual sensors exhibit a strong linear relationship with temperature. Compared with the single-sensor measurements ( $\text{Pitot}_{\text{det}}$ ), the temperature sensitivity of the differential output decreased by a factor of 6.4 times. Taking the differential output effectively reduced the temperature effect. However, the differential output still shows a linear response to temperature. The lower  $R^2$  value of the differential

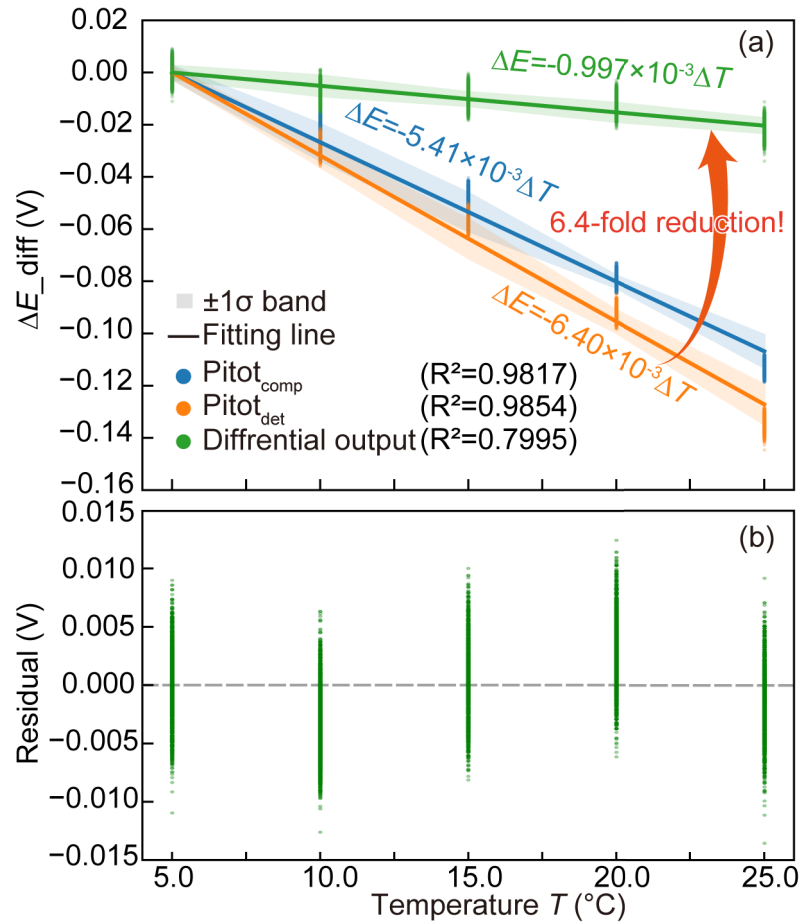


Fig. 3.15 (a) Relationship between sensor P-R output and applied temperature. (b) Residuals representing the deviation of the differential output from the fitting line.

output's fitting line does not indicate degraded performance. Because temperature sensitivity is strongly suppressed, the overall variation in the differential signal decreased. It makes noise relatively more dominant and lowers  $R^2$ . Thus, the reduced  $R^2$  likely reflects the effective reduction of temperature-induced drift. The Fig. 3.15 (b) shows residuals between differential output and calculated fitting line. The residuals show no systematic bias and remain narrowly distributed around zero across the entire temperature range. It indicates that the linear model accurately captures the temperature dependence of the differential output. Therefore, by using Eq. (3.7), the temperature effect can be further corrected from the differential output.

### 3.5.3 Experimental result of the sensor D

During the experiment with the Sensor D, the temperature of the thermostatic water tank was changed every 30 minutes. The resulting sensor output is shown in Fig. 3.16. Both the  $Pitot_{det}$  and  $Pitot_{comp}$  responded to temperature change. For temperature effect evaluation, a 160-s stable segment (500 samples) was extracted from each interval. Figure 3.17 (a) shows the relationship between the sensor D output and the applied temperature. After extracting 500 samples for each interval, the output at 5 °C was averaged, and the average was set as the zero baseline. All other samples were expressed as differential values  $\Delta E_{diff}$  relative to this baseline. Using all data points, a linear relationship between  $\Delta E_{diff}$  and the temperature difference  $\Delta T$  relative to 5 °C was obtained using the least-squares method. Both  $Pitot_{comp}$  and  $Pitot_{det}$  showed negative responses to temperature. The relationship between the  $Pitot_{comp}$  output and temperature is expressed as follows

$$\Delta E = 0.944 \times 10^{-4} \Delta T \quad (3.8)$$

The relationship between the  $Pitot_{det}$  output and temperature is given by

$$\Delta E = 1.03 \times 10^{-4} \Delta T, \quad (3.9)$$

and the relationship for differential output is given by

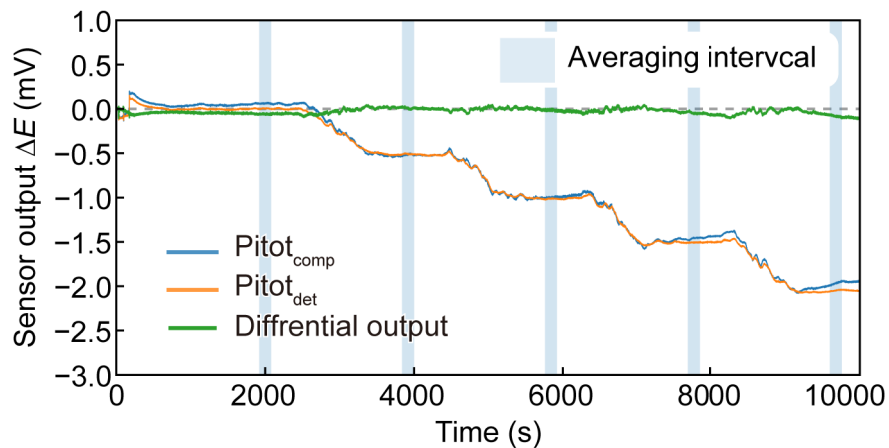


Fig. 3.16 Output of sensor D during the temperature calibration experiment.

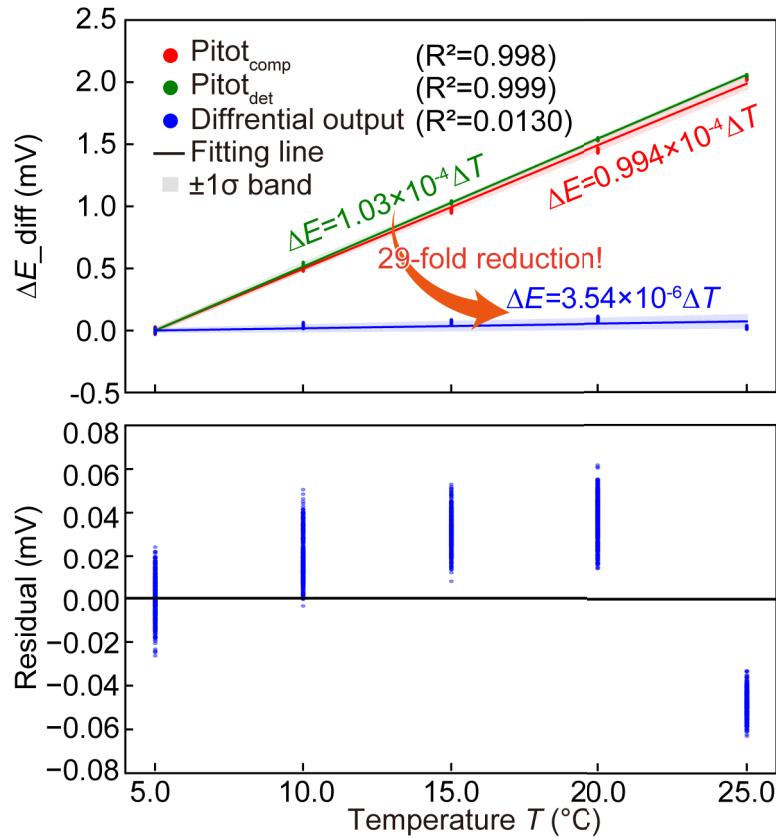


Fig. 3.17 (a) Relationship between sensor D output and applied temperature. (b) Residuals representing the deviation of the differential output from the fitting line.

$$\Delta E = 3.54 \times 10^{-6} \Delta T. \quad (3.10)$$

The coefficients of determination for the fitting lines of  $\text{Pitot}_{\text{det}}$ ,  $\text{Pitot}_{\text{comp}}$  and the differential output were 0.998, 0.998, and 0.0130, respectively. Compared with using the single sensor ( $\text{Pitot}_{\text{det}}$ ), taking the differential output reduced the temperature effect by a factor of 29. The sensor D also showed effective reduction of temperature drift, similar to the Sensor P-R. Hence, the coefficient determination of the fitting line of the differential output shows low value. Each sensor exhibited a linear response to temperature. The output slopes of Sensor P-R and Sensor D showed opposite signs, which can be attributed to differences in the internal oil chamber volumes between the front and side inlets of each sensor. In both cases, taking the differential output effectively reduced the temperature sensitivity. Figure 3.17 (b)

shows the residuals between differential output and calculated fitting line. The residuals showed no bias and remained low across all temperature intervals. Therefore, although the differential output shows low sensitivity to temperature changes, the temperature effect can be further compensated by applying Eq. (3.10).

### 3.6 Evaluation of sensor response to acceleration

---

Because the proposed sensor is designed to be attached to a sea turtle's carapace, it is exposed to accelerations from body movements and flow-induced vibrations. In addition, the sensor is filled with silicone oil, and the internal fluid can move in response to acceleration, generating noise in the waterflow measurement. Hence, the sensor is affected by these accelerations, including rigid-body accelerations acting uniformly on the entire sensor, such as gravitational acceleration and uniform translational acceleration of the sensor body.

To suppress these common-mode acceleration components, which do not generate differential pressure, the sensor system uses a differential configuration comprising two sensors. Importantly, this configuration preserves pressure variations associated with temporal changes in waterflow speed caused by sea turtle swimming. Because such pressure variations are only applied to the  $\text{Pitot}_{\text{det}}$ .

In this experiment, controlled common-mode acceleration was applied to evaluate the effectiveness of this differential design in reducing acceleration-induced disturbances.

#### 3.6.1 Experimental setup

Figure 3.18 shows experimental setup of acceleration calibration. In this experiment, measurements were performed using the combination of Sensor D and the Ninja logger. The sampling rate was set to 3.125 Hz. The two sensors were connected to the logger and mounted on a rate turntable (TA4635, Tamagawa Motortronics Co., Ltd., Nagano, Japan). Each sensor was positioned 2.0 m from the center of rotation to ensure a precisely defined acceleration. The system was rotated at a constant angular velocity, and by adjusting this



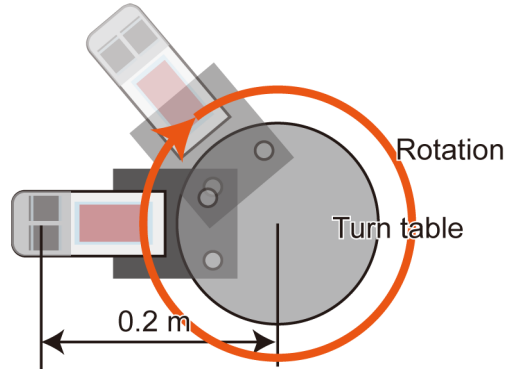


Fig. 3.18 Setup of the acceleration response experiment.

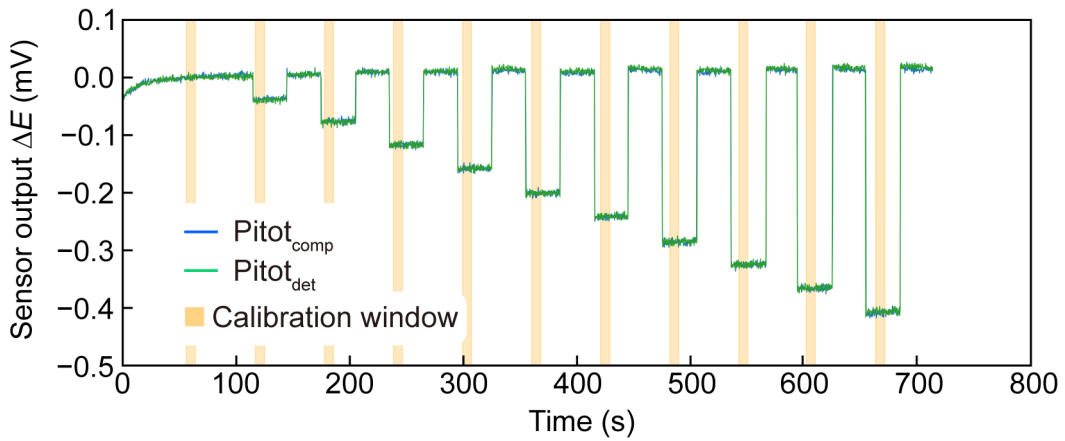


Fig. 3.19 Output of sensor D during the acceleration response experiment.

velocity, accelerations ranging from 0 g to 2.0 g were applied in 0.2 g increments. The corresponding sensor outputs were recorded for each acceleration level.

### 3.6.2 Experimental results

Figure 3.19 shows the sensor output during the acceleration response experiment. During the experiment,  $\text{pitot}_{\text{det}}$  and  $\text{pitot}_{\text{comp}}$  exhibited similar outputs and responded in a stepwise manner to changes in the angular velocity of the turn table. To derive the relationship between the applied acceleration  $a$  and the sensor output  $\Delta E$ , 26 data points on the orange-shaded calibration window corresponding to 8.32 s of stable output were extracted for each applied acceleration. In total, 286 samples were extracted. These data were used to obtain the

fitting line using the least-squares method.

Figure 3.20 (a) shows the relationship between the sensor output and the applied acceleration. The sensors exhibited a linear response to acceleration. As in the temperature experiment, taking the differential output between the two sensors significantly reduced sensitivity to acceleration. The sensitivity of  $\text{pitot}_{\text{comp}}$  and  $\text{pitot}_{\text{det}}$  were nearly identical values, as shown below.

$$\Delta E = -2.06 \times 10^{-4} \Delta a \quad (3.11)$$

Whereas with the differential output, the sensitivity decreased to

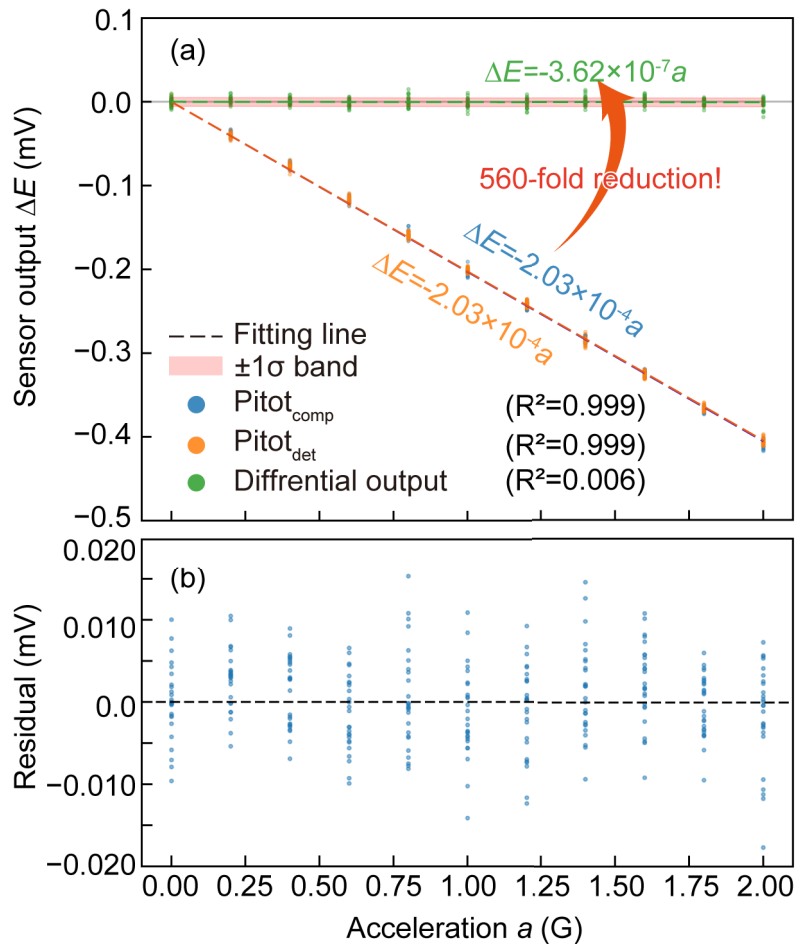


Fig. 3.20 (a) Relationship between the sensor output and applied acceleration. (b) Residuals represent the deviation of the differential output from the fitting line.

$$\Delta E = -3.62 \times 10^{-7} \Delta a, \quad (3.12)$$

representing a 560-fold reduction in sensitivity. The coefficients of determination for each fitting lines were 0.999 and 0.006. Figure 3.20 (b) shows residuals between the extracted experimental data points and the fitting line of the differential output. The residuals are randomly distributed around zero with no systematic dependence on acceleration. In addition, the coefficient of determination for the fitting line of the differential output was very small. These indicate that the differential output does not have a meaningful correlation with the applied acceleration. This result further demonstrates the high compensation performance of the differential configuration. From the Sections 3.5 and 3.6, it was demonstrated that taking the differential output effectively reduces the influence of external disturbances, confirming the dual-sensor configuration's effectiveness in improving the robustness of the sensor system.

### 3.7 Water tunnel experiment

To evaluate the sensor's response to waterflow speed, experiments were conducted in a water tunnel under controlled flow conditions. The objective was to establish the relationship between the sensor output and the applied waterflow speed, thereby enabling quantitative estimation of flow speed from the measured output.

#### 3.7.1 Experimental setup

To evaluate the response of the sensor system to waterflow speed, a waterflow-speed calibration experiment was conducted. The sensor system was fixed in a compact water tunnel (Nishinippon Fluid Engineering Laboratory Co., Ltd., PT-100). To minimize the effects of the boundary layer and the air–water interface, the system was positioned at the center of the tunnel, ensuring that the waterflow was applied parallel to the sensor. A photograph of the experimental setup is shown in Fig. 3.21. The sensor system was mounted on a machined aluminum stage that securely fixed it within the tunnel.

During the experiment, waterflow speeds ranging from 0.0 m/s to 2.0 m/s were

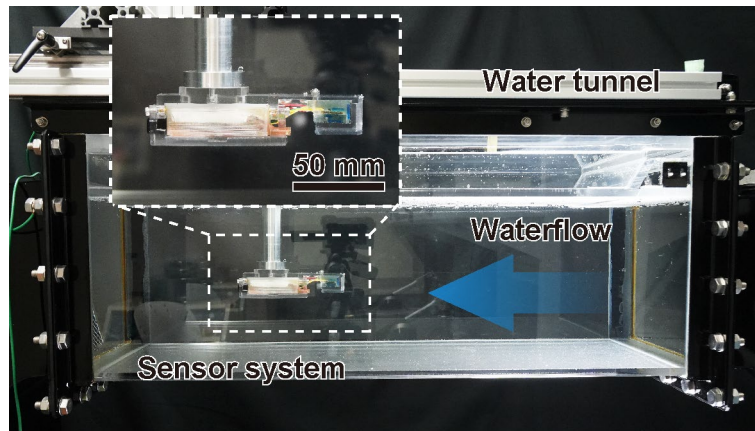


Fig. 3.21 Photograph of the experimental setup for the water tunnel experiment.

sequentially applied in 0.2 m/s increments. The flow control was automated using a custom Python program that communicated with the water tunnel's inverter via a Modbus interface. For each flow condition, the tunnel was first stopped for 60 s to ensure flow stabilization, followed by the application of the target flow speed for 90 s while data were recorded. This sequence of stopping and flow application was repeated for each speed step.

The waterflow-speed calibration experiments were conducted using two types of sensors: sensor P-R and sensor D. The measurements for sensor P-R were performed using the HTR logger, while those for sensor D were recorded using the Ninja logger. The results obtained from each configuration are presented below.

### 3.7.2 Experimental result of sensor P-R

The output of sensor P-R during the experiment is shown in Fig. 3.22. The sensor outputs were converted from bit values to voltage using Eq. 2.90. As the theoretical model predicted in Section 2.10, the  $Pitot_{det}$  output varied with waterflow speed, while the  $Pitot_{com}$  output remained almost constant. In addition, oscillatory fluctuations appeared in both  $Pitot_{det}$  and  $Pitot_{com}$  outputs as the waterflow speed increased. Four factors mainly caused these fluctuations:

- (i) Turbulent speed fluctuations in the water tunnel
- (ii) Wake generated by flow separation

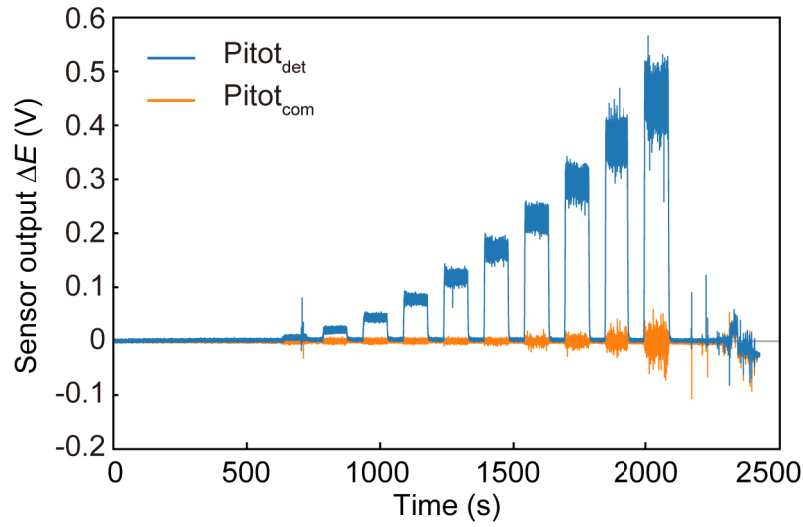


Fig. 3.22 Output of Sensor P-R during the water tunnel experiment

- (iii) Surface fluctuations at the open port of the water tunnel
- (iv) Periodic vibration from the water tunnel system

Other factors may also have contributed. The oscillatory fluctuations are expected to be a combination of these multiple sources. The water tunnel has an inner width of 0.30 m. Therefore, if a waterflow speed is assumed to be  $U = 1$  m/s and a kinematic viscosity is  $1 \times 10^{-6}$  m<sup>2</sup>/s, the Reynolds number becomes  $Re = 3 \times 10^5$ . The waterflow at this Reynolds number is in the turbulent region. Even with flow-straightening elements in the water tunnel, dynamic pressure is expected to fluctuate.

In addition, flow separation generates a wake behind the sensor system. The sensing system has a complex shape, including the rectangular Pitot-type waterflow sensor, the sensor case, and the data logger. Furthermore, the cylindrical aluminum stage is used to mount the system in the water tunnel. These components generate wakes that contain vortices of many different scales. To estimate the order of the oscillatory fluctuation frequency generated by the wake, the sensor is approximated as a rectangular cylinder in waterflow. The frequency can be estimated using the Strouhal number  $St$ , which is expressed as follows:

$$St = \frac{fD}{U} \quad (3.13)$$

where  $f$  is the vortex shedding frequency (Hz),  $D$  is the characteristic length of the object (m),

and  $U$  is the flow speed (m/s). Assuming the Reynolds number is sufficiently high, the Strouhal number  $St$  is taken as 0.13. Given the flow speed of  $U = 2.0$  m/s and a characteristic length of  $D = 0.020$  m. Substituting the values to eq. (3.13),

$$f = St \frac{U}{D} = 0.13 \times \frac{2.0}{0.020} = 13 \quad (3.14)$$

Thus, the frequency of the vortices generated behind the sensor is approximately 13 Hz. In practice, the sensor system has the complex structure, so this value represents only an approximate order of magnitude.

The sensing system is mounted in the water tunnel using a cylindrical aluminum stage. As a result, the water surface remains exposed around the opening where the sensing system is inserted. At this opening, the air-water interface deforms. As the waterflow speed increases, the surface motion grows stronger and is transmitted to the sensor as pressure fluctuations. Furthermore, the water tunnel generates waterflow using a motor and propeller. When the water tunnel operates, these components can introduce mechanical vibrations that may be transmitted to the sensor.

To identify the frequency components in the sensor signal, frequency analyses were conducted. First, a continuous wavelet transform (CWT) was applied to examine how the spectral content evolved over time. Figure 3.23 shows CWT results for  $Pitot_{com}$ ,  $Pitot_{det}$ , and their differential output. The differential signal was obtained by subtracting the  $Pitot_{com}$  value from  $Pitot_{det}$  value. The CWT was performed using the complex Morlet (amor) mother wavelet. The transform produces a two-dimensional distribution of wavelet power  $|W(t, f)|^2$ , over frequencies from 0.1 to 50 Hz. To visualize fluctuations over several orders of magnitude, the wavelet power was plotted using a logarithmic color scale ( $\log_{10}Power$ ).

The resulting wavelet power maps show low power levels in the no-waterflow condition, while higher power appears during the periods when waterflow is applied. For both  $Pitot_{com}$  and  $Pitot_{det}$ , the low-waterflow regions exhibit stronger power mainly in the mid-frequency band (approximately 10–40 Hz), with relatively little energy at lower or higher frequencies. As the waterflow speed increases, the power spreads across a much broader range of frequencies.

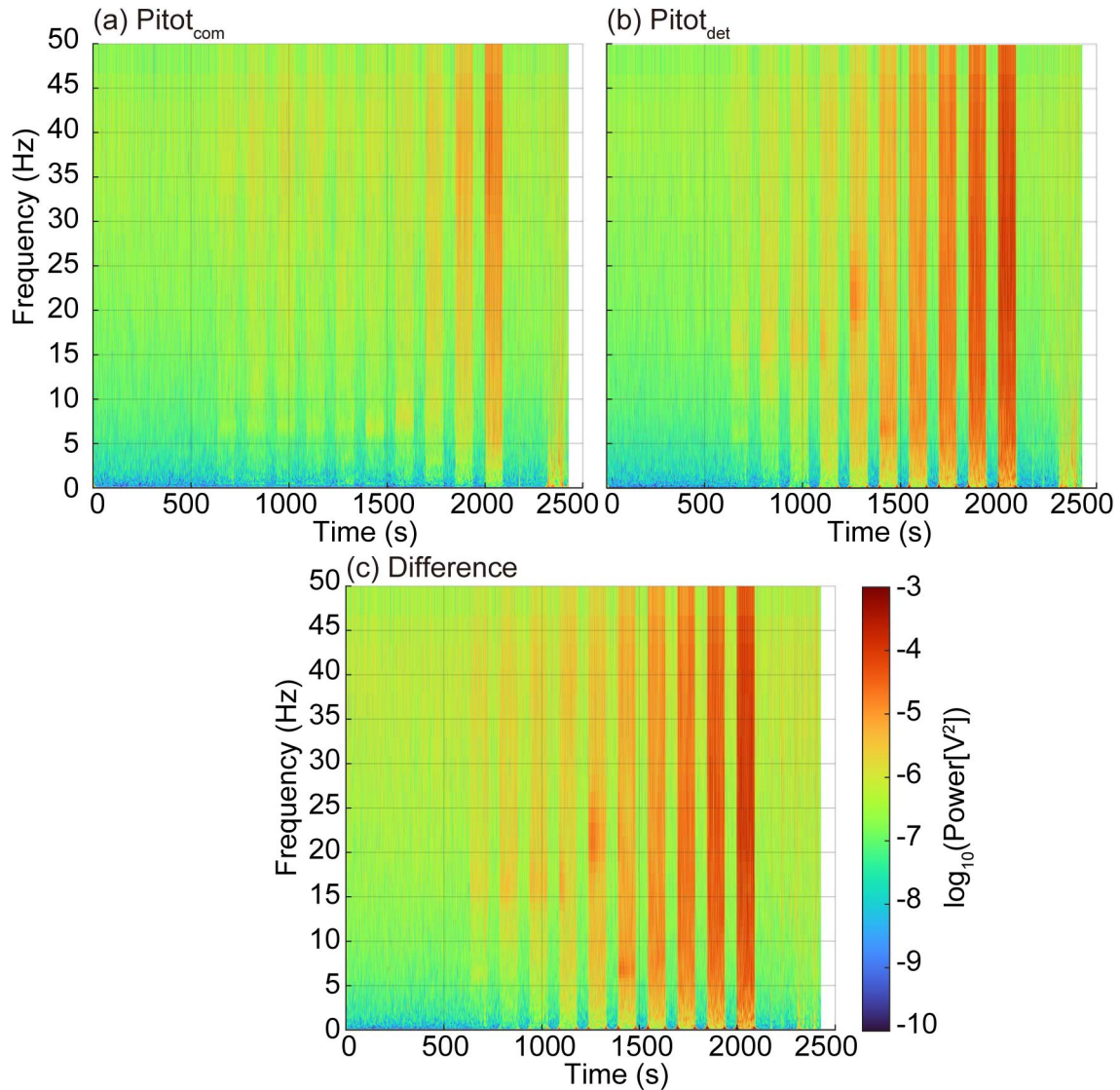


Fig. 3.23 Continuous wavelet transform (CWT) result of (a) Pitot<sub>com</sub>, (b) Pitot<sub>det</sub>, and (c) their differential output.

To perform a more detailed frequency analysis, a Fast Fourier Transform (FFT) algorithm was applied to the data segments corresponding to each applied waterflow speed interval. For each waterflow-speed interval, the corresponding time segment was extracted based on the experimental timeline. To obtain stable spectra from these finite-length segments, the FFT was computed using Welch's method. Each segment was divided into overlapping sub-windows of 256 samples, and a Hann window was applied to suppress spectral leakage.



Adjacent windows overlapped by 50%, and the resulting periodograms were averaged to produce the power spectral density (PSD). The spectrum represents the distribution of pressure-fluctuation energy over frequencies up to 50 Hz, consistent with the 100Hz sampling rate. Fig. 3.24 shows the PSD for each waterflow-speed interval. The FFT results were consistent with the wavelet analysis. In the low-speed region (0.2 m/s – 0.8 m/s),

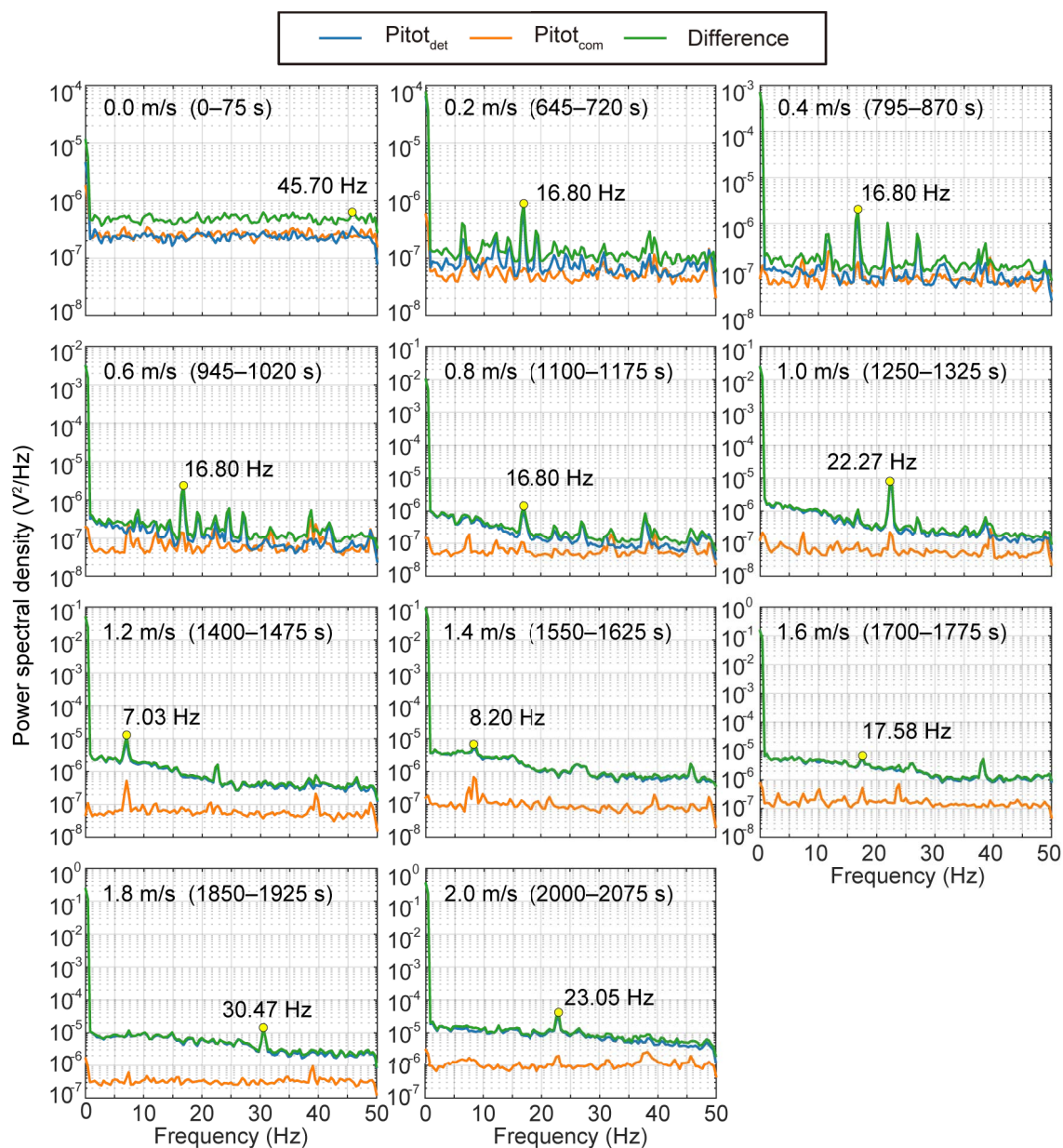


Fig. 3.24 Power spectral density of the sensor outputs for each waterflow-speed interval.



multiple peaks appeared in the 10–40 Hz band. In the high-speed region, the PSD spanned a much broader frequency range. To identify the dominant oscillation frequencies at each waterflow speed, the peak frequency was extracted from the PSDs. Frequencies below 2 Hz were removed to eliminate the DC (Direct Current) component from the signal. The remaining spectrum was searched for peaks. Peak detection used a prominence-based criterion to select components while suppressing noise. Among the detected peaks, the one with the largest amplitude in the 2–50 Hz range was taken as the dominant frequency.

For waterflow speeds between 0.2 and 0.8 m/s, all measurements showed a peak at 16.8 Hz, with several additional peaks in the 10–30 Hz range. These vibrations are likely due to mechanical oscillations in the water tunnel. These peaks are likely due to vibrations from the motor and other moving parts being transmitted to the sensor. As a result, a similar frequency peak appears at all low waterflow speeds (0.2–0.8 m/s). At speeds above 1.0 m/s, additional oscillation components grow stronger and gradually mask these peaks.

Several peaks were also observed in the high-speed region (1.0–2.0 m/s). These oscillation components are likely due to multiple factors, including turbulent speed fluctuations in the water tunnel, wake effects from flow separation, and surface motion at the open port. However, all these peaks appear at frequencies above 5 Hz. Therefore, to reduce these vortex-induced oscillations, a low-pass filter with a cutoff frequency of 5 Hz was applied. It ensured that the filter effectively attenuates vortex noise while preserving the signals associated with the turtle's flipper strokes. Figure 3.25 shows the differential pressure calculated from four signals:  $P_{\text{tot}_{\text{com}}}$  and  $P_{\text{tot}_{\text{det}}}$  outputs, the differential output, and the low-pass-filtered differential output. The result demonstrates that filtering process effectively reduced oscillations in the output. 45s segments (4500 samples) of stable data for each waterflow speed from 0 to 2.0 m/s, yielding a total of 49500 samples used for calibration. These intervals correspond to the gray-shaded regions in the Fig. 3.25. Using data within the gray-shaded regions, the relationship between measured differential pressure and applied waterflow speed was derived. These relationships are presented in Fig. 3.26. Because the theoretical model predicts a quadratic relationship of the form  $\Delta P = aU^2$ , the calibration

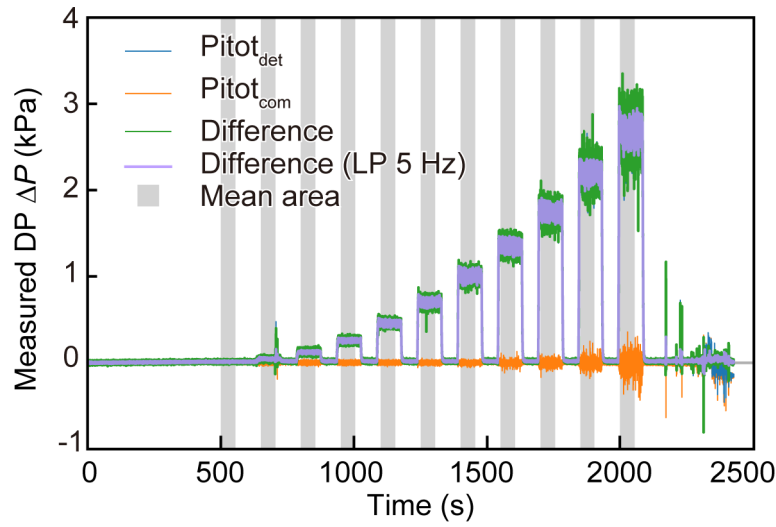


Fig. 3.25 Measured differential pressure using sensor P-R during the water tunnel experiment.

coefficient  $a$  was estimated by nonlinear least-squares fitting to this model. The fit was applied directly to the data in the gray-shaded regions. As predicted by the theoretical model described earlier, the sensor responded in proportion to the square of the waterflow speed, similar to a conventional Pitot tube. The relationship between the differential pressure measured by the sensor and the waterflow speed was obtained as

$$\Delta P = \frac{1.35}{2} U^2. \quad (3.15)$$

The goodness of fit was the coefficient of determination. The resulting  $R^2$  value was 0.9993, indicating that the quadratic model explains more than 99.9% of the variance in the measured differential pressure. It demonstrates that the sensor shows good agreement with the expected sensor response across the entire speed range. Using Eq. (3.9), the sensor system can accurately calculate the waterflow speed from the measured differential pressure. The green-shaded area represents the sensor output's standard deviation. Although the standard deviation increased with higher waterflow speeds, it remained as low as 0.0274 m/s even at 2.0 m/s. Fig. 3.27 shows the residuals between the measured differential pressure and the fitted model (Eq. (3.9)). The residuals remain close to zero across the entire waterflow speed range, with no systematic trend such as monotonic drift or curvature. Although the absolute

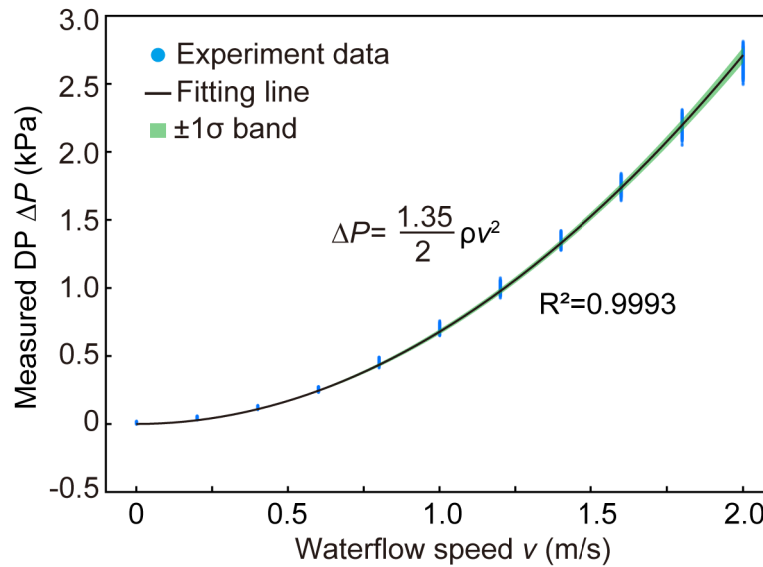


Fig. 3.26 Relationship between the measured differential pressure and the waterflow speed of sensor P-R.

residuals increase at high speeds, the sensor response does not deviate significantly from the fitted model. This indicates that a specific error does not cause these residuals. Overall, the narrow, zero-centered residual distribution and the high coefficients of determination show that the derived calibration model accurately represents the Pitot-type waterflow sensor response across the entire speed range.

The accuracy and resolution of the sensor P-R were calculated using the measured differential pressure within the gray-shaded region. Figure 3.28 shows calculated sensor accuracy and resolution of the sensor P-R. For each waterflow speed interval, the low-pass-filtered differential pressure was converted to an estimated waterflow speed using Eq. (3.15). The mean of the estimated waterflow speeds was used as the representative speed  $U_{\text{est}}$  for that condition. Sensor accuracy was calculated by comparing the  $U_{\text{est}}$  and the applied waterflow speed  $U_{\text{set}}$  applied by the water tunnel. Because the sensor response follows a quadratic relationship ( $\Delta P = aU^2$ ), the measurement accuracy and resolution inherently vary with waterflow speed. For this reason, these performance metrics were evaluated separately for each waterflow-speed interval. Absolute accuracy is shown as the deviation between the  $U_{\text{est}}$  and  $U_{\text{set}}$ , expressed as

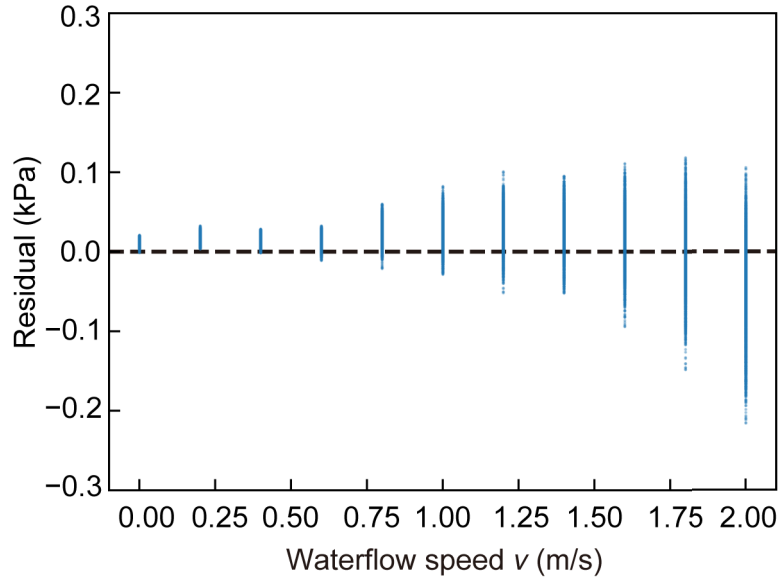


Fig. 3.27 Residuals between the measured differential pressure and the fitting line.

$$|U_{est} - U_{set}|. \quad (3.16)$$

In addition, relative accuracy expresses this deviation as a percentage of the  $U_{set}$ ,

$$\frac{|U_{est} - U_{set}|}{U_{set}} \times 100. \quad (3.17)$$

The resolution of the sensor P-R was using the noise characteristic measured at zero waterflow speed. In this study, resolution was defined using two different measures: noise-floor intrinsic resolution and operational resolution. First, the noise-floor intrinsic resolution was defined from the noise level of the measured differential pressure  $\Delta P$  under no-waterflow conditions (0 m/s). This noise level was quantified as the standard deviation of the low-pass-filtered differential pressure signal. The resulting pressure noise was converted into an equivalent speed resolution using the Eq. (3.15). Second, the operational resolution was defined to evaluate output fluctuations under actual watertunnel conditions. It was calculated as the standard deviation of the low-pass-filtered differential pressure within each applied waterflow speed interval. These values were converted into a speed resolution by uncertainty propagation using the Eq. (3.15). These definition enable a quantitative comparison between the resolution limited by intrinsic noise and the resolution observed

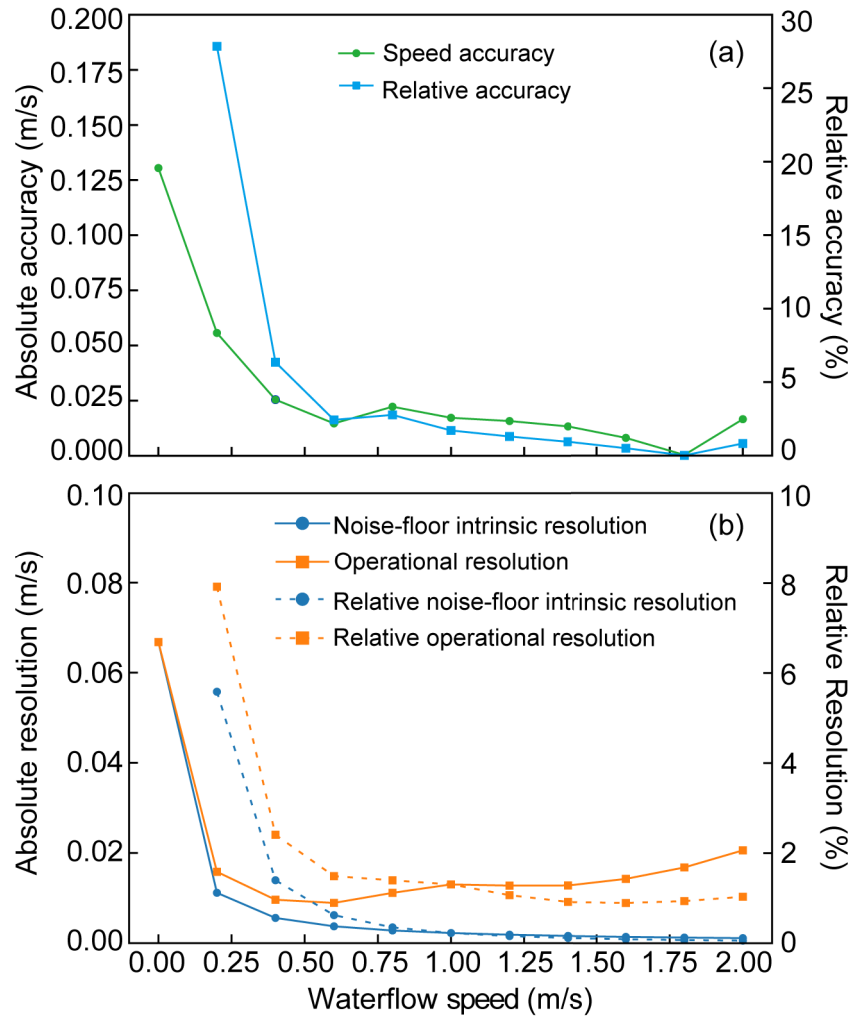


Fig. 3.28 (a) Accuracy and (b) resolution of sensor P-R at each waterflow speed.

under watertunnel condition.

The noise-floor intrinsic resolution was derived as follows. The standard deviation of the low-pass-filtered differential pressure in the 0 m/s interval within the gray-shaded region was calculated as  $\sigma_P(0)$ . This pressure noise was converted to an equivalent speed noise  $\sigma_U(0)$ , by using Eq. (3.15). This value represents the absolute resolution at 0 m/s. Because this sensor follows the quadratic relationship (Eq. (3.15)), the sensor's sensitivity increases with waterflow speed. Thus, the noise-floor intrinsic resolution  $\sigma_{U,int}(U)$  at each applied waterflow speed  $U_{set}$  was obtained by scaling the 0 m/s pressure noise deviation according to

$$\sigma_{U,int}(U) = \frac{2}{1.35} \frac{\sigma_P(0)}{2U}. \quad (3.18)$$

The relative noise-floor intrinsic resolution was calculated by normalizing  $\sigma_{U,int}(U)$  by the applied waterflow speed  $U_{set}$ .

The operational resolution was derived as follows. For each applied waterflow speed interval, the low-pass-filtered differential pressure within the corresponding gray-shaded was also extracted. The output fluctuation under operating conditions was quantified as the standard deviation of the low-pass-filtered differential pressure, denoted as  $\sigma_P(U)$ , for each  $U_{set}$ . The operational resolution  $\sigma_{U,op}(U)$  was obtained by converting  $\sigma_P(U)$  into an equivalent speed resolution through uncertainty propagation based on Eq. (3.15). For  $U_{set} > 0$  m/s, it is expressed as

$$\sigma_{U,op}(U) = \frac{2}{1.35} \frac{\sigma_P(U)}{2U}. \quad (3.19)$$

At  $U_{set} = 0$  m/s, the operational resolution and the noise-floor intrinsic resolution are identical, because both are defined by the differential pressure noise under no-waterflow conditions. Therefore,  $\sigma_{U,op}(0) = \sigma_{U,int}(0) = \sigma_U(0)$ . The relative operational resolution was calculated by normalizing  $\sigma_{U,op}(U)$  by the applied waterflow speed  $U_{set}$ .

Table 3.3 shows the calculated accuracy and resolution of sensor P-R. The fabricated sensor showed low values for both accuracy and resolution. The sensor follows the quadratic relationship. So, the sensor tends to exhibit lower resolution and accuracy at low speeds. However, the sensor satisfied the required specifications for accuracy and resolution at all waterflow speeds. At 0.2 m/s, which conventional propeller loggers have difficulty measuring, the sensor achieved a noise-floor intrinsic resolution of 0.0112 m/s, operational resolution of 0.0158 m/s, and an accuracy of 0.0557 m/s. The operational resolution includes not only the intrinsic noise of the sensing system but also additional disturbances specific to the water tunnel environment. Even when the applied waterflow speed  $U_{set}$  is set to constant, the water tunnel can exhibit time-varying speed fluctuations due to turbulence and facility dependent unsteadiness. In the present setup, the sensor system was inserted through an open port, leaving the surrounding free water surface exposed. As the applied waterflow speed increased, fluctuations of the air-water interface at this opening

---

Fundamental Characteristics of the Pitot-Type Waterflow sensor

---

Table 3.3 Accuracy and resolution of sensor P-R.

| Speed<br>[m/s] | Speed<br>accuracy<br>[m/s] | Relative<br>accuracy<br>[%] | Noise-floor<br>intrinsic<br>resolution<br>[m/s] | Relative<br>noise-floor<br>intrinsic<br>resolution<br>[%] | Operational<br>resolution<br>[m/s] | Relative<br>operational<br>resolution<br>[%] |
|----------------|----------------------------|-----------------------------|-------------------------------------------------|-----------------------------------------------------------|------------------------------------|----------------------------------------------|
| 0.0            | 0.130                      |                             | 0.0668                                          |                                                           | 0.0668                             |                                              |
| 0.2            | 0.0557                     | 27.8                        | 0.0112                                          | 5.58                                                      | 0.0158                             | 7.91                                         |
| 0.4            | 0.0255                     | 6.36                        | 0.00558                                         | 1.39                                                      | 0.00961                            | 2.40                                         |
| 0.6            | 0.0147                     | 2.44                        | 0.00372                                         | 0.620                                                     | 0.00891                            | 1.49                                         |
| 0.8            | 0.0223                     | 2.78                        | 0.00279                                         | 0.349                                                     | 0.0111                             | 1.39                                         |
| 1.0            | 0.0172                     | 1.72                        | 0.00223                                         | 0.223                                                     | 0.0130                             | 1.30                                         |
| 1.2            | 0.0158                     | 1.31                        | 0.00186                                         | 0.155                                                     | 0.0128                             | 1.06                                         |
| 1.4            | 0.0133                     | 0.950                       | 0.00159                                         | 0.114                                                     | 0.0128                             | 0.913                                        |
| 1.6            | 0.00805                    | 0.503                       | 0.00139                                         | 0.0871                                                    | 0.0143                             | 0.893                                        |
| 1.8            | 0.000307                   | 0.0170                      | 0.00124                                         | 0.0689                                                    | 0.0168                             | 0.934                                        |
| 2.0            | 0.0165                     | 0.827                       | 0.00112                                         | 0.0558                                                    | 0.0206                             | 1.03                                         |

became larger and were transmitted to the sensor as pressure disturbances. In addition, flow separation around the sensor system and the mounting stage can generate wakes. These flow features introduce unsteady pressure fluctuations around the sensor. Mechanical vibrations originating from the experiment setup, such as those from the motor and propeller, may also be transmitted to the sensor signal. Consequently, the operational resolution  $\sigma_{U,op}(U)$  represents an effective resolution under water tunnel operating conditions that includes facility-dependent contributions. In practical field deployments, the sensor is typically fully submerged and is therefore not influenced by free-surface motion at an open port. In addition, the mounting configuration differs from the stage used in the water tunnel. As a result, the magnitude of pressure oscillations in practical field deployments is expected to be smaller than that observed in the water tunnel experiments, although unsteady flow may still remain.

Based on these considerations, the resolution in actual use is expected to lie between the noise-floor intrinsic resolution  $\sigma_{U,int}(U)$  and the operational resolution  $\sigma_{U,op}(U)$ .

At  $U_{set} = 0.2$  m/s, the noise-floor intrinsic resolution  $\sigma_{U,int}(U)$  and the operational resolution  $\sigma_{U,op}(U)$  were 0.0112 m/s (5.58%) and 0.0158 m/s (7.91%), respectively. This result indicates that the effective resolution under field conditions is expected to be approximately 0.011–0.016 m/s at 0.2 m/s. This resolution is sufficiently smaller than the applied speed, indicating that the sensor can measure sub-0.2 m/s waterflow without being dominated by measurement noise. As applied waterflow speed increases, the accuracy and resolutions improve. For example, at  $U_{set} = 0.4$  m/s, the accuracy was 0.0255 m/s (6.36%), while the noise-floor intrinsic and operational resolutions were 0.00558 m/s (1.39%), respectively. In the range of 0.6–2.0 m/s, the relative accuracy remained 3%, and the relative operational resolution remained close to approximately 0.9–1.5% for  $U_{set} \geq 1.0$  m/s. These results demonstrate that the fabricated sensor satisfies the required specifications for both accuracy and resolution over the entire tested range. Importantly, the sensor provides measurable performance in the low-speed region around 0.2 m/s, where the conventional propeller loggers cannot measure.

### 3.7.3 Experimental result of sensor D

Using the same setup and time setting, waterflow was applied to Sensor D, and the corresponding sensor output is shown in Fig. 3.29. The sensor output  $\Delta E$  was defined as the voltage referenced to the sensor output voltage  $E$  at 0 s. In this measurement, the Ninja logger captured the sensor output. The sampling rate was set to 3.125 Hz. Similar to Sensor P-R, Pitot<sub>det</sub> responded to the waterflow, whereas Pitot<sub>com</sub> did not. The output drift observed between 0 and 200 s was attributed to temperature variation caused by rapid cooling when the sensor was submerged in the water tunnel. The noise observed near 2000 s occurred when the sensor was removed from the tunnel and was caused by acceleration. The differential output between the two sensors, shown by the green line, remained stable even under temperature drift and acceleration disturbances. These results demonstrate that the dual-sensor differential configuration effectively suppresses drift effects while accurately



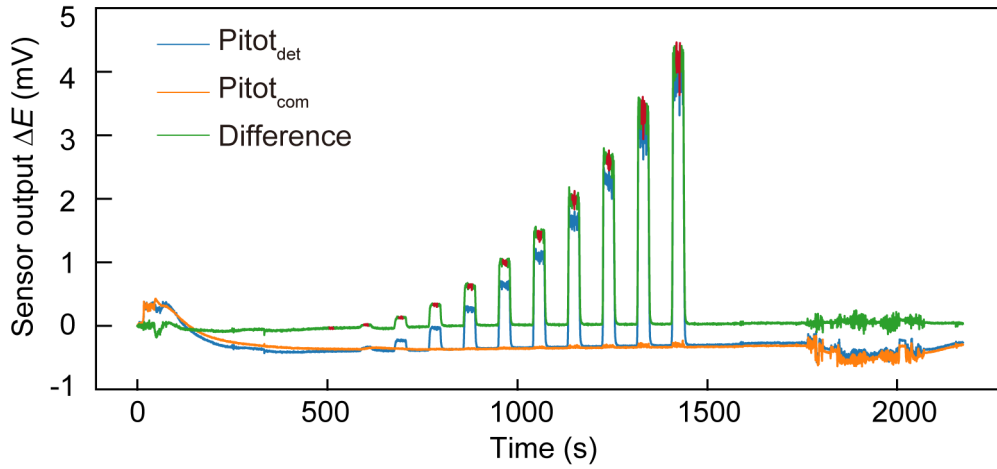


Fig. 3.29 Output of Sensor D during the water tunnel experiment.

measuring the waterflow speed.

To derive the relationship between the sensor output  $\Delta E$  and the applied waterflow speed  $U$ , the stable period of the differential output indicated by the red line was extracted. Figure 3.30 (a) shows the differential pressure measured by the sensor and the corresponding waterflow speed for the extracted periods. For each applied waterflow speed, 31 data points corresponding to 9.92 s were extracted. In total, 341 data points (109.12 s) were used to derive the relationship between waterflow speed  $U$  and the measured differential pressure  $\Delta P$  by using least-squares fitting in the form of  $\Delta P = aU^2/2$ . As with a conventional Pitot tube, the sensor response was proportional to the square of the flow speed, and the relationship can be expressed as

$$\Delta P = \frac{1.17}{2} U^2. \quad (3.19)$$

The coefficient of determination  $R^2$  is 0.9967. Using this equation, the waterflow speed can be calculated directly from the sensor output. Figure 3.30 (b) shows residuals between measured differential pressure and derived fitting line. The residuals are distributed around zero over the entire range of applied waterflow speeds, and no systematic deviation is observed. These results indicate that the derived relationship represents the sensor response without systematic bias. As the applied waterflow speed increased, the amplitude of the sensor output oscillations also increased, similar to sensor P-R. The sampling rate in this

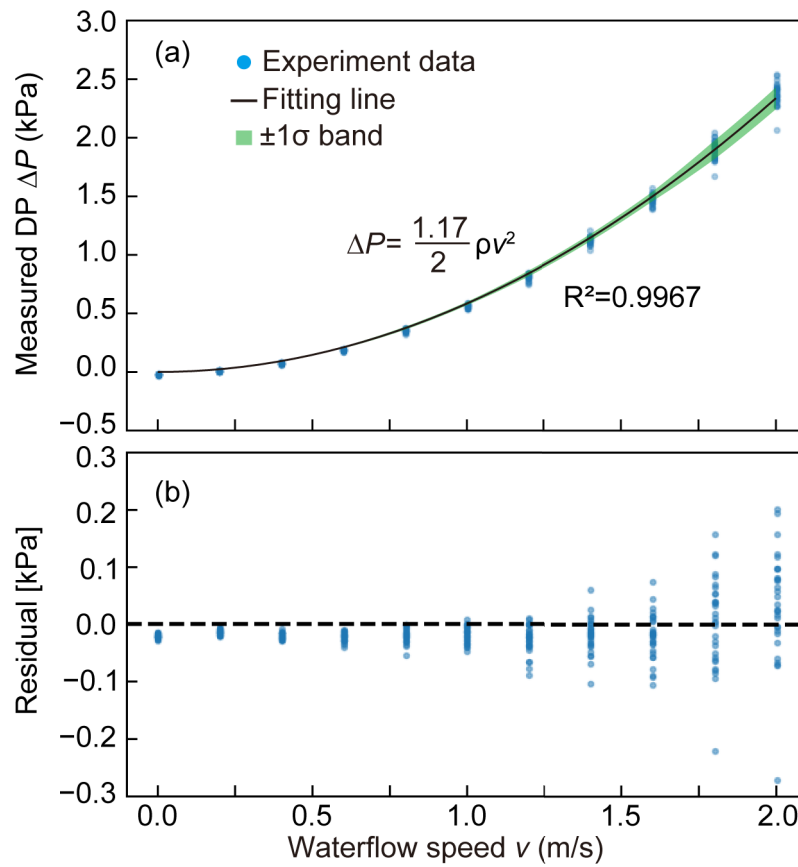


Fig. 3.30 (a) Relationship between the measured differential pressure and the waterflow speed. (b) Residuals between the measured differential pressure and the fitting line.

measurement was 3.125 Hz, corresponding to a Nyquist frequency of 1.5625 Hz. Therefore, frequency-domain analysis was not performed. The observed increase in the amplitude of the sensor output oscillations with increasing waterflow speed. This behavior suggests that unsteady waterflow effects, such as turbulence and vortex-induced pressure fluctuations, may contribute to the observed variability, as also observed for sensor D.

The accuracy and resolution of the sensor D were calculated using the measured differential pressure within the red line region. Figure 3.31 shows calculated the sensor accuracy and resolution for the sensor D. For each waterflow speed interval, the accuracy, noise-floor intrinsic resolution, and operational resolution were calculated using the same definitions and procedures as those applied to sensor P-R. Specifically, accuracy was calculated using Eq. 3.16. The noise-floor intrinsic resolution was calculated as

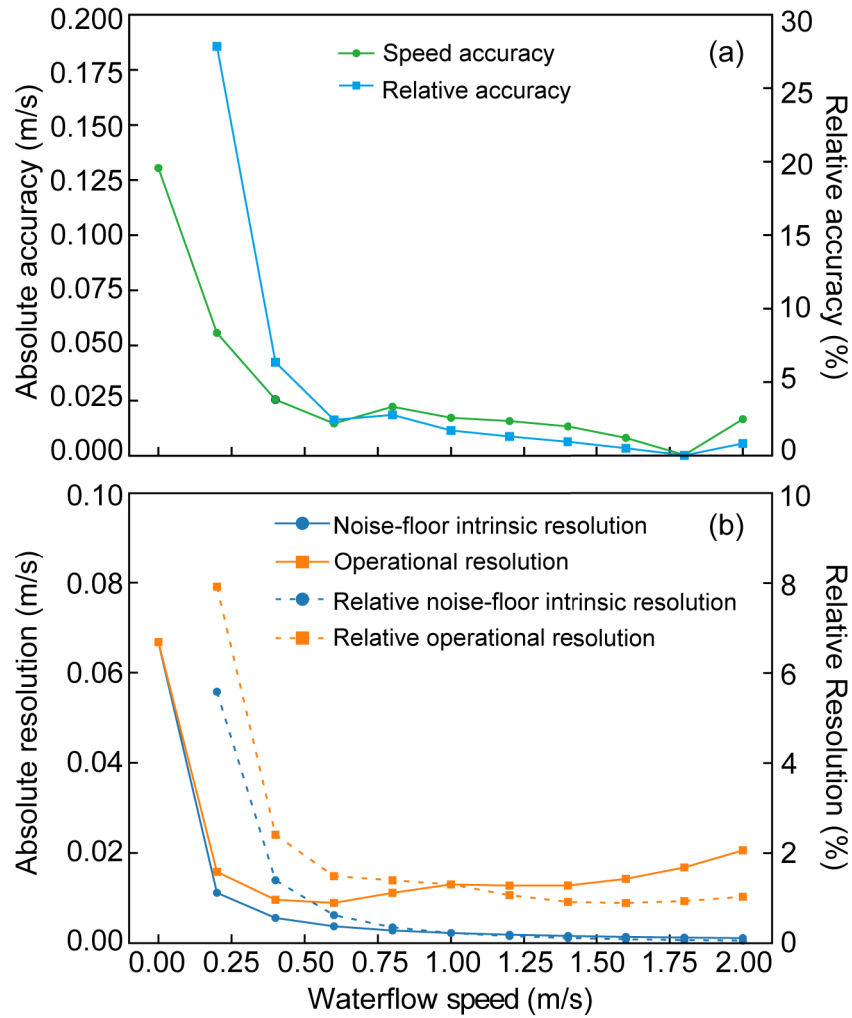


Fig. 3.31 (a) Accuracy and (b) resolution of sensor D at each waterflow speed.

$$\sigma_{U,int}(U) = \frac{2}{1.17} \frac{\sigma_P(0)}{2U}, \quad (3.20)$$

and the operational resolution was calculated as

$$\sigma_{U,op}(U) = \frac{2}{1.17} \frac{\sigma_P(U)}{2U}. \quad (3.21)$$

Table 3.4 summarizes the calculated accuracy and resolution of sensor D. At  $U_{set} = 0.2$  m/s, sensor D achieved a noise-floor intrinsic resolution of 0.00910 m/s (4.55%) and an operational resolution of 0.0109 m/s (5.45%). This result indicates that the effective resolution under field conditions is expected to be approximately 0.009–0.011 m/s at 0.2 m/s. Although the relative accuracy at this speed was relatively large (37.9%), the absolute

---

Fundamental Characteristics of the Pitot-Type Waterflow sensor

---

Table 3.4 Accuracy and resolution of sensor D.

| Speed<br>[m/s] | Speed<br>accuracy<br>[m/s] | Relative<br>accuracy<br>[%] | Noise-floor<br>intrinsic<br>resolution<br>[m/s] | Relative<br>noise-floor<br>intrinsic<br>resolution<br>[%] | Operational<br>resolution<br>[m/s] | Relative<br>operational<br>resolution<br>[%] |
|----------------|----------------------------|-----------------------------|-------------------------------------------------|-----------------------------------------------------------|------------------------------------|----------------------------------------------|
| 0.0            | 0.188                      |                             | 0.0603                                          |                                                           | 0.0603                             |                                              |
| 0.2            | 0.0757                     | 37.9                        | 0.00910                                         | 4.55                                                      | 0.0109                             | 5.45                                         |
| 0.4            | 0.0462                     | 11.5                        | 0.00455                                         | 1.14                                                      | 0.00851                            | 2.13                                         |
| 0.6            | 0.0322                     | 5.36                        | 0.00303                                         | 0.506                                                     | 0.00866                            | 1.44                                         |
| 0.8            | 0.0199                     | 2.49                        | 0.00228                                         | 0.284                                                     | 0.00734                            | 0.918                                        |
| 1.0            | 0.0158                     | 1.58                        | 0.00182                                         | 0.182                                                     | 0.00867                            | 0.867                                        |
| 1.2            | 0.0189                     | 1.57                        | 0.00152                                         | 0.126                                                     | 0.0107                             | 0.894                                        |
| 1.4            | 0.0107                     | 0.765                       | 0.00130                                         | 0.0928                                                    | 0.0104                             | 0.746                                        |
| 1.6            | 0.0109                     | 0.679                       | 0.00114                                         | 0.0711                                                    | 0.0103                             | 0.646                                        |
| 1.8            | 0.00236                    | 0.131                       | 0.00101                                         | 0.0562                                                    | 0.0304                             | 1.69                                         |
| 2.0            | 0.0151                     | 0.757                       | 0.000910                                        | 0.0455                                                    | 0.0296                             | 1.48                                         |

accuracy was 0.0757 m/s. These values are smaller than the applied speed and indicate the sensor output was not dominated by measurement noise and Sensor D can measure low waterflow speeds around 0.2 m/s.

As the applied waterflow speed increased, both accuracy and resolution improved. In the range of 0.6–1.6 m/s, the relative accuracy decreased from 5.36% to 0.07%, while the relative noise-floor intrinsic resolution decreased from 0.51% to 0.05%. Over the same range, the relative operational resolution remained within 0.6–1.5%. These values indicate stable performance under operating conditions. Overall, sensor D met the required specifications for accuracy and resolution across the entire tested range. In particular, the sensor demonstrated measurable performance in the low-speed region around 0.2 m/s, a range that conventional propeller loggers cannot measure, and achieved high accuracy and resolution, confirming its applicability to field deployments.

### 3.8 Verification of sensor performance against the sensor system requirement

---

Based on the experimental results, it was evaluated whether the fabricated sensor satisfies the defined sensor system requirement as shown in Table 2.1. This assessment was conducted using Sensor P-R and Sensor D, which underwent extensive experimental evaluation. The total mass and frontal area of the Sensor P-R equipped with the HTR logger and sensor case was 159.1 g and 19 cm<sup>2</sup>, while the total mass and frontal area of the Sensor D equipped with the Ninja logger and sensor case were 125.8 g and 9.8 cm<sup>2</sup>. The required system mass and frontal area were 2.8 kg and 20 cm<sup>2</sup>, respectively, and the fabricated sensor system met both requirements. Although resistance to the full hydrostatic pressure of 3.4 MPa was not verified, the sensors were confirmed to withstand pressure up to 0.6 MPa, indicating partial compliance with the pressure resistance requirement.

The required waterflow speed specifications were a measurement range of 0–2.0 m/s and a resolution of 0.01 m/s. Both sensors responded over the entire measurement range. Near the cruising speed range (0.4 m/s and 0.6 m/s), Sensor P-R achieves operational resolutions of 0.00961 m/s at 0.4 m/s and 0.00891 m/s at 0.6 m/s, while Sensor D achieved a resolution of 0.00851 m/s at 0.4 m/s and 0.00866 m/s at 0.6 m/s.

The required response time was 50 ms or less, whereas the fabricated sensor achieved a response time of 3.9 ms. These results confirm that the proposed sensor satisfies all required specifications except for the allowable pressure, which was not fully verified experimentally.

The proposed sensor incorporates the oil-filled internal structure, making it conceptually similar to oil-filled pressure-compensated devices [108] that are widely used in deep-sea applications and whose pressure resistance has been well established. Based on this similarity, the proposed sensor is considered to theoretically possess sufficient pressure resistance to meet the specified allowable pressure requirements.

### 3.9 Conclusion

---

In this chapter, the performance of the developed Pitot-type waterflow sensor was experimentally validated through a series of fundamental evaluations. First, the sensor was subjected to hydrostatic pressure, demonstrating that the internally sealed incompressible liquid effectively maintained the structural integrity of the sensor under high-pressure conditions. Next, differential pressure calibration was conducted by applying controlled pressure to the sensor inlets. Experiments were performed using sensors filled with either an incompressible liquid or a compressible gas and equipped with membranes of various thicknesses. The results showed that sensors filled with the incompressible liquid exhibited no dependence of sensitivity on membrane thickness, whereas those filled with the compressible gas showed sensitivity variations consistent with the theoretical model, thereby experimentally confirming the theoretical predictions.

A dynamic response test was then performed by applying a step-like change in differential pressure. The sensor exhibited a response time shorter than 4 ms, indicating its capability to measure pressure fluctuations up to 250 Hz. The effects of temperature and acceleration on the sensor output were also evaluated. Both Sensor P and Sensor D demonstrated that the dual-sensor differential configuration significantly reduced the influence of environmental disturbances compared with single-sensor measurements, confirming the effectiveness of the dual-sensor design in suppressing external noise.

Finally, a waterflow speed calibration was conducted using a water tunnel. The differential configuration effectively suppressed drift, enabling accurate measurement of waterflow speed. At a low speed of 0.2 m/s, sensor P-R achieved noise-floor intrinsic and operational resolutions of 0.0112 m/s and 0.0158 m/s, respectively, while sensor D achieved 0.00910 m/s and 0.0109 m/s. These results indicate that both sensors can measure waterflow speed around 0.2 m/s, a range that is difficult to measure with conventional propeller loggers. As waterflow speed increased, the sensor's accuracy and resolution improved. As the waterflow speed increased, the relative accuracy decreased to below a few percent, and the relative operational resolution remained approximately at the 1% level for both sensor P-R

and sensor D. The obtained accuracy and resolution indicate that the developed sensors can measure waterflow speed with sufficient accuracy and resolution over the entire tested range. These results confirm that the proposed Pitot-type waterflow sensor system meets the required specifications in biologging measurements.

Overall, these results demonstrate that the developed Pitot-type waterflow sensor system achieves high accuracy, rapid temporal response, and strong robustness against environmental disturbances, and confirm that it satisfies all required sensor system specifications except for the allowable pressure, thereby demonstrating its suitability for high-resolution waterflow measurement in biologging applications.

## CHAPTER 4.

# Multi-Inlet Two-Dimensional Waterflow Vector Sensor

### 4.1 Introduction

---

In This chapter describes the theory, design, fabrication, and evaluation of a two-axis waterflow sensor developed to measure the direction and speed of marine animals. First, the physical parameters determining the differential pressure distribution on the sensor housing were analyzed to establish a theoretical framework for constructing the neural network (NN) model used to estimate the sensor outputs. Based on this framework, an NN-based estimation model was implemented, and a compact sensor system was fabricated to be small enough for attachment to a sea turtle. The fabricated sensor was then tested under controlled differential pressures to evaluate its pressure-response characteristics. Finally, a series of water-tunnel experiments were conducted, in which steady waterflows with controlled speed and angle were applied to the sensor to collect training data for the NN model. Using these data, the relationships between flow speed, flow angle, and sensor response were analyzed, the neural network was trained, and the performance of the trained model was evaluated. Through this evaluation, the Pitot-type waterflow sensor demonstrates its extensibility to multi-axis measurements, which are difficult to achieve with a propeller-based sensor.



## 4.2 Sensor design

### 4.2.1 Sensor system requirement

A schematic representation of the proposed sensor is presented in Fig. 4.1. The device functions as a two-dimensional waterflow sensor that can be mounted on a marine animal to record both the swimming speed and direction relative to the ambient water. Similar to the previously developed Pitot-type waterflow sensor in Chapter 2, the loggerhead turtle was selected as the target species. Sea turtles sometimes exhibit complex three-dimensional swimming patterns, including both turning and lateral motions [43], [55]. Sea turtles primarily swim along their body axis (longitudinal axis). Therefore, during turning maneuvers, both the heading angle and the bearing angle change simultaneously, as shown in Fig. 4.2 (a). The heading angle is defined as the orientation of the turtle's longitudinal axis, whereas the bearing represents the direction of the velocity vector relative to a fixed external reference frame (world coordinate system). Therefore, during turning, a mismatch (sideslip angle) arises between the direction of the sea turtle's longitudinal axis (heading angle) and the actual direction of movement (bearing angle). Thus, capturing waterflow velocity as a vector rather than a scalar quantity is crucial for identifying these behaviors. The proposed sensor is designed to measure the relative waterflow velocity vector, as depicted in Fig. 4.2 (b). By mounting the sensor along the longitudinal axis, it can measure the sideslip angle.

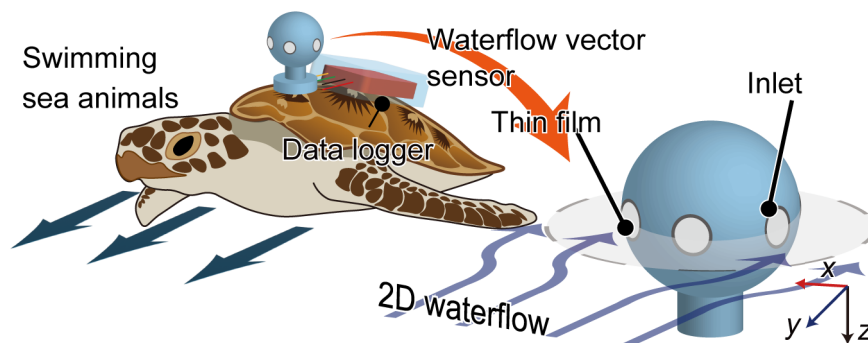


Fig. 4.1 Schematic of the proposed 2D waterflow sensor for marine animal biologging.

This enables analysis of turning behavior and helps to better understand the excellent maneuverability of sea turtles.

The morphological features of the loggerhead turtle and the corresponding sensor specifications are summarized in Table 4.1. Because the target animal for the two-axis waterflow sensor was the same loggerhead turtle inhabiting the Sanriku coastal region as the single-axis Pitot-type waterflow sensor, the system mass, frontal area, allowable pressure,

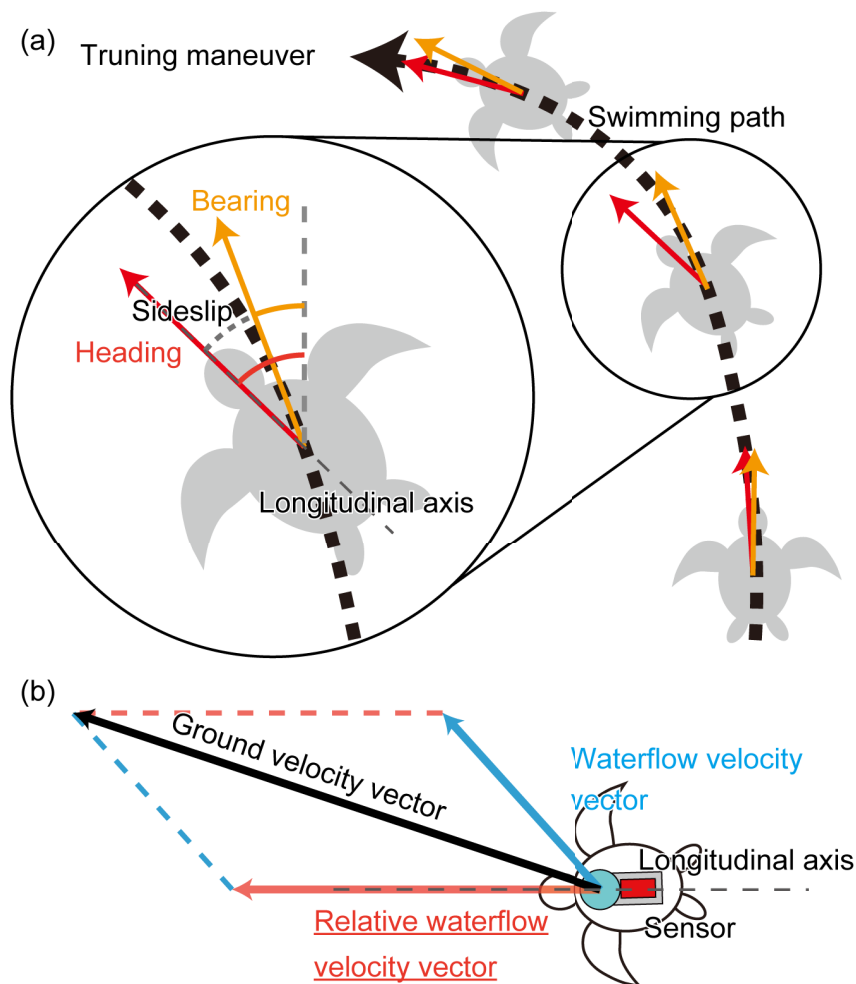


Fig. 4.2 (a) Definitions of body orientation angles, heading angle, and bearing angle, following the representation style [44] (b) Definition of the relative waterflow velocity vector.

Table 4.1 Characteristics of the sea turtle and sensor requirements of two-dimensional waterflow sensor.

| Characteristics of loggerhead turtles |                    | Sensor requirement                    |                    |
|---------------------------------------|--------------------|---------------------------------------|--------------------|
| Mean body mass [30]                   | $55.5 \pm 13.5$ kg | System mass                           | 2.8 kg             |
| Mean SCLn-t [30]                      | $70.8 \pm 6.4$ cm  | Frontal area                          | 20 cm <sup>2</sup> |
| Maximum diving depth [30]             | 340 m              | Allowable pressure                    | 3.4 MPa            |
| Cruising speed [74]                   | 0.50 m/s           | Measurement range                     | 0–2.0 m/s          |
|                                       |                    | Speed accuracy<br>(at cruising speed) | 0.1 m/s            |
|                                       |                    | Angle accuracy<br>(at cruising speed) | 10°                |

and speed range were defined as those adopted for the single-axis sensor. Unlike the single-axis sensor, the proposed sensor estimates the waterflow vector using a neural network (NN), resulting in a non-analytical and non-monotonic input-output relationship. Under such conditions, defining a physically meaningful speed resolution is difficult. Therefore, in this chapter, sensor performance is evaluated based on estimation accuracy.

The target speed accuracy was set to 0.1 m/s. The primary objective of this chapter is to evaluate whether the proposed sensor structure can achieve two-dimensional waterflow measurements, rather than to pursue highly precise velocity estimation. Accordingly, a relatively moderate accuracy requirement was adopted. The speed accuracy of 0.1 m/s corresponds to only 5% of the full-scale speed range (0–2.0 m/s). From a full-scale perspective, this level of accuracy is neither excessive nor insufficient to verify the feasibility of two-axis sensing. In this study, two-dimensional turning maneuvers were selected as the target for measurement within three-dimensional swimming behavior. The sensor's sensing surface was configured to align with the x–y plane shown in , allowing measurement of horizontal flow velocity and direction over a full 360° range. The angular accuracy was set to 10° at the cruising speed. At a representative cruising speed of 0.5 m/s, an angular error of 10° results in a lateral velocity uncertainty of approximately 0.09 m/s, which is comparable to the specified speed accuracy of 0.1 m/s. Accordingly, the speed and angular accuracy

requirements were set to be consistent with each other.

#### 4.2.2 Design of the two-dimensional waterflow sensor

Figure 4.3 presents a schematic of the developed waterflow sensor, which consists of a spherical housing incorporating three differential pressure elements (E1, E2, and E3). Each element is connected to a pair of inlets (1–1', 2–2', and 3–3') positioned on the housing surface. The inlet pairs are arranged  $60^\circ$  apart around the sphere in the x–y plane to measure two-dimensional waterflow within this plane. Inside the housing, pressure tubes filled with incompressible silicone oil connect each sensor element to its corresponding inlet pair. A thin polyimide film is attached over each inlet to prevent the entry of marine debris. Because the volume change of the incompressible fluid under isostatic pressure is minimal, the sensor is

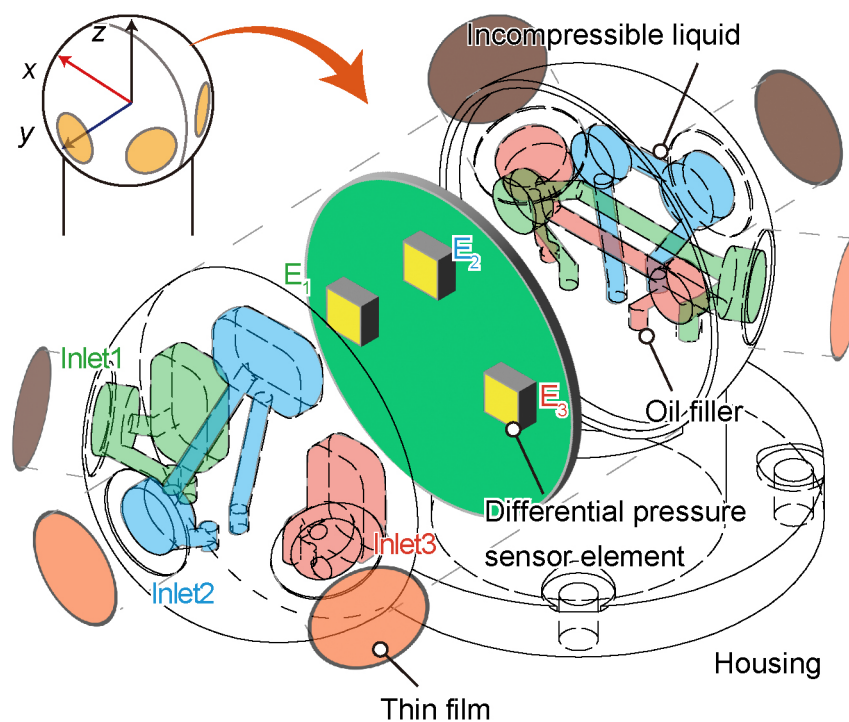


Fig. 4.3 Schematic diagram of the proposed spherical waterflow vector sensor components. The sensor is composed of three differential pressure sensor elements, six

protected from damage due to hydrostatic pressure, ensuring high resistance to harsh underwater environment.

### 4.3 Waterflow vector detection principle

#### 4.3.1 Theoretical analysis of the pressure distribution around a spherical sensor housing

Figure 4.4 (a) illustrates a cross-sectional view of the spherical sensor housing subjected to a uniform waterflow. The pressure acting on each film is transmitted through the incompressible liquid to the corresponding differential pressure element. Because the film area is much larger than that of the sensor element, the measured pressure difference,  $\Delta P_D$  is unaffected by film properties such as stiffness. Consequently,  $\Delta P_D$  can be regarded as approximately equal to the inlet pressure difference  $\Delta P$  [109], enabling the sensor to measure the differential pressure between each connected inlet pair.

Figure 4.4 (b) shows a schematic representation of the relationship between the sensor inlets and the waterflow direction. The incoming waterflow is assumed to be steady and uniform, with a velocity  $v$  and an angle  $\varphi$  relative to the reference plane, which corresponds to the plane of the sensor substrate. As an example, the plane midway between inlets 1 and 3' in Fig. 4.4 (b) is defined as the  $0^\circ$  reference plane; accordingly, the positive pressure inlets 1, 2, and 3 are positioned at  $30^\circ$ ,  $90^\circ$ , and  $150^\circ$ , respectively. When waterflow is applied, pressure is distributed around the sensor, and the device determines the waterflow speed and direction based on the relationships among the differential pressures  $\Delta P$  measured between the three inlet pairs.

The theoretical derivation of  $v$  and  $\varphi$  was conducted under the assumption that the water is an ideal, incompressible, non-viscous, and irrotational fluid in steady flow, and that the flow around the sensor follows the same streamlines as the surrounding water. In addition, the heights of the measurement points and the upstream flow were assumed to be identical, and the sensor was modeled as a perfect sphere with a radius  $R$ . Figure 4.5 (a) shows a cross-

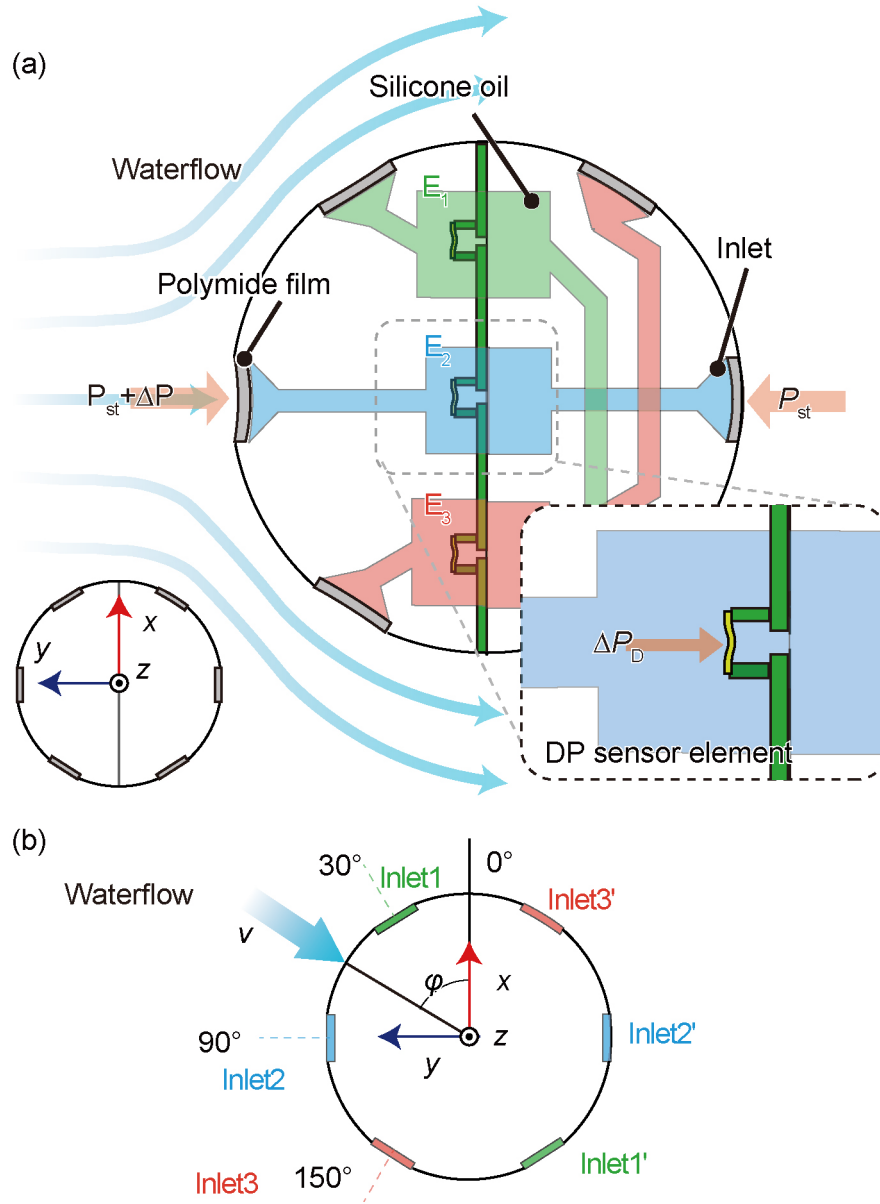


Fig. 4.4 (a) Cross-sectional diagram representing the internal structure of the proposed sensor. (b) Relationship between the pressure applied to the inlets and waterflow.

sectional view of the sensor housing, where a uniform flow  $U$  is directed toward the housing,  $r$  denotes the position vector, and  $\theta$  represents the angle between the surface normal vector  $n$

and the flow vector  $U$ . The velocity field  $v$  can be expressed in terms of the velocity potential  $\Phi$  as follows:

$$v = \nabla \Phi \quad (4.1)$$

Because the fluid is assumed to be incompressible, the following continuity equation applies:

$$\nabla \cdot v = 0 \quad (4.2)$$

Substituting the definition of the velocity field from Eq. (4.1) into Eq. (4.2) yields the Laplace equation:

$$\Delta \Phi = 0 \quad (4.3)$$

The solution to the Laplace equation is uniquely determined by the specified boundary conditions. When an object is immersed in a fluid and displaces the surrounding water, the fluid velocity field is influenced by the object's motion, resulting in a defined velocity at its surface. Accordingly, the velocity potential must satisfy certain boundary conditions at both the surface of the object and at infinity. Considering the symmetry of uniform flow, the Laplacian operator in spherical coordinates can be expressed as follows [110]:

$$\Delta \Phi = \frac{1}{r} \frac{\partial^2 (r\Phi)}{\partial r^2} + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left( \sin \theta \frac{\partial \Phi}{\partial \theta} \right). \quad (4.4)$$

Because the fluid is non-viscous, it slips along the surface of the stationary sphere. Therefore, the following boundary condition can be applied:

$$n \cdot v = n \cdot u \Leftrightarrow n \cdot \nabla \Phi = n \cdot u. \quad (4.5)$$

Furthermore, since the fluid velocity at infinity approaches the uniform velocity  $U$ , the velocity potential that satisfies these boundary conditions is given by [111]

$$\Phi = U \cos \theta \left( r + \frac{R^3}{2r^2} \right). \quad (4.6)$$

As the velocity field  $v$  is obtained from the gradient of the velocity potential (Eq. (4.1)), the radial component of the velocity in spherical coordinates is expressed as

$$v_r = \frac{\partial \Phi}{\partial r} = U \left( 1 - \frac{R^3}{r^3} \right) \cos \theta. \quad (4.7)$$

The velocity component in the angular direction is

$$v_{\theta} = \frac{1}{r} \frac{\partial \Phi}{\partial \theta} = -U \left( 1 + \frac{R^3}{2r^3} \right) \sin \theta. \quad (4.8)$$

Accordingly, the velocity field can be expressed as

$$\begin{aligned} v &= v_r e_r + v_{\theta} e_{\theta} \\ &= U \left( 1 - \frac{R^3}{r^3} \right) \cos \theta e_r - U \left( 1 + \frac{R^3}{2r^3} \right) \sin \theta e_{\theta}. \end{aligned} \quad (4.9)$$

On the surface of the sphere ( $r = R$ ), the velocity field is uniform and is given by

$$v|_{|r|=R} = -\frac{3}{2}U \sin \theta \quad (4.10)$$

Because the velocity field on the sphere's surface depends only on the angle  $\theta$ ,  $v|_{|r|=R}$  can be expressed as  $v(\theta)$ . Under the slip boundary condition, the radial velocity component becomes zero. The square of the magnitude of  $v(\theta)$  therefore be calculated as

$$\begin{aligned} |v(\theta)|^2 &= \left( -\frac{3}{2}U \sin \theta \right)^2 \\ &= \frac{9}{4}U^2 (1 - \cos^2 \theta). \end{aligned} \quad (4.11)$$

The pressure distribution on the sensor surface can then be derived from the velocity field obtained in Eq. (4.9) using Bernoulli's principle, which is expressed as

$$P + \frac{1}{2}\rho v^2 + \rho gh = \text{constant}. \quad (4.12)$$

By considering a streamline extending from a point far from the sphere to a point on its surface, the relationship between  $v(\theta)$  and the pressure distribution on the surface of the sensor  $P|_{|r|=R}$  can be obtained from Bernoulli's principle. Assuming that the potential energy term is identical at both locations (i.e., the height difference is negligible), the following relation is obtained:

$$P_{\infty} + \frac{1}{2}\rho U^2 = P|_{|r|=R} + \frac{1}{2}\rho |v(\theta)|^2. \quad (4.13)$$

Rearranging Eq. (4.13) to express  $P|_{|r|=R}$  and substituting (4.11) yields

$$P|_{|r|=R} = P_{\infty} + \frac{1}{2}\rho U^2 - \frac{9}{8}\rho U^2 (1 - \cos^2 \theta)$$



$$= P_{\infty} - \frac{5}{8}\rho U^2 + \frac{9}{8}\rho U^2 \cos^2 \theta. \quad (4.14)$$

Eq. (4.14) shows that the pressure distribution in an ideal fluid is determined by the flow velocity  $U$  and the position on the sphere's surface, that is, by the flow speed and direction relative to the sensor. Therefore, by measuring the pressure distribution on the sensor surface, the flow velocity and direction can theoretically be obtained. However, in real fluids that deviate from the ideal assumptions, additional factors such as viscosity and vortex formation must be considered. These effects are governed by the Reynolds number of fluid flow.

#### 4.3.2 Effect of the Reynolds number

The flow around a sphere in a real viscous fluid varies depending on the Reynolds number, which is defined as

$$Re = \frac{Dv}{\nu}, \quad \nu = \frac{\mu}{\rho} \quad (4.15)$$

where  $D$  is the diameter of the spherical housing and  $\nu$ ,  $\mu$ , and  $\rho$  represent the kinematic viscosity, dynamic viscosity, and density of the fluid, respectively. As discussed in section 4.3.1, the relationship between pressure distribution and flow in an actual fluid is difficult to describe analytically using theoretical equations. Therefore, simulation-based analyses [112] or experimental methods [113] are typically employed to investigate such flow behaviors. Figure 4.5 (b) presents a schematic diagram illustrating the expected relationship between the pressure coefficient  $C_p$  and the angle  $\theta$  around a sphere under different flow regimes; these data were obtained from experimental measurements [113]. Significant differences are observed in the pressure distributions on the sphere surface between laminar separation, which occurs when the flow is below the critical Reynolds number  $Re_c$  and turbulent separation, which occurs when the flow exceeds  $Re_c$ . Under turbulent separation, the pressure distribution closely resembles that of the surrounding fluid flow, whereas laminar separation occurs at a smaller separation angle than in the turbulent case. The value of  $Re_c$  depends on factors such as surface roughness and turbulence intensity of the flow and is known to be on the order of several hundred thousand for flow around a sphere [113].

A schematic diagram illustrating the calculated differential pressure  $\Delta P$  between two points separated by  $180^\circ$  using the  $C_p$  values shown in Fig. 4.5 (b) is presented in Fig. 4.5 (c). Although the  $\Delta P$  generally exhibits a sinusoidal response to changes in the flow angle under both laminar and turbulent conditions, the behavior does not form a perfect sine wave. Instead,

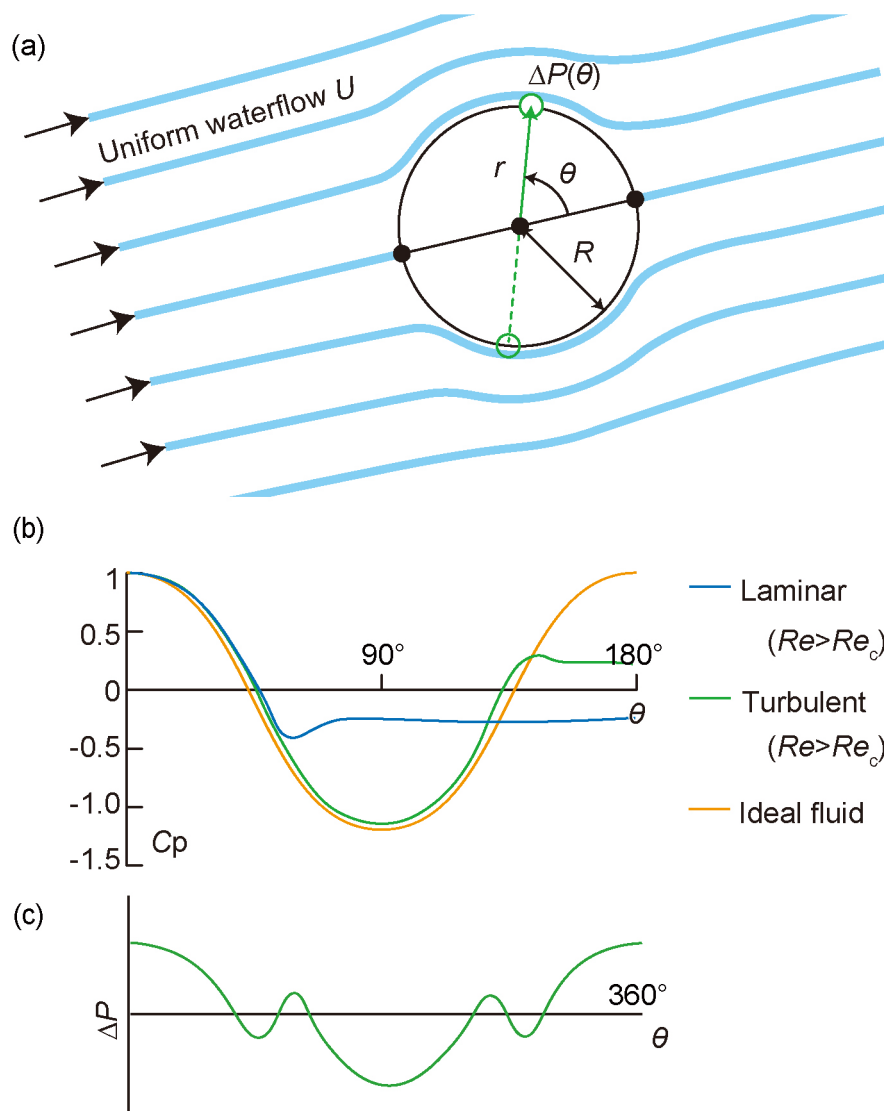


Fig. 4.5 (a) Relationship between the waterflow stagnation point and the pressure on the spherical housing. (b) Variation of the pressure coefficient depending on flow condition [113]. (c) Relationship between the waterflow angle and differential pressure.

non-monotonic pressure variations occur depending on the size of the sensor sphere [76], [77]. The value of  $C_p$  is highly dependent on the Reynolds number  $Re$ , resulting in an interdependent relationship between the waterflow angle and speed. Furthermore, flow separation and vortex formation, both influenced by  $Re$ , introduce nonlinear variations in the differential pressure, rendering the relationship among waterflow speed, direction, and differential pressure highly complex. Consequently, it is difficult and inherently limited to determine the flow characteristics mathematically based solely on the differential pressure distribution [79].

Neural networks (NNs) can directly learn such relationships from data without relying on the geometric configuration of the sensor or assuming data linearity. Given the spherical geometry of the sensor used in this study, substantial flow separation and nonlinear pressure variations were observed. Therefore, NNs are particularly suitable for modeling the relationships among flow velocity, direction, and differential pressure in our waterflow sensor. This suitability is supported by previous studies in which NNs were applied to spherical multi-hole pressure probes, achieving high-accuracy airflow estimation [77]. Accordingly, in this study, we utilized the theoretical relationship between flow speed, direction, and differential pressure distribution derived in Eq. (4.14) to establish their correlation through machine learning-based regression.

#### 4.3.3 Construction of the neural network

A neural network (NN) model was constructed to predict the waterflow speed and angle based on the measured outputs from the three differential pressure sensor elements. The architecture of the NN consists of an input layer, three hidden layers, and an output layer, as illustrated in Fig. 4.6. The input layer receives the outputs of the three differential pressure elements. The three hidden layers are fully connected and contain 32, 64, and 8 neurons, respectively, each employing the rectified linear unit (ReLU) as the activation function. The stochastic gradient descent (SGD) algorithm was used for optimization with a learning rate of 0.01. Because angles near the boundaries (e.g.,  $0^\circ$  and  $360^\circ$ ) can cause discontinuities in the learning process, periodic functions were employed as explanatory variables in the output

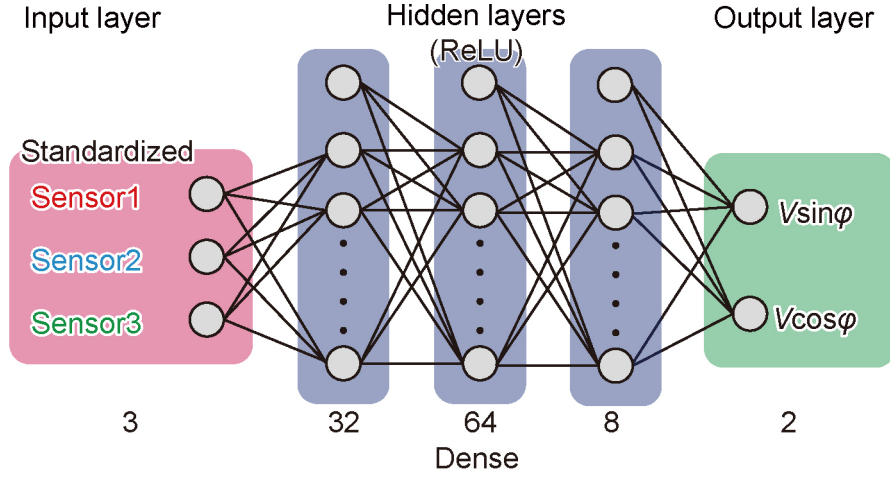


Fig. 4.6 Conceptual diagram of the constructed NN model.

layer. The velocity field, which determines the pressure distribution, depends on the flow speed  $v$  and direction  $\varphi$ , as expressed in Eq. (4.14). Therefore, the objective function must be periodic and defined in terms of these two parameters. To satisfy this condition,  $v\cos\varphi$  and  $v\sin\varphi$  were adopted as the objective functions, and the predicted values were subsequently converted into  $v$  and  $\varphi$  using the following equations:

$$v = \sqrt{v^2 \cos^2 \varphi + v^2 \sin^2 \varphi} \quad (4.16)$$

$$\varphi = \arctan \frac{v \sin \varphi}{v \cos \varphi}. \quad (4.17)$$

When these processes were implemented using PyTorch, the sensor successfully predicted the two-dimensional waterflow speed and direction from the outputs of the three differential pressure sensor elements. In biologging applications, sensor data are typically recorded in a data logger and subsequently transferred to an external PC for NN-based inference. Therefore, real-time computation and model complexity are not major constraints in such analyses. Nevertheless, the proposed NN model consists of only 2,778 parameters—substantially fewer than those of conventional deep learning architectures incorporating convolutional layers or attention mechanisms, which often contain millions or even billions of parameters. This lightweight architecture greatly reduces computational demands, allowing

implementation on low-performance edge devices. Consequently, the proposed approach is well suited for standard offline analyses in biologging studies and also exhibits potential for real-time applications where rapid responsiveness is required.

#### 4.4 Development of the two-dimensional waterflow sensor

The structure of the sensor housing is shown in Fig. 4.7 (a). It consists of two hemispherical shells designed to sandwich a substrate on which the differential pressure sensor elements were mounted. The housing had a diameter of 36 mm, and each inlet had a diameter of 6 mm, with a 9.5 mm recessed area where a thin film was attached. The housings were fabricated from acrylic resin using a three-dimensional stereolithography printer (Form3, Formlabs Inc., Massachusetts, USA). The thin film was made of 25  $\mu\text{m}$  thick polyimide owing to its excellent insulating properties and ease of fabrication. The polyimide film was cut into 9 mm diameter discs using a laser cutter. The internal circuit configuration of the sensor is illustrated in Fig. 4.7 (b). The substrate held three membrane-type piezoresistive pressure sensor elements (L1O-10 K-RT, Merit Sensor Inc., Jordan, USA). The

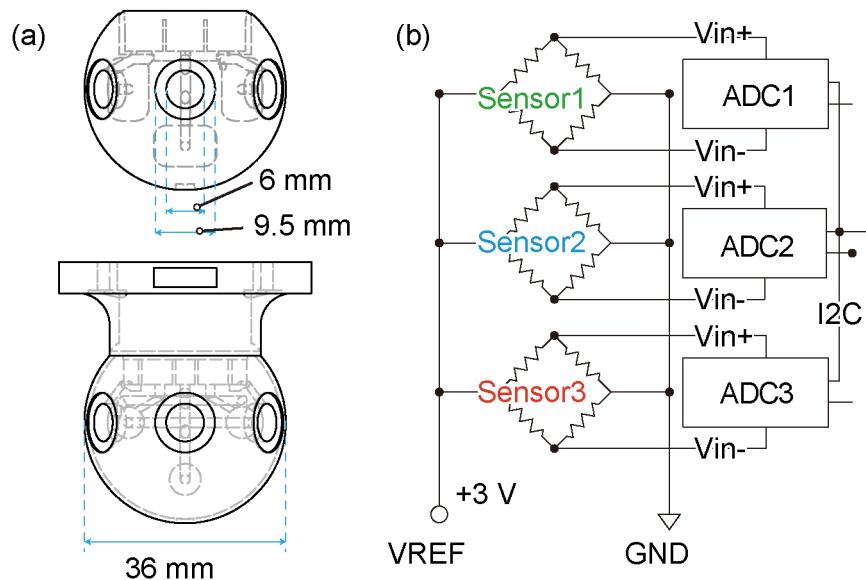


Fig. 4.7 Design of the (a) sensor housing and (b) internal circuit.

resistance changes in these elements were converted into voltage signals using a Wheatstone bridge circuit. A 3 V voltage reference ( $V_{ref}$ ; LM4120IM5-3.0, Texas Instruments Inc., Dallas, USA) was supplied to the bridge circuit, and the output voltage was digitized using a

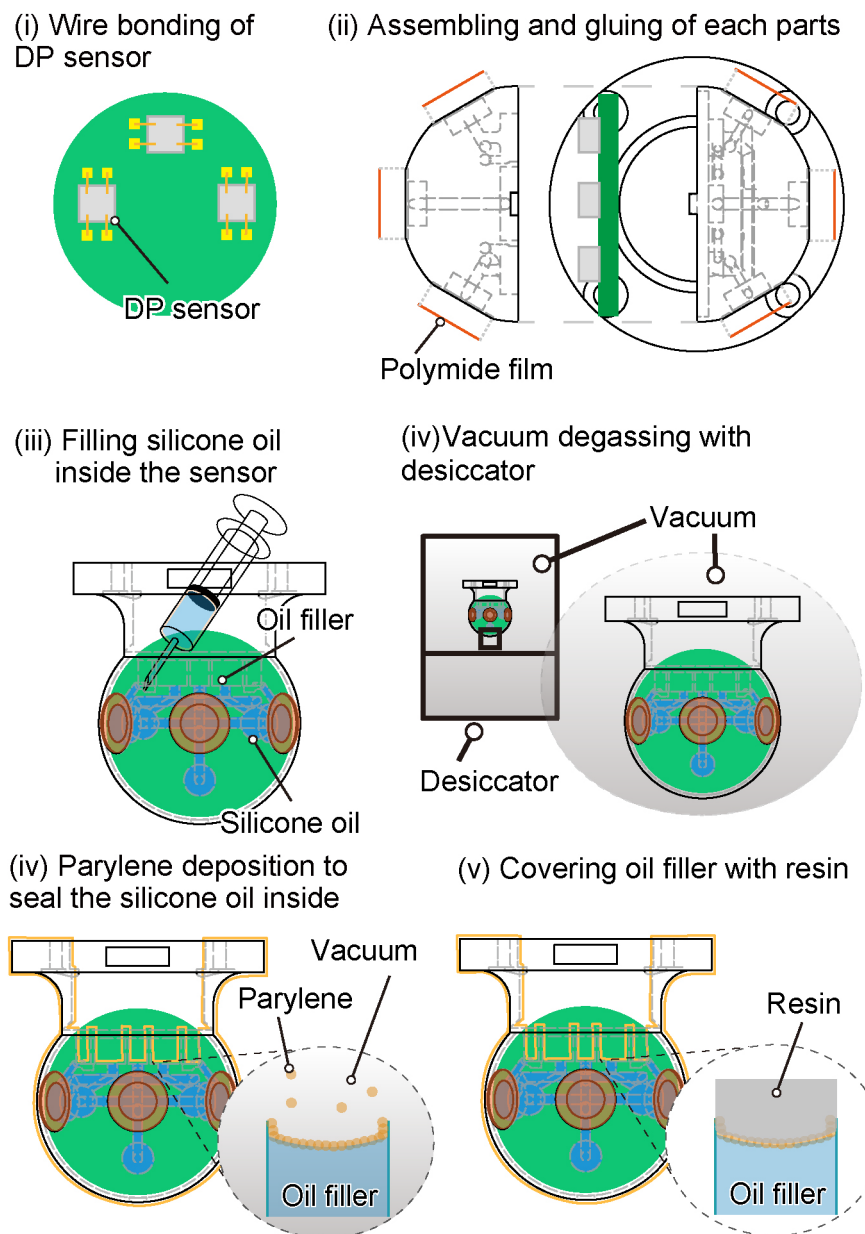


Fig. 4.8 Fabrication process of the two-dimensional waterflow sensor.

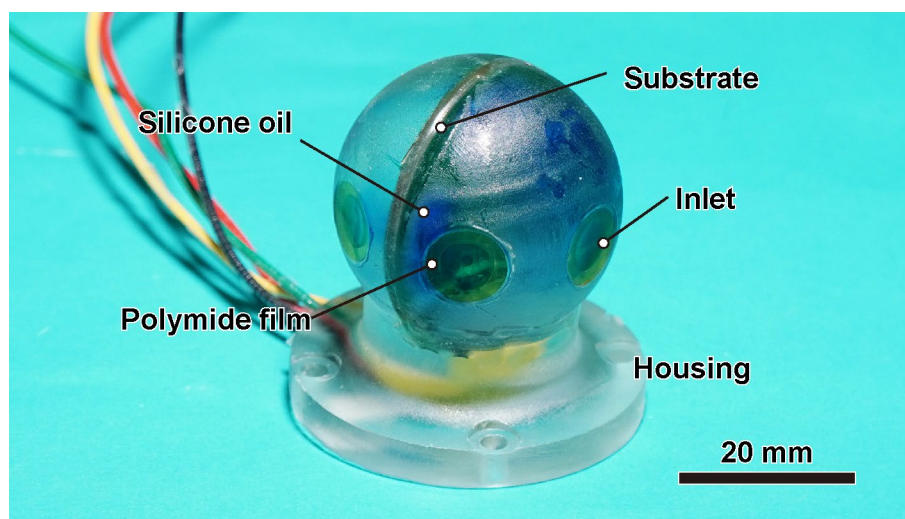


Fig. 4.9 Photograph of the fabricated two-dimensional waterflow sensor.

16-bit analog-to-digital converter (ADC) (ADS1110, Texas Instruments Inc., Dallas, USA). This ADC includes a programmable gain amplifier (PGA) that amplifies the signal by a factor of eight. Each of the three pressure sensor elements was connected to its corresponding ADC, and each ADC was assigned a unique inter-integrated circuit (I<sup>2</sup>C) address, allowing simultaneous and independent control of all elements.

Figure 4.8 illustrates the fabrication process of the sensor. First, the pressure sensor elements were attached to the substrate and electrically connected via wire bonding. Subsequently, the two housing hemispheres, the substrate, and the polyimide films were assembled and bonded together. The internal tubes were then filled with silicone oil through an oil filler valve provided in the housing. Because the presence of air bubbles in the oil can affect the sensor sensitivity due to the high compressibility of air, any trapped bubbles were removed by vacuum degassing using a desiccator and vacuum pump. After degassing, parylene C was vapor-deposited over the entire sensor surface. Since parylene can be directly deposited onto the oil, this process ensured bubble-free sealing of the internal fluid. Finally, a resin (Devcon ET, ITW Performance Polymers, Danvers, USA) was applied to the oil filler to prevent deformation of the deposited parylene layer. As a result, the only deformable components of the device were the polyimide films attached over each inlet. Fig. 4.9 shows

the completed waterflow sensor, which forms a compact structure suitable for attachment to a sea turtle.

## 4.5 Experimental performance evaluation of the two-dimensional waterflow sensor

---

### 4.5.1 Pressure resistance experiment

First, the pressure resistance of the proposed sensor structure was evaluated. The fabricated sensor was placed inside a pressure application device (PV-5-90-120-750-AC-DG, Syn Corporation Inc., Japan) and subjected to a water pressure of 1 MPa for one hour. Fig. 4.10 shows photographs of the sensor before and after the application of pressure. Even after being exposed to the pressure load, the sensor exhibited no visible damage, and the polyimide films remained undeformed. These results demonstrate that the proposed sensor possesses sufficient pressure resistance for biologging applications.

### 4.5.2 Calibration of the differential pressure

Next, the response of the fabricated sensor to differential pressure was evaluated to calibrate its sensitivity. Figure 4.11 (a) and (b) show, respectively, a photograph and schematic diagram of the pressure calibration setup. A custom-fabricated jig was used to

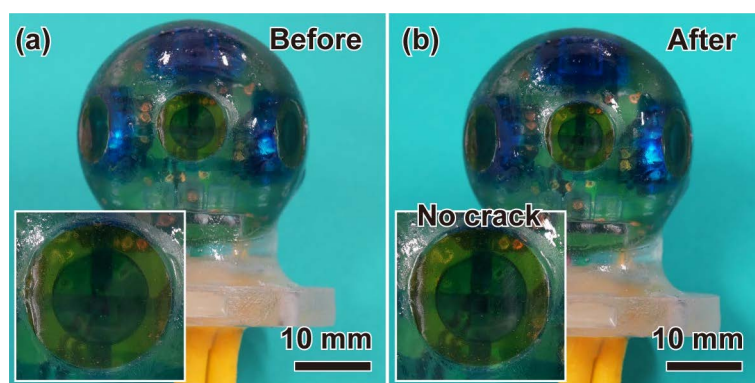


Fig. 4.10 Photographs of the sensor (a) before and (a) after pressure application.



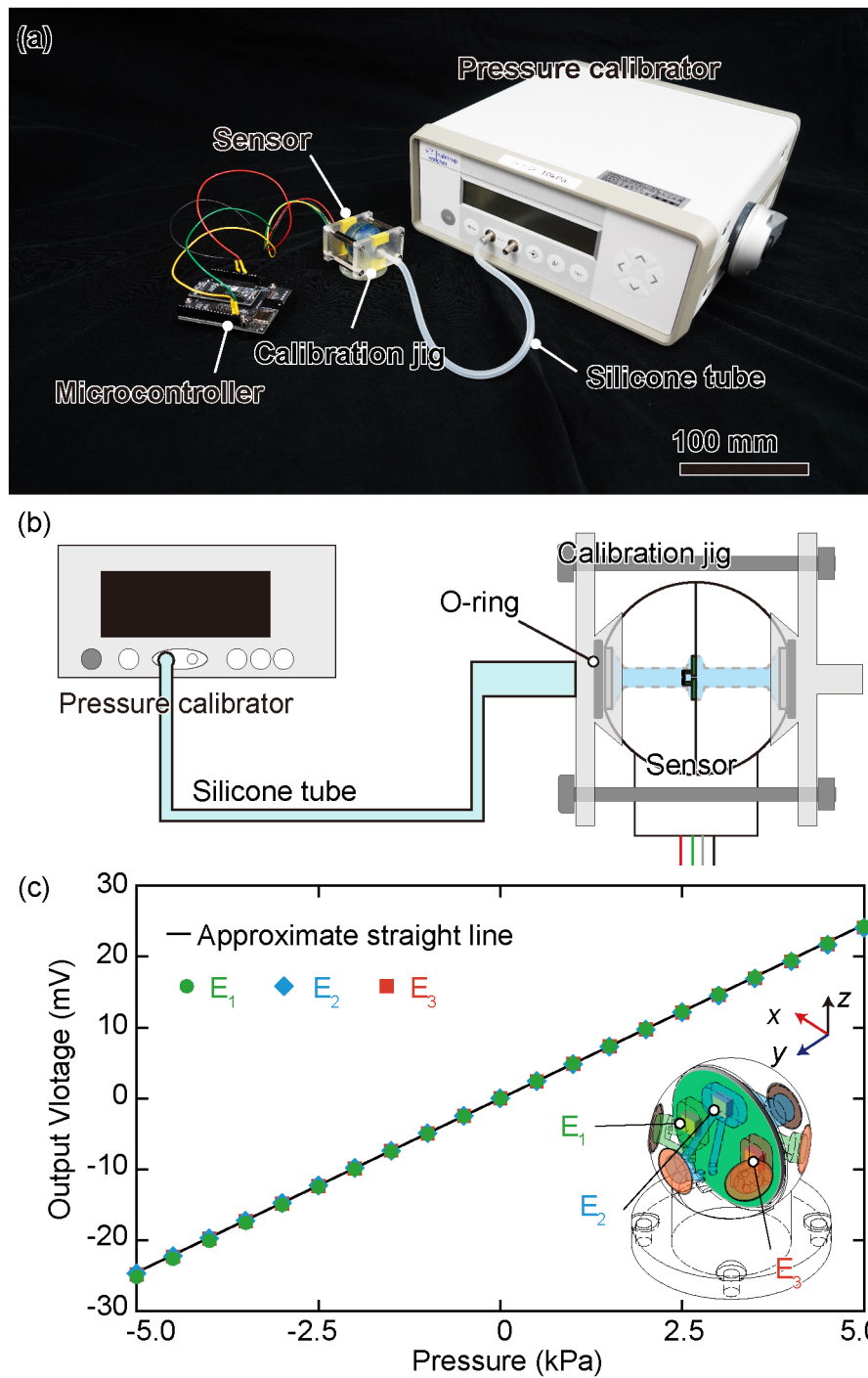


Fig. 4.11 (a) Photograph and (b) schematic image of the pressure calibration process. (c) Relationship between applied differential pressure and output voltage of the sensor elements.

secure the sensor, and a silicone tube connected the jig to a pressure calibrator (KAL200, Halstrup-Walther GmbH, Kirchzarten, Germany). An O-ring was placed between the sensor and the jig to ensure airtight sealing. This configuration allowed a differential pressure  $\Delta P$  to be applied to one pair of inlets at a time, increasing from  $-5$  to  $5$  kPa in increments of  $500$  Pa, with each step maintained for  $5$  s. The sensor output  $\Delta V$  was defined as the difference between the average voltage at  $0$  kPa and that at the applied pressure.

Figure 4.11 (c) shows the relationship between the sensor output voltage and the applied differential pressure for each inlet pair. All three elements exhibited nearly identical linear increases in output with increasing  $\Delta P$ , indicating consistent sensitivity across the sensor elements. Therefore, the relationship between the output voltage and the applied differential pressure was fitted using the least-squares method with a linear model  $y = ax$ . The proportionality constants obtained for the three elements were averaged to yield the following calibration relationship:

$$\Delta V = 4.91 \times 10^{-3} \Delta P. \quad (4.18)$$

### 4.5.3 Water tunnel experiment

Next, the responses of the fabricated sensor to the waterflow speed and angle were evaluated. Figure 4.12 (a) shows a photograph of the experimental setup used for this evaluation. The sensor was mounted in a water tunnel (PT-100 kai, Nishinihon Fluid Giken, Nagasaki, Japan) using a rotating stage (OSMS-60YAW, SIGMA KOKI Co., Ltd., Saitama, Japan). The sensor, water tunnel, and rotating stage were connected to a PC through an I<sup>2</sup>C–USB converter (CRESCENT-018, Switch Science, Japan), an RS485–USB converter (DINV-U4, Diatrend Corp., Japan), and a stage controller (GSC-01, SIGMA KOKI Co., Ltd., Japan), respectively, enabling simultaneous data acquisition and control of all components, as shown in Fig. 4.12 (b). The water tunnel generated a controlled waterflow applied to the sensor, while the rotation stage was used to vary the sensor's orientation, as illustrated in Fig. 4.12 (c). The reference angle for rotation was defined as the position at which the front of the sensor directly faced the water inlet of the tunnel. For each combination of waterflow speed

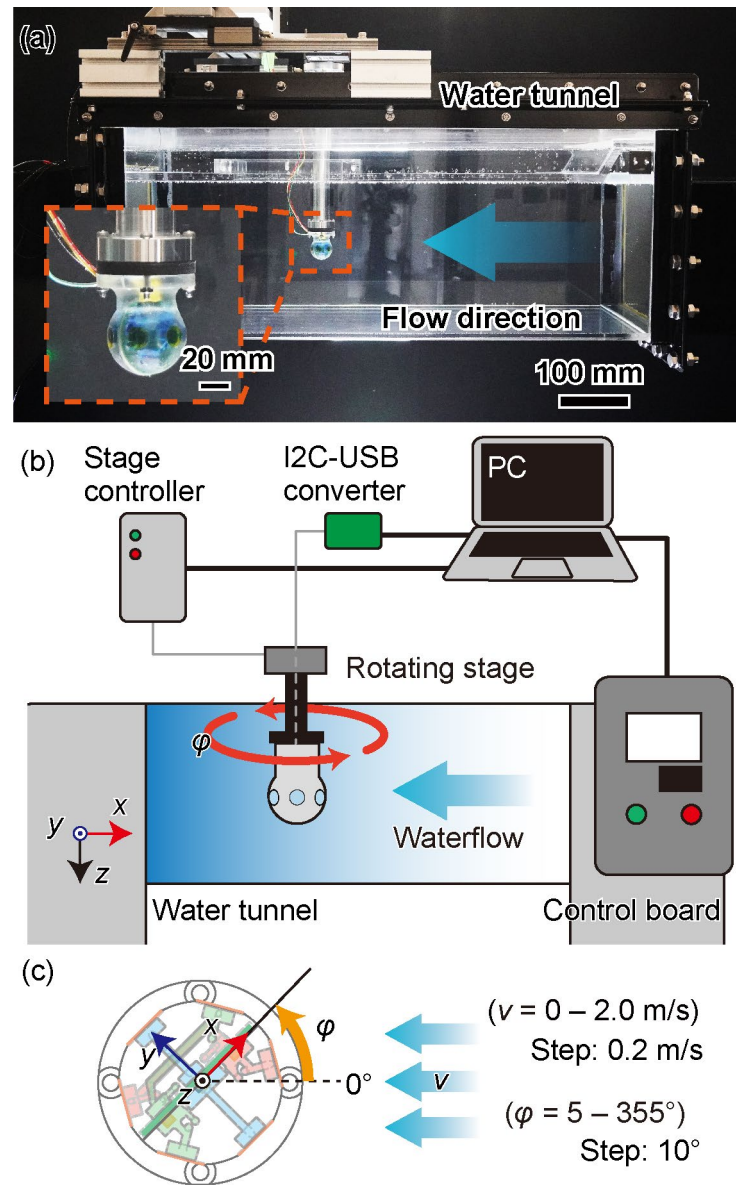


Fig. 4.12 (a) Conceptual diagram and (b) photograph of the experimental setup used to measure the sensor response according to waterflow speed and angle. (c) Rotation of the sensor during the experiment.

and angle, 50 data points were recorded as sensor outputs. The differential output  $\Delta V$  was defined as the difference between each measured output and the average baseline output obtained at a waterflow speed of zero.

To ensure accurate control of the applied flow speed, the water tunnel was calibrated using a JIS-standard Pitot tube, with the flow velocity determined from the impeller rotation frequency. For each target speed, the impeller was allowed to stabilize for 20 s before data collection, which was conducted at a sampling rate of 10 Hz. The sensor angle was incremented by  $10^\circ$  from  $5^\circ$  to  $355^\circ$ , resulting in a total of 36 measurement steps. A waiting period of 15 s was applied after each angular adjustment to allow the flow to stabilize, and the water tunnel was stopped for 60 s between trials to eliminate any residual

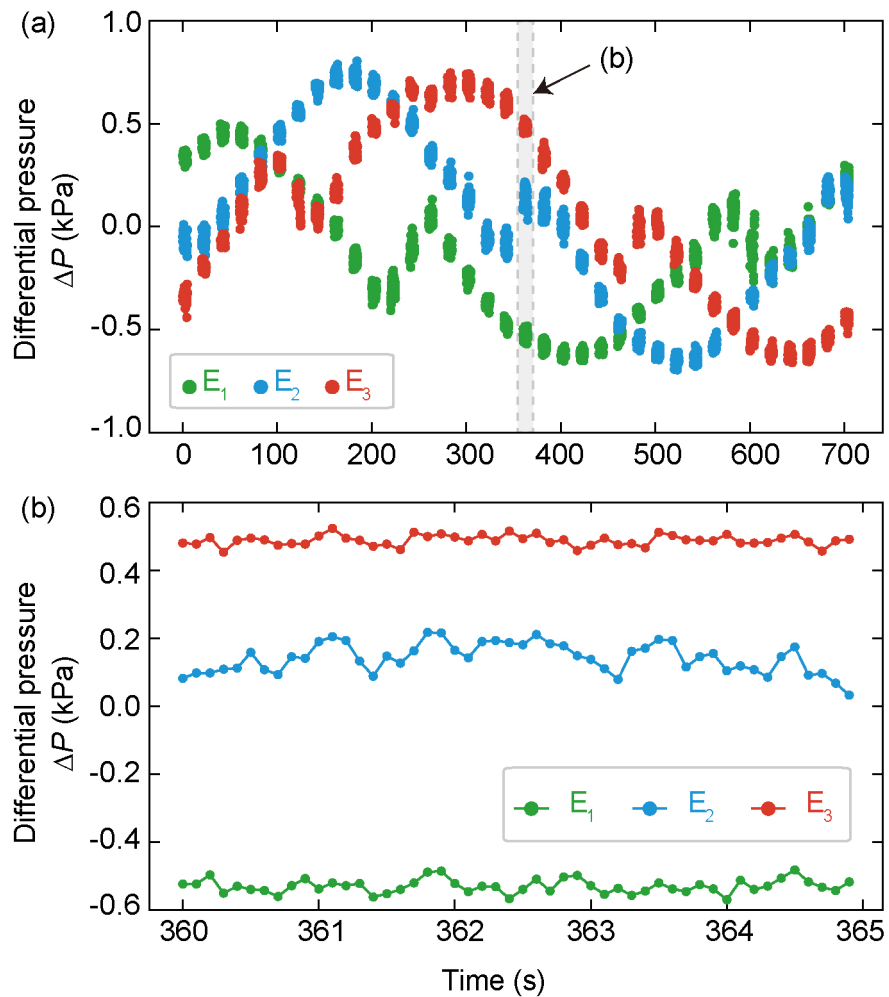


Fig. 4.13 (a) Temporal response of the sensor during angle variation with an applied waterflow velocity of 1 m/s. (b) Temporal response of the sensor at an applied waterflow velocity of 1 m/s and a angle of  $185^\circ$ .

flow. After recording the initial output, the waterflow speed increased from 0 to 2.0 m/s in increments of 0.2 m/s, and data were collected for each speed as the sensor angle was varied from 5° to 355°. Figure 4.13 (a) shows the output of each sensor element as the angle was varied in 10° increments at a waterflow velocity of 1.0 m/s. Each element clearly responded to changes in the flow direction. Figure 4.13 (b) shows the output of one element at a waterflow velocity of 1.0 m/s and an angle of 185°. Although minor fluctuations were observed, the sensor consistently exhibited stable outputs in response to the applied flow. These small variations are attributed to vortex formation in the flow field.

Figure 4.14 (a) shows the relationship between the applied waterflow speed and the

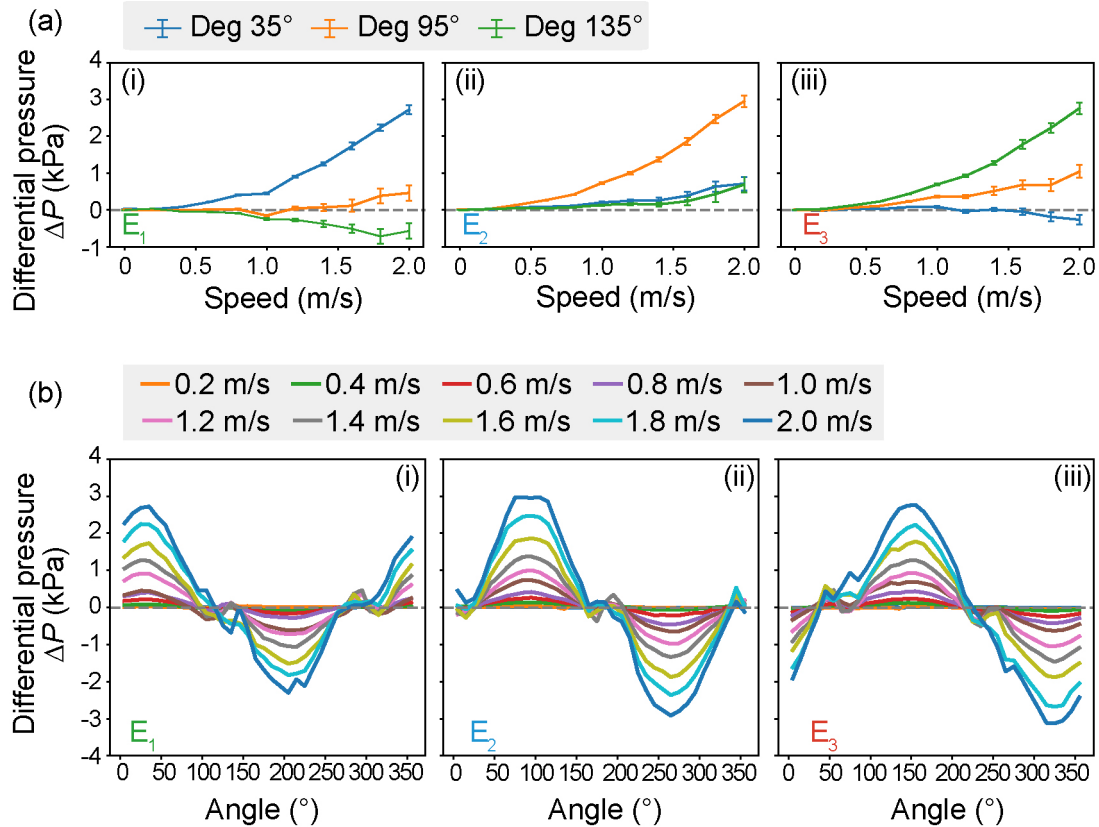


Fig. 4.14 (a) Relationship between the waterflow speed and the differential pressure measured by the sensor elements for each degree of rotation: (i)  $E_1$ , (ii)  $E_2$ , and (ii)  $E_3$ . (b) Relationship between the waterflow angle and the differential pressure measured by the sensor elements for each inlet: (i)  $E_1$ , (ii)  $E_2$ , and (ii)  $E_3$ .

differential pressure  $\Delta P$  measured by the sensor elements. The sensor output  $\Delta V$  was converted into  $\Delta P$  using Eq. (4.18). Figures 4.13(a-i), (a-ii), and (a-iii) present the  $\Delta P$  values measured by E1, E2, and E3, respectively, showing that  $\Delta P$  clearly varied with the waterflow speed. When the inlets corresponding to each element were oriented perpendicular to the waterflow direction, the output of each element increased proportionally to the square of the flow velocity. Figure 4.14 (b-i), (b-ii), and (b-iii) show the relationships between the waterflow angle and the measured  $\Delta P$  at E1, E2, and E3, respectively, under all applied flow speeds. The overall response exhibited a sinusoidal-like pattern, with a  $60^\circ$  phase shift observed among the outputs of the three elements. As reported in previous studies [76], [114], non-monotonic behaviors, including localized singularities, were observed for inlets 1, 2, and 3 at flow angles of approximately  $100\text{--}130^\circ$  and  $280\text{--}310^\circ$ ,  $160\text{--}190^\circ$  and  $340\text{--}10^\circ$ , and  $40\text{--}70^\circ$  and  $220\text{--}250^\circ$ , respectively.

#### 4.5.4 Conversion to waterflow speed and angle

A dataset comprising 19,800 data points ( $36 \times 11 \times 50$ ) was obtained from the water tunnel experiment, corresponding to 50 samples for each combination of waterflow speed and angle. The feature data consisted of the outputs from the three differential pressure sensor elements, and the label data corresponded to the applied waterflow speed and angle. Each data point was treated as an independent sample, and the dataset was used as discretized (non-time-series) input for the neural network. Of the total dataset, 70%, 15%, and 15% were used for training, validation, and testing, respectively. Accordingly, the training dataset contained 13,860 points, the validation dataset contained 2,970 points, and the test dataset contained 2,970 points. The NN model was trained using a batch size of 32 for 500 epochs. The mean squared error (MSE) was employed as the loss function, and the model performance was evaluated at the end of each epoch. The validation dataset performance was used to monitor potential overfitting during training.

Figure 4.15 shows that the learning curve for the water tunnel dataset converged within the first few epochs and remained stable up to the 500-epoch limit. The trained NN model exhibited consistent performance on the validation dataset, indicating that overfitting

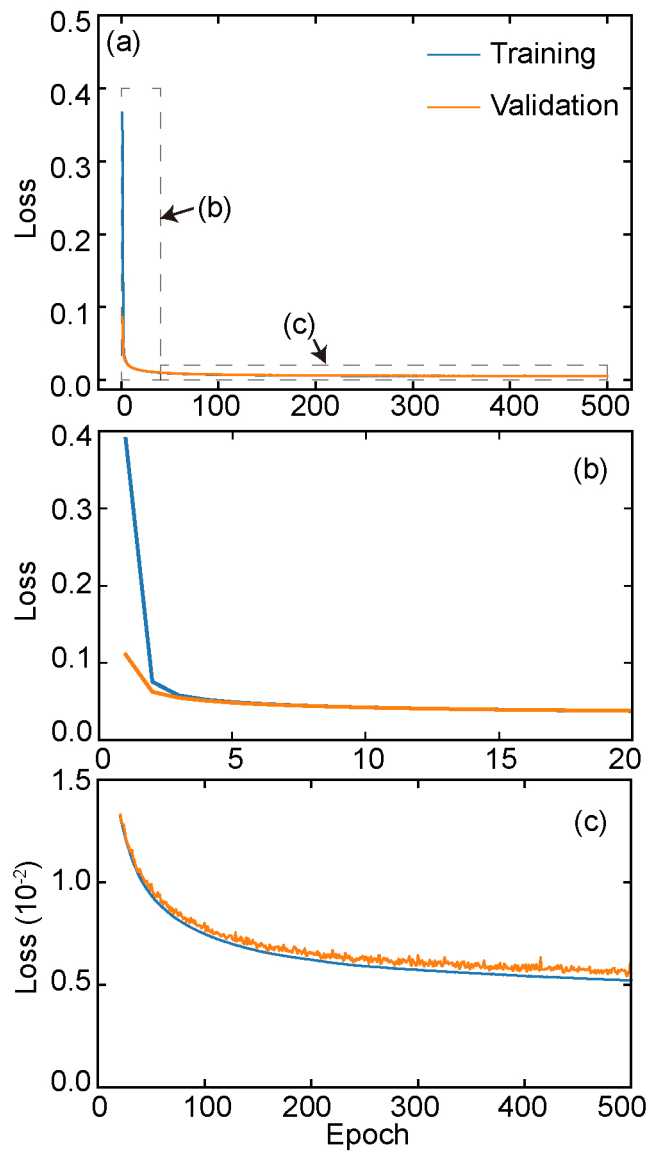


Fig. 4.15 Comparison of the training and validation learning curves for the water tunnel experiment data at epochs (a) 0–500, (b) 0–20, and (c) 20–500.

did not occur.

In this study, validation was performed by evaluating the trained model on an independent validation dataset that was not used for weight updates during training. At each epoch, the model parameters optimized using the training dataset were applied to the

validation dataset, and the corresponding validation loss was computed. The training,

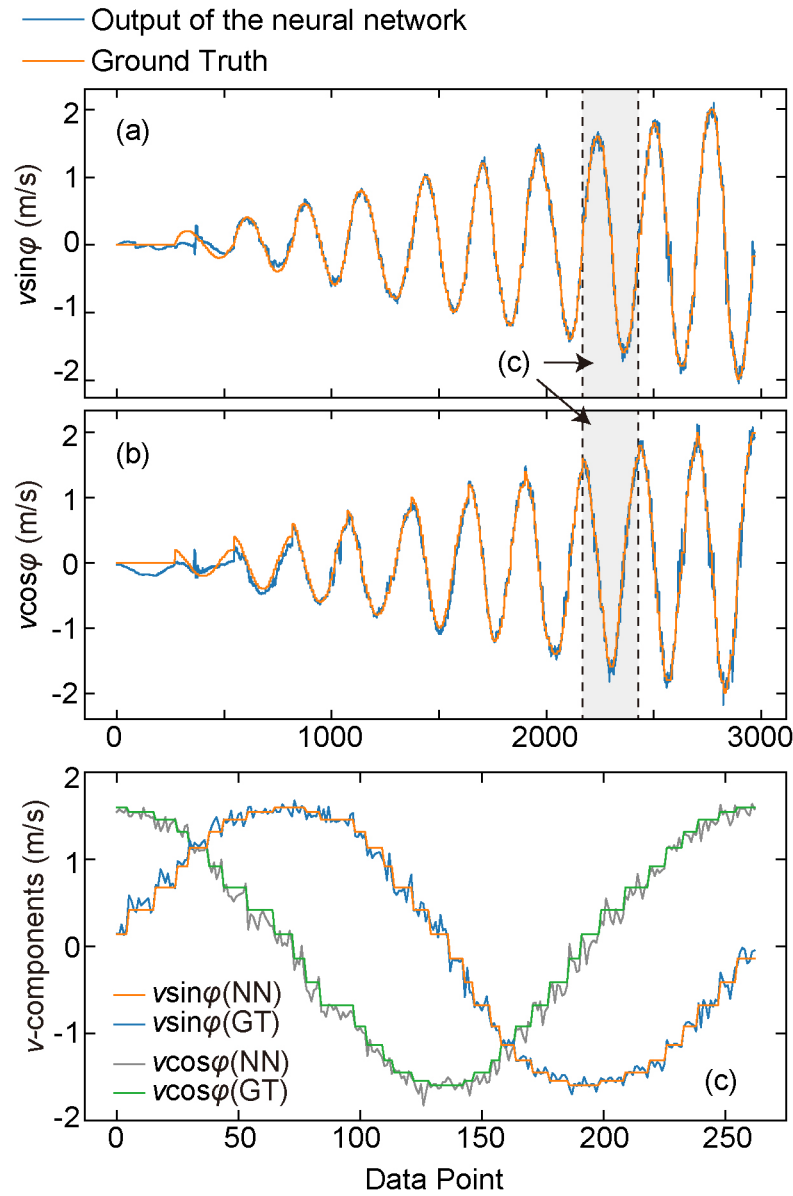


Fig. 4.16 Results of converting the output of the three sensor elements to (a)  $v\cos\theta$  and (b)  $v\sin\theta$  using the NN trained on the experimental data. (c) Comparison between the neural network outputs and the ground truth at a waterflow velocity of 1.6 m/s. The ground truth was obtained using the waterflow speed applied in the water tunnel and the waterflow angle set by the rotating stage during the experiment.



validation, and test datasets were generated by randomly splitting the full dataset into mutually exclusive subsets. Because the data were obtained under controlled and repeatable water tunnel conditions, and each subset contained samples spanning all combinations of waterflow speed and angle, the random splitting procedure effectively reduced potential sampling bias among the subsets. This chapter's objective is to demonstrate the feasibility of two-dimensional waterflow estimation using the proposed sensor structure, rather than optimize the neural network model. Although cross-validation was not employed, the use of a sufficiently large dataset and randomized data splitting was considered sufficient for the purpose. In addition, the validation dataset was used exclusively for model selection and overfitting assessment, while the test dataset was reserved for final performance evaluation. Taken together with the stable convergence observed in the learning curves, this single train-validation-test split was deemed adequate to demonstrate the feasibility of two-dimensional waterflow estimation using the proposed sensor structure.

Figure 4.16 (a) and (b) show the NN output results for the test dataset and the corresponding ground truth data labels, respectively. The predicted outputs closely matched the ground truth, and both  $v\cos\phi$  and  $v\sin\phi$  were accurately estimated without noticeable influence from internal amplifier noise, particularly in the higher flow velocity range (0.6–2.0 m/s). Fig. 4.16 (c) presents a comparison between the NN-predicted outputs and the ground truth when a waterflow velocity of 1.6 m/s was applied to the sensor while the flow angle was varied in  $10^\circ$  increments. The NN outputs successfully tracked the variations in the waterflow angle with high fidelity.

Finally, the predicted  $v\cos\phi$  and  $v\sin\phi$  values were converted into  $v$  and  $\phi$  using Eq. (4.17) and the accuracy of the model was evaluated using the root mean square error (RMSE), defined as

$$RMSE = \sqrt{\frac{1}{k} \sum_{i=1}^k (y_i - \hat{y}_i)^2} \quad (4.19)$$

where  $\hat{y}_i$  represents the model-predicted value of the target variable, and  $y_i$  denotes the corresponding ground-truth value. The RMSE values for the predicted  $v$  and  $\phi$  as a function

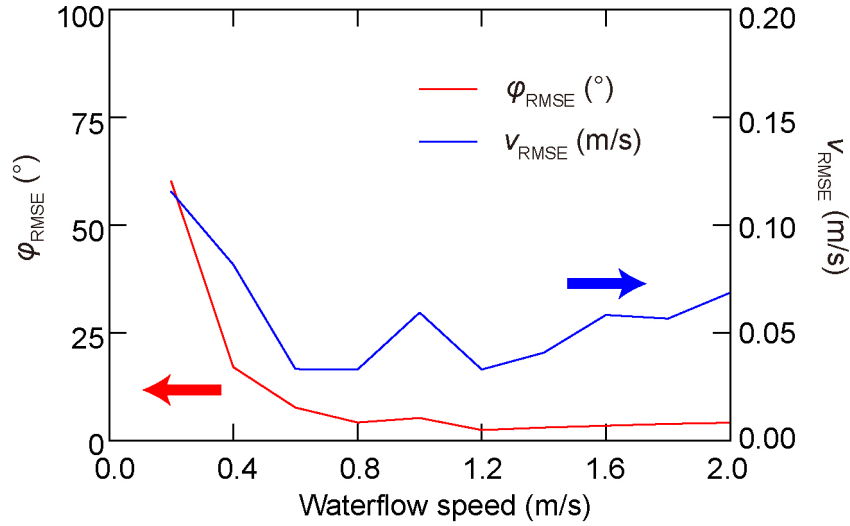


Fig. 4.17 Root mean square error (RMSE) of predicted waterflow angle  $\phi$  and speed  $v$  when converting the water tunnel experimental results obtained using the constructed NN at each applied speed.

of the applied waterflow speed in the range of 0.2–2.0 m/s as shown in Fig. 4.17. Because the waterflow direction  $\phi$  becomes physically undefined when the waterflow speed approaches zero, data points corresponding to near-zero speed conditions were excluded from the evaluation of angular estimation accuracy. Accordingly, the RMSE was evaluated only under non-zero waterflow conditions, where both the waterflow speed and direction are meaningfully defined.

The sensor noise level was defined as the standard deviation of the output when the sensor was stationary. The noise levels for  $E_1$ ,  $E_2$ , and  $E_3$  measured at 10 Hz over 60 s were 0.12, 0.21, and 0.33 mV, respectively, corresponding to pressures of 24.5, 41.9, and 67.8 Pa, respectively. In the low-speed range (0.2–0.4 m/s), the applied differential pressure ranged from approximately 20 to 80 Pa. These noise levels are attributed to internal amplifier noise introduced by the programmable gain amplifier (PGA) and drift caused by temperature fluctuations. Consequently, the sensor noise was relatively large compared with the signal output of each differential pressure sensor element, leading to a slight reduction in model accuracy. In contrast, the influence of noise was considerably smaller in the high-speed range (0.6–2.0 m/s), resulting in more accurate estimations. The average RMSE values for the

predicted waterflow speed ( $v_{RMSE}$ ) and angle ( $\phi_{RMSE}$ ) in the high-speed range (0.6–2.0 m/s) were 0.048 m/s and  $4.33^\circ$ , respectively. Therefore, the proposed sensor satisfied the performance requirements for sea turtle applications, confirming its suitability for biologging measurements.

#### 4.6 Multi-inlet two-dimensional waterflow vector sensor system

To enable standalone measurements, the fabricated sensor was integrated into a data-logging system by connecting it to the HTR logger. This configuration allowed high-time-resolution acquisition of flow data under field conditions. The overall configuration of the sensor system is illustrated in Fig. 4.18. The two-dimensional flow sensor, as previously described, was controlled and read out via an I<sup>2</sup>C communication interface. Three differential-pressure sensing elements (ADCs) were connected to the same I<sup>2</sup>C bus, each assigned a unique address, enabling simultaneous control and data acquisition over a single communication line. The fabrication procedure for the HTR logger followed the same steps described in Chapter 2. A photograph of the fabricated sensor system is shown in Fig. 4.19. The developed system enables simultaneous in-water acquisition of output signals from the three differential-pressure sensing elements.

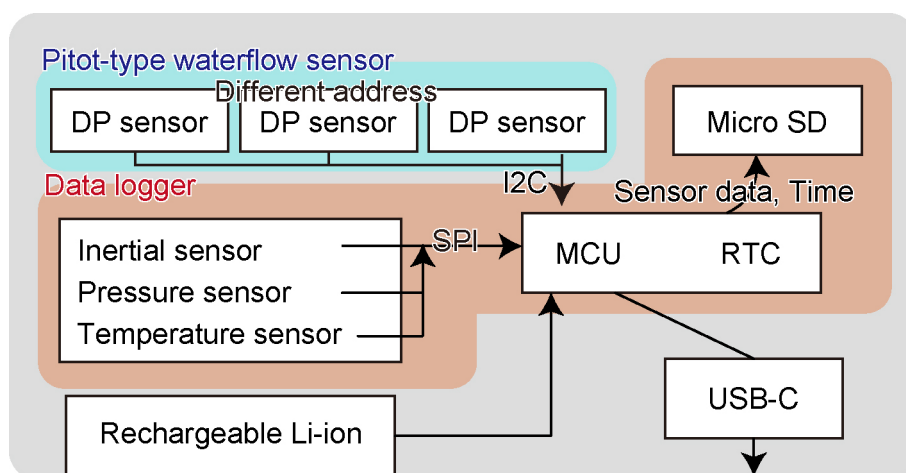


Fig. 4.18 Configuration of the two-dimensional waterflow vector sensor system.

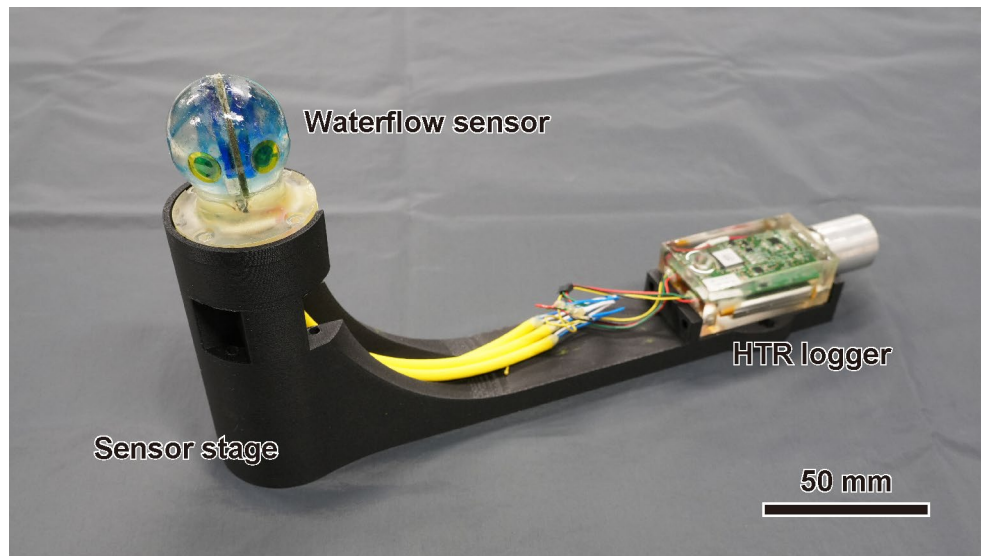


Fig. 4.19 Fabricated two dimensional waterflow vector sensor system.

The total mass of the sensor system was 116.8 g, and the frontal area was 11.55 cm<sup>2</sup> (3.3 cm × 3.5 cm). Therefore, through these fabrication and evaluation steps, the sensor was confirmed to satisfy the sensor system requirements: a mass of less than 2.8 kg, a frontal area of less than 20 cm<sup>2</sup>, and a measurement range of 0–2.0 m/s. Near the cruising speed range (around 0.6 m/s), the RMSE values for waterflow speed and angle was largely achieved, although not exhaustively verified. In the high-speed range (0.6–2.0 m/s), the average RMSE values for the predicted waterflow speed ( $v_{RMSE}$ ) and angle ( $\phi_{RMSE}$ ) were 0.048 m/s and 4.33°, respectively. These results confirm that, except for the allowable pressure requirement, the proposed sensor satisfied the sensor system requirements and demonstrated the feasibility of two-axis waterflow measurements over the high-speed range.

#### 4.7 Engineering novelty of the two-dimensional waterflow vector sensor

Conventional propeller-type waterflow sensors used in biologging require multiple moving components to achieve multi-axis measurements, which makes it difficult to simultaneously ensure robustness in the marine environment and multi-axis measurement

capability. Hot-wire, electromagnetic, and Doppler-based sensors can also be applied to multi-axis measurements. However, hot-wire sensors require direct exposure of the sensing element to the waterflow, resulting in poor robustness. In contrast, electromagnetic and Doppler-based sensors are limited by relatively slow temporal response, high mass, and high-power consumption.

The proposed sensor achieved two-dimensional waterflow measurement while preserving the advantages of Pitot-type waterflow sensors, including robustness, low power consumption, compactness, lightweight design, and fast response. Therefore, the proposed Pitot-type waterflow sensor retains these advantageous characteristics while providing high extensibility to multidimensional waterflow measurements. The proposed sensor is therefore well-suited for applications that require compact size, rapid temporal response, and multi-axis measurement, such as biologging of marine animals and small underwater drones, where achieving such performance has previously been challenging. Accordingly, the proposed sensor can be regarded as a novel waterflow sensor.

## 4.8 Conclusion

---

In this chapter, the design, fabrication, and validation of a two-dimensional waterflow sensor employing a neural network (NN) for marine biologging were presented. The developed sensor is compact enough to be attached to marine animals and resistant to clogging by marine debris, making it suitable for two-dimensional waterflow measurements in harsh underwater environments.

The proposed sensor consists of a spherical housing containing three differential pressure elements, each connected to a pair of polyimide film-covered inlets through silicone oil-filled tubes. The sensor determines the magnitude and direction of waterflow by measuring the differential pressures generated between the inlets. The measured output voltage exhibited a linear response to differential pressure and a quadratic relationship with flow velocity, consistent with theoretical predictions. Moreover, the output varied sinusoidally with flow angle.

A neural network model was trained using datasets acquired in a controlled water tunnel to estimate the waterflow speed and angle from the measured differential pressures. The trained model achieved root-mean-square errors (RMSEs) of  $0.048 \text{ m s}^{-1}$  for speed and  $4.33^\circ$  for angle within the typical swimming velocity range of green turtles ( $0.6\text{--}2.0 \text{ m s}^{-1}$ ).

The fabricated sensor system had a total mass of 116.8 g and a frontal area of  $11.55 \text{ cm}^2$ , satisfying the predefined sensor system requirements for animal-borne deployment. Together with the estimation accuracy over the relevant swimming speed range, these results confirm that the proposed sensor system meets the required specifications in terms of mass, frontal area, measurement range. These results demonstrate the feasibility of two-dimensional waterflow sensing for marine biologging applications.

## CHAPTER 5.

# Field and Experimental Validation of the Developed Waterflow Sensor System

### 5.1 Introduction

---

In this chapter, verification experiments using the developed Pitot-type waterflow sensor and a two-dimensional waterflow sensor are presented.

First, the Pitot-type sensor was attached to loggerhead turtles housed in an aquarium to measure its swimming speed under controlled pool conditions. The measured waterflow speed was then compared with the turtle's actual swimming speed to validate the sensor performance.

Next, the Pitot-type waterflow sensors were mounted on an electric fishing reel, and in situ measurements were conducted in the ocean to demonstrate the feasibility of underwater flow sensing.

Finally, the Pitot-type sensor was integrated into a biologging system and deployed on wild loggerhead turtles during field experiments. The obtained data were compared with those from a conventional biologging system, demonstrating that the proposed sensor can accurately measure the turtle's swimming speed relative to the surrounding water with high temporal resolution.

## 5.2 Aquarium experiment for biologging validation

As a preliminary experiment prior to biologging measurements in the natural environment, the swimming speeds of green turtles kept in an aquarium were measured using the developed sensor system. The measured speed was compared with the swimming speed estimated from video recordings to evaluate the accuracy of the sensor output. In addition, the experiment verified that the fabricated sensor system can be securely attached to the turtle's carapace without affecting its movement.

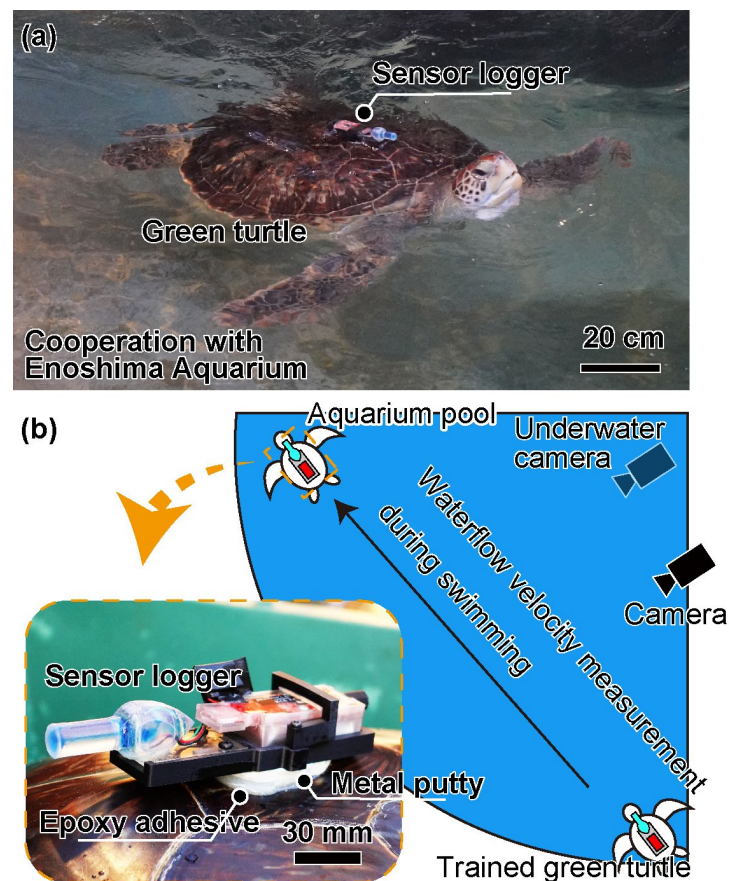


Fig. 5.1 (a) A loggerhead turtle equipped with the sensor system on its carapace. (b) Schematic diagram of the aquarium swimming experiment. The sensor system was attached to the turtle's carapace, and the turtle was allowed to swim from one end of the pool to the other.



Table 5.1 Basic characteristics of the green turtles used in the aquarium experiment.

| Turtle | Body mass (BM) | Carapace length (SCL) | Carapace width (SCW) | Height  |
|--------|----------------|-----------------------|----------------------|---------|
| Naru   | 61.3 kg        | 74.5 cm               | 59.7 cm              | 29.9 cm |
| Ruru   | 49.7 kg        | 68.0 cm               | 56.7 cm              | 26.8 cm |

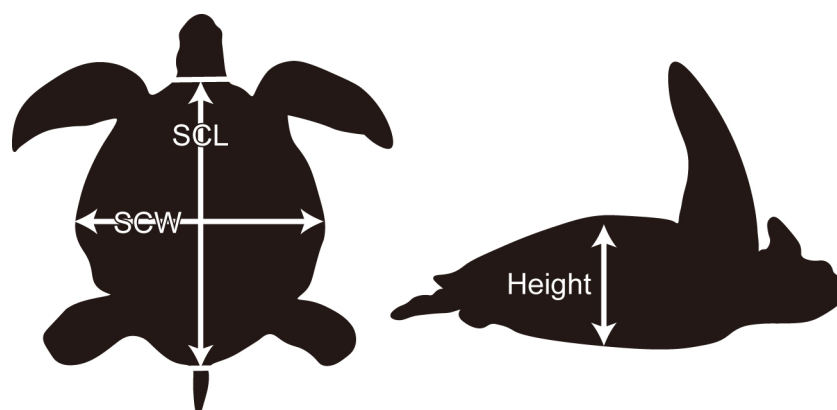


Fig. 5.2 Definition of morphometric parameters of the loggerhead turtle.

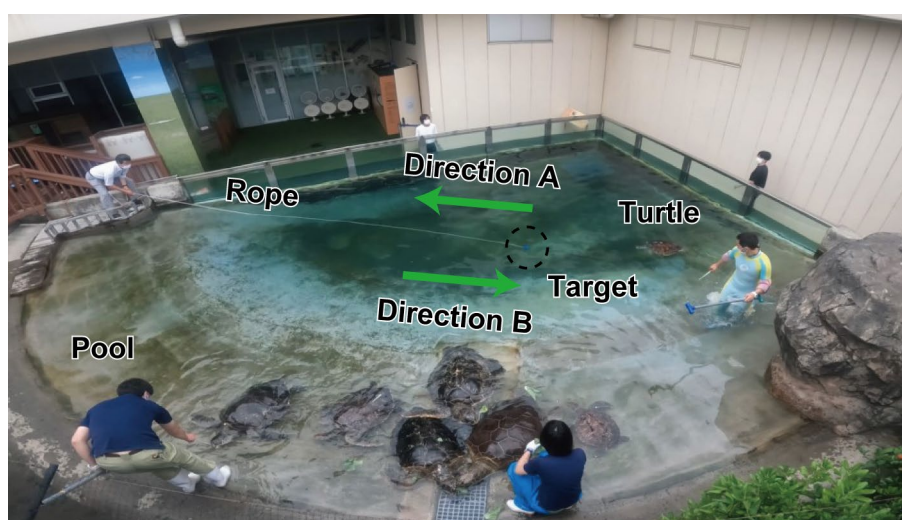


Fig. 5.3 Photograph of the swimming experiment. The turtle was guided to swim across the pool, and its movement was recorded by a camera positioned above the pool.

### 5.2.1 Experiment setup

The experiment was conducted at the Enoshima Aquarium under the supervision of the Sato Laboratory at the University of Tokyo, which specializes in biologging research. A metallic putty was applied to the turtle's carapace, and the stage of the sensor system was attached on top of the putty. The carapace, stage, and putty were bonded using an epoxy adhesive. Before attaching the putty, the carapace surface was cleaned with alcohol to remove oil and debris to ensure strong adhesion.

After mounting the system, the turtle was allowed to swim from one end of the pool to the other while the waterflow speed was measured by the sensor system. Photographs of

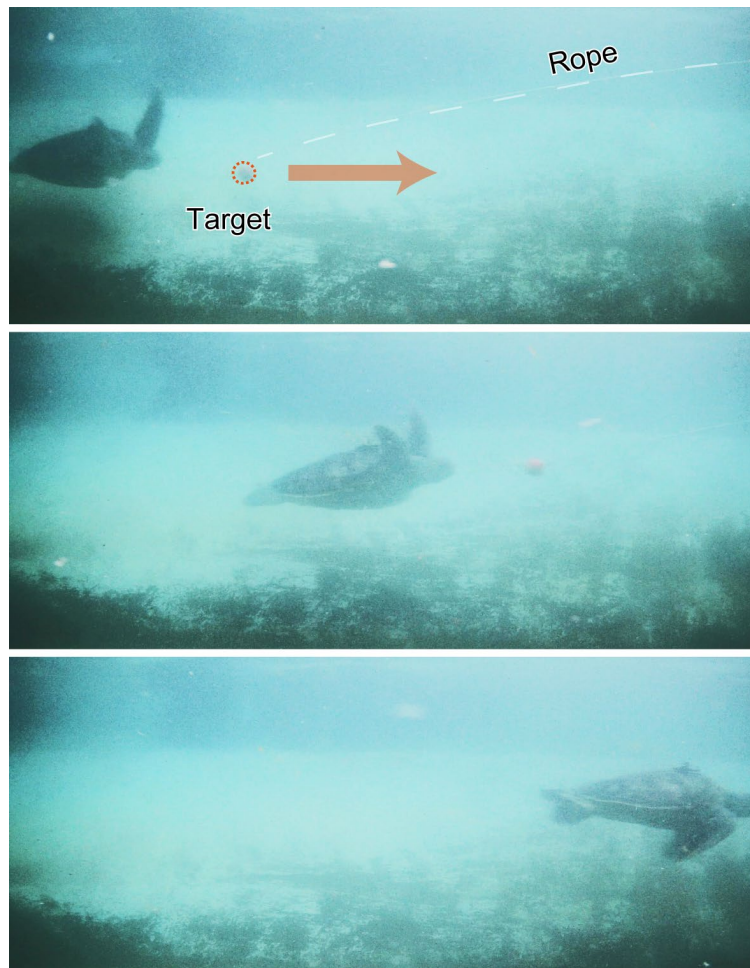


Fig. 5.4 Underwater photograph of the turtle during the towing experiment.

the turtle equipped with the system and a schematic diagram of the experimental setup are shown in Fig. 5.1.

In this experiment, two green turtles (*Chelonia mydas*) , named *Naru* and *Ruru*, were used. Their basic morphometric parameters are listed in Table 5.1. The standard curved carapace length (SCL), standard curved carapace width (SCW), and body height were defined as shown in Fig. 5.2. Both turtles were juvenile individuals hatched in 2013. The morphometric measurements were performed by the staff of the Enoshima Aquarium.

The two green turtles used in the experiment had been trained to associate a specific color with food rewards and to follow an object of that color. Therefore, each turtle was guided by pulling a colored ball attached to the end of a rope, where the ball was painted in the turtle's trained color. To account for the potential effect of water flow within the pool, the turtles were towed in two opposite directions, labeled as Direction A and Direction B, as shown in Fig. 5.3.

Because *Naru* and *Ruru* had been trained to follow different colors, independent experiments could be conducted with each individual. Cameras were installed both above and inside the pool to record the swimming behavior. The rope used for towing had markers at distances of 10 m and 1 m, which allowed the swimming speed of the turtles to be calculated from the video footage. A photograph taken underwater during the towing experiment is shown in Fig. 5.4, where the turtle can be seen following the colored target ball during the guided swimming trial.

The experiment was conducted on June 24, 2022. *Naru* began swimming at 17:40 and completed ten towing trials across the pool, whereas *Ruru* started swimming at 18:38 and completed seven trials. Prior to the experiment, the density of the aquarium water was determined by collecting a water sample from the pool, yielding a calculated density of 1017.4 kg/m<sup>3</sup>.

For the first five trials of *Naru* and the first three trials of *Ruru*, a swimming drag parachute was attached to each turtle to increase hydrodynamic resistance. An pad eye was bonded to the posterior part of the carapace near the tail after cleaning the surface with alcohol for degreasing, and the parachute was tied to the plate as shown in Fig. 5.5.

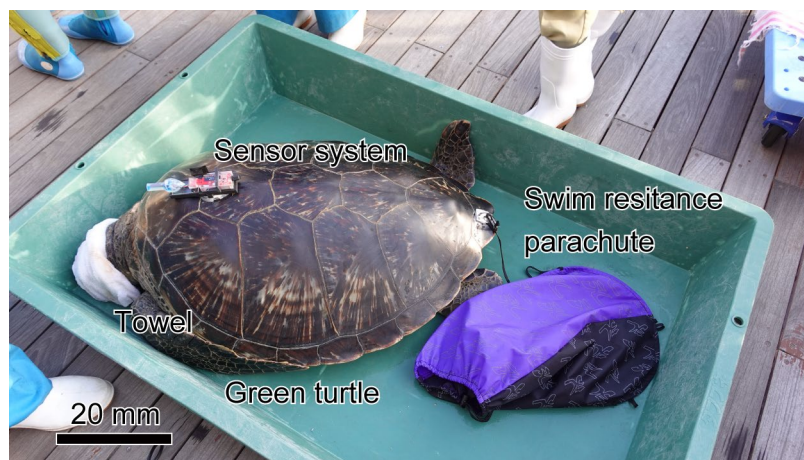


Fig. 5.5 Drag parachute attached to the loggerhead turtle.

During the attachment of both the sensor system and the drag parachute, a towel was placed over each turtle to keep it calm. The times when the turtles began diving and when each guided swimming trial across the pool occurred were recorded. These timestamps were later used for a detailed analysis of the turtles' swimming behavior. Because these experiments were conducted in a controlled aquarium pool environment, environmental disturbances such as water temperature and hydrostatic pressure variations were considered negligible. Therefore, measurements were performed using a single sensor (Sensor P-S) rather than a dual-sensor configuration. The sensor data were recorded using the Ninja logger.

### 5.2.2 Experimental result

The output of the Pitot-type waterflow sensor obtained during the aquarium experiment is shown in Fig. 5.6. Naru and Ruru began diving at 17:40 and 18:38, respectively. In both cases, the sensor output exhibited clear peaks corresponding to the onset of swimming, indicating that the sensor successfully detected the turtles' motion. Based on these signals, the waterflow speed was calculated by setting the output during the turtle's stationary periods in water as the zero reference. The computed waterflow speeds are shown in Fig. 5.7. For both turtles, the sensor system successfully detected variations in waterflow speed corresponding to their swimming activity. Because the dataset also included periods when the turtles were freely moving around in the pool, these data were first excluded from the

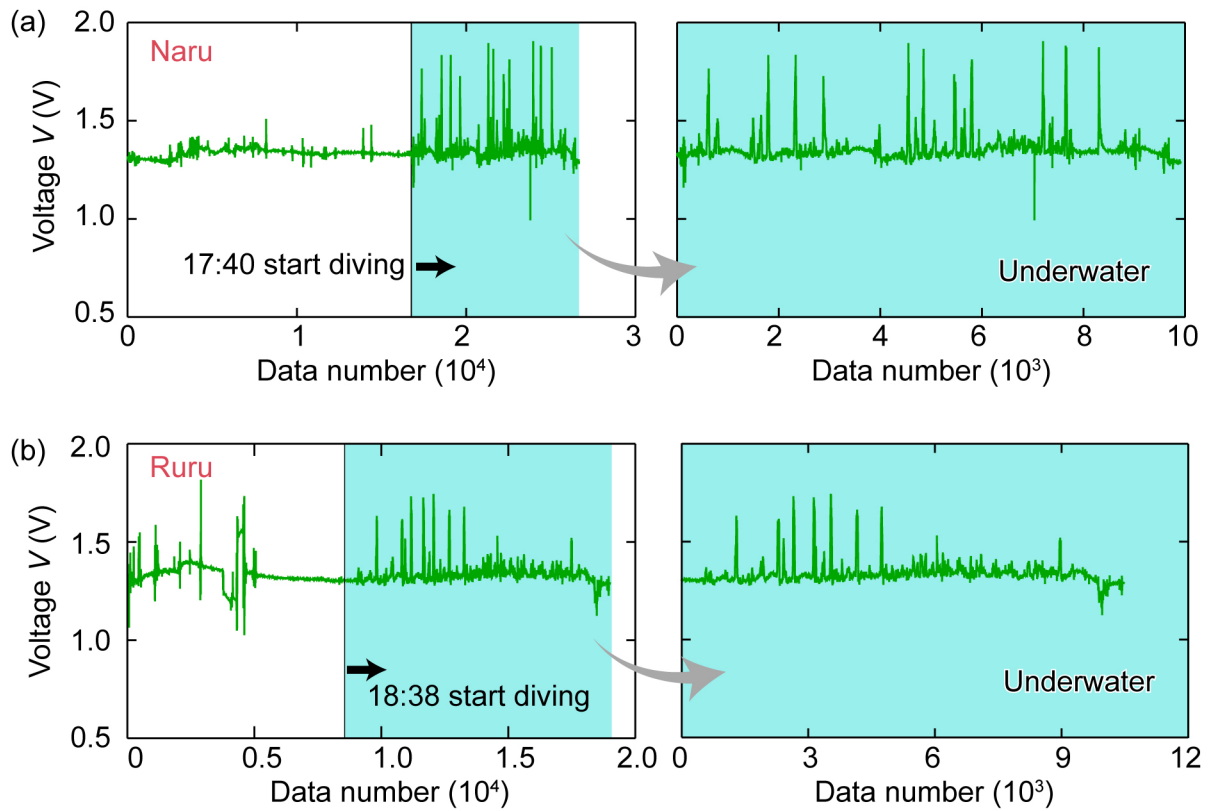


Fig. 5.6 Outputs of the Pitot-type waterflow sensors during the aquarium experiment: (a) output from *Naru*'s trial and (b) output from *Ruru*'s trial.

analysis. Only the time intervals corresponding to guided towing events, identified from the recorded timestamps, were extracted for detailed examination.

The waterflow speeds recorded by the system during *Naru*'s ten swimming trials are shown in Fig. 5.8. In contrast, the second turtle, *Ruru*, did not perform consistent guided swimming because the drag parachute and sensor system were not firmly attached. Additionally, the video footage lacked timestamps, preventing synchronization between the sensor data and the video. Therefore, only *Naru*'s data were used for further analysis.

*Naru* completed ten swimming trials, showing consistent responses to the colored target ball and successfully performing all ten guided swims. However, during the seventh trial, the turtle swam close to the water surface, causing the Pitot tube to intermittently emerge from the water and resulting in repeated meandering motion. Consequently, this trial's data was excluded from the analysis as unreliable.

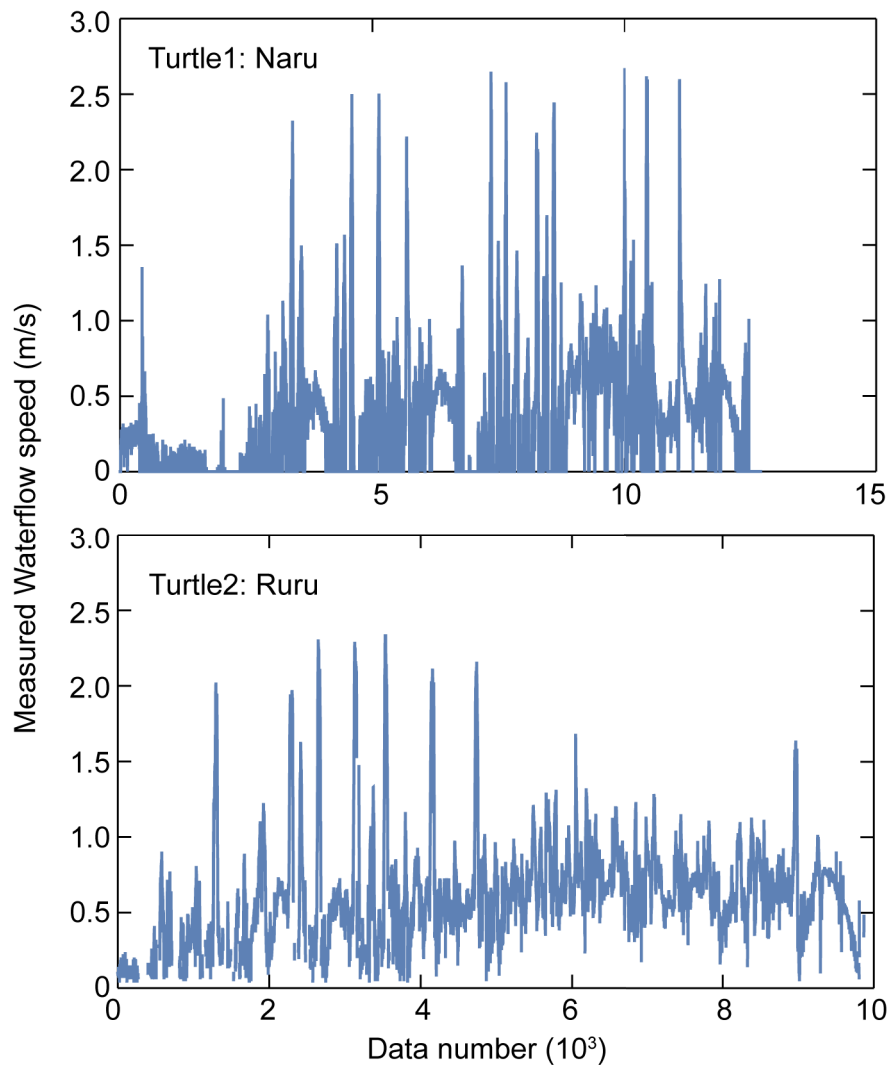


Fig. 5.7 The waterflow speed of each sea turtle measured by the waterflow sensor underwater

Each trial's sensor output is presented in Fig. 5.8. The blue arrows indicate the moments when the turtle began swimming toward the target from the pool's edge, while the red arrows denote when it reached the opposite side of the pool.

The swimming conditions for each of *Naru*'s trials are summarized in Table 5.2. A drag parachute was attached during the first five swims. However, because the turtle was guided by the target ball, it actively swam toward the target with full effort during towing. As a result, in most cases, *Naru* caught up with the target being manually pulled, leading to



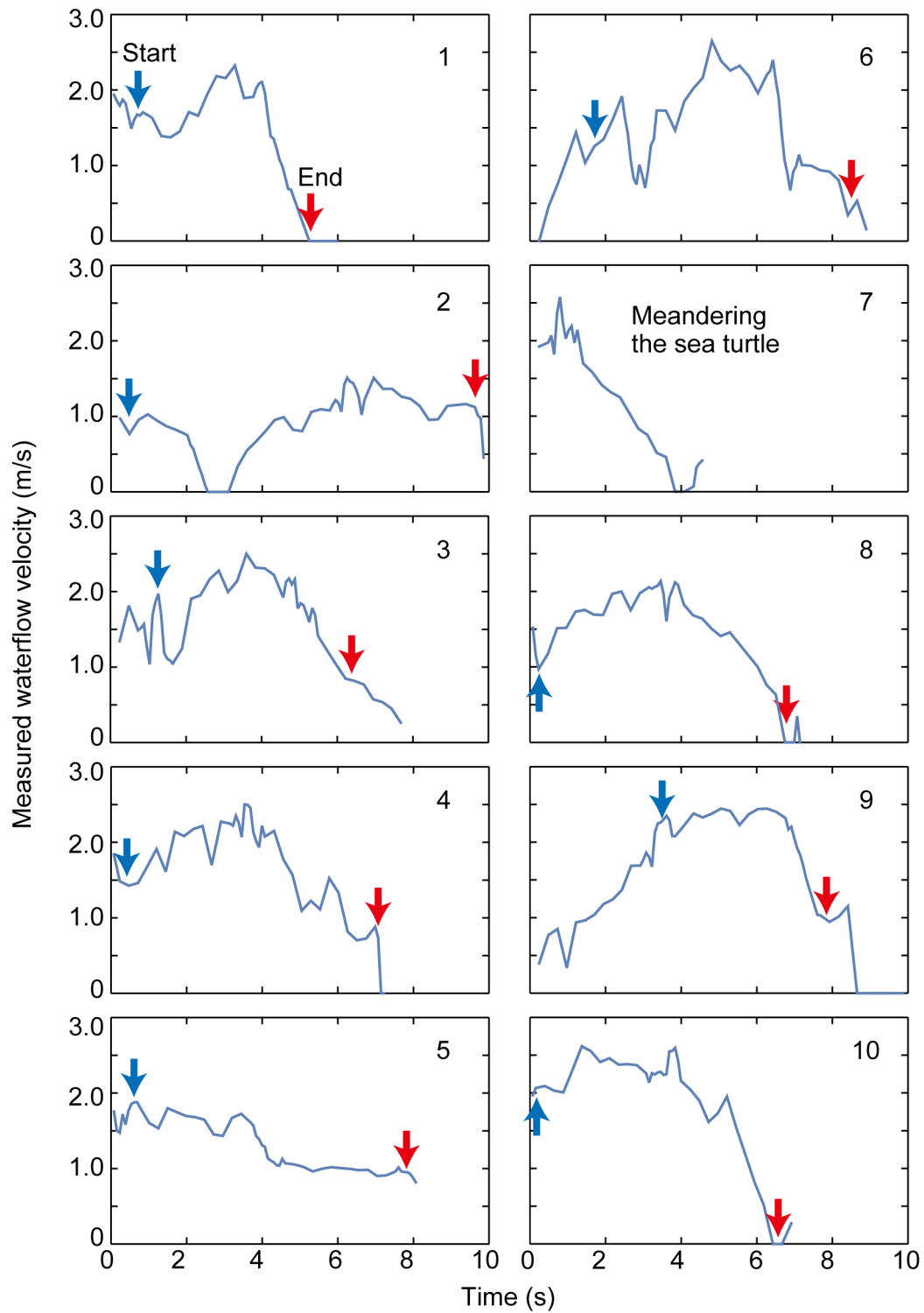


Fig. 5.8 Output of the waterflow sensor recorded during each swimming trial of *Naru* (the first turtle).

Table 5.2 Swimming conditions of the sea turtle (*Naru*) during each trial.

| Trial NO. | Parachute | Swimming direction | Observation                                                             |
|-----------|-----------|--------------------|-------------------------------------------------------------------------|
| 1         | Yes       | A                  | Surfaced to breathe during swimming.                                    |
| 2         | Yes       | A                  | Swam with a tilted body posture.                                        |
| 3         | Yes       | A                  | Irregular flapping and speed variation were observed.                   |
| 4         | Yes       | B                  | Flapping and speed were nearly constant.                                |
| 5         | Yes       | B                  | Caught up with the target and swam slightly meanderingly.               |
| 6         | No        | A                  | Caught up with the target; slight irregularities in flapping and speed. |
| 7         | No        | A                  | Pitot tube emerged from the water surface.                              |
| 8         | No        | A                  | Flapping and speed were nearly constant.                                |
| 9         | No        | A                  | Slightly meandering swimming path.                                      |
| 10        | No        | B                  | Flapping and speed were nearly constant.                                |

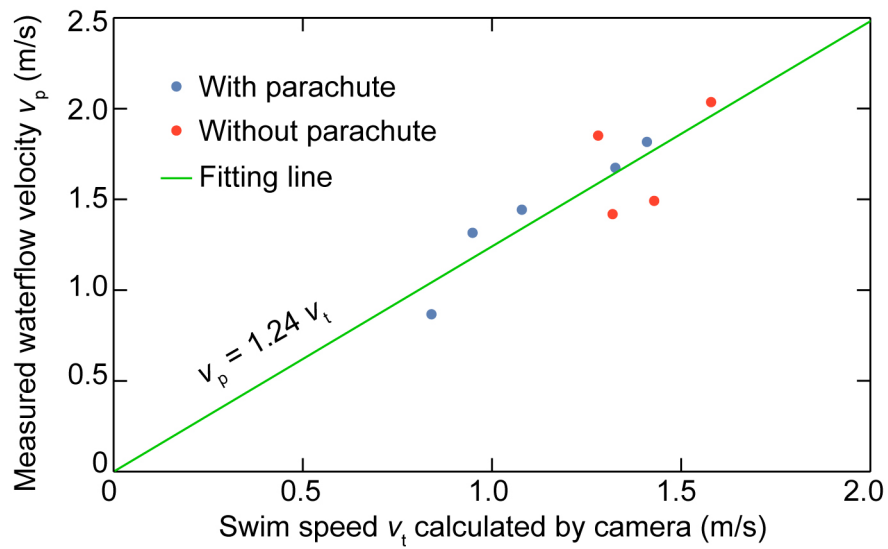


Fig. 5.9 Comparison between the output of the sensor system and the actual swimming speed of the sea turtle.

difference in swimming speed was observed between the conditions with and without the parachute.



This suggests that to quantitatively evaluate the effect of the parachute on swimming speed, a dedicated towing system with controlled retraction speed would be required. Despite this limitation, acceleration and deceleration patterns corresponding to the video footage were clearly identified in all trials, confirming that the sensor system successfully captured the turtle's swimming behavior.

The comparison between the average sensor output for each swimming trial and the actual swimming speed of the sea turtle, calculated from the video footage, is shown in Fig. 5.9. The sensor output was obtained by averaging the waterflow speed values recorded from the start of swimming at one end of the pool until the turtle stopped at the other end. The swimming speed was calculated from the video by dividing the horizontal travel distance by the time required to reach the opposite end. Because the pool used in the experiment was approximately 1 m deep and the turtle did not perform deep dives, the calculated speed represents only the horizontal component of the turtle's movement. In all trials, the waterflow speed measured by the sensor ( $v_p$ ) was higher than the actual swimming speed ( $v_t$ ) estimated from the video. A positive correlation was observed between the two, and their relationship can be expressed as follows:

$$v_p = 1.24 v_t \quad (5.1)$$

This result indicates that the sensor output was approximately 1.24 times greater than the actual swimming speed. This discrepancy is attributed to the fact that the sensor system directly measures the waterflow over the turtle's carapace. Because of the streamlined shape of the carapace, the local flow accelerates relative to the turtle's swimming velocity, leading the sensor to record a higher value. Therefore, it was suggested that, in actual measurements, the Pitot tube should be positioned at a sufficient distance from the turtle's carapace to avoid the influence of accelerated flow along the shell surface.

### 5.3 Electric fishing reel experiment

As a preparatory step before the animal experiment, an experiment was conducted

to compare the outputs of the fabricated Pitot-type waterflow sensor and a conventional propeller logger using an electric fishing reel.

### 5.3.1 Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 5.10. The propeller logger and the Pitot-type waterflow sensor were mounted on a fishing rod, and a motorized reeling device was used to wind the line at a controlled rate. By pulling the sensors upward through the water in this manner, a controlled flow speed was applied to both the propeller logger and the Pitot-type flow sensor, allowing direct comparison of their output responses under nature conditions as shown in Fig. 5.10 (a). As shown in Fig. 5.10 (b), the Pitot-type waterflow sensor and the propeller logger were secured to a PVC pipe using self-fusing and vinyl tape. A sinker and fishing line were attached to the lower end of the pipe to ensure that the sensors maintained an upward orientation throughout the experiment. The assembly was connected to an electric fishing reel and submerged to a predetermined depth before being automatically reeled in. The electric reel was equipped with multiple winding-speed settings (“gears”), allowing controlled variation of the waterflow speed applied to the sensors.

Each trial was conducted using a different reeling speed (*gear setting*) to apply

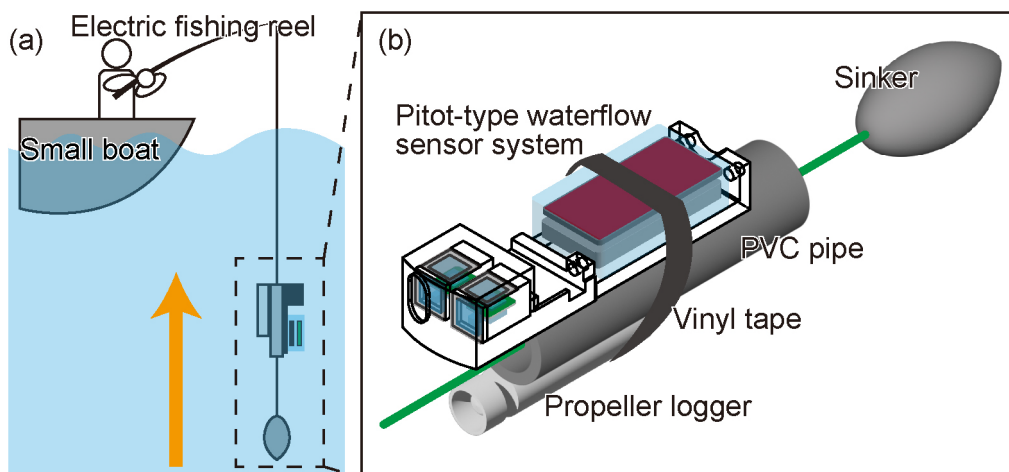


Fig. 5.10 Experimental setup of electric fishing reel experiment. (a) Schematic illustration of the experimental setup. (b) Mounting method of the sensors to the fishing reel.

Table 5.3 Timeline of the electric fishing reel experiment

| Gear | Depth<br>x[m] -> y[m] | Distance[m] | Start Time<br>hh:mm:ss~ | $\Delta$ Time[s] |
|------|-----------------------|-------------|-------------------------|------------------|
| 3    | 51 -> 6               | 45          | 08:54:30~               | 298.24           |
| 4    | 60 -> 10              | 50          | 09:01:30~               | 224.94           |
| 5    | 60 -> 10.4            | 49.6        | 09:07:30~               | 35.92            |
| 6    | 60 -> 10              | 50          | 09:10:00~               | 36.57            |
| 8    | 60 -> 10.3            | 49.7        | 09:12:30~               | 35.67            |
| 10   | 60 -> 10.3            | 49.7        | 09:18:00~               | 34.29            |
| 13   | 60 -> 9.7             | 50.3        | 09:20:30~               | 31.24            |
| 16   | 60 -> 9.2             | 50.8        | 09:23:00~               | 27.40            |

distinct flow speed to the sensors. Table 5.3 summarizes the experimental timeline and parameters for each trial. The Gear column indicates the reeling-speed setting used on the motorized reel. The Depth column represents the range of depths through which the sensors were towed during each trial, from the initial depth at the start of reeling to the final depth after retrieval. The Distance denotes the total vertical distance the sensors traveled through the water. The Start Time indicates the moment when reeling began, and  $\Delta$ Time represents the total duration of the retrieval for that trial. As shown in Table 5.3, the trials were performed sequentially from 08:54 to 09:23, with gear settings ranging from 3 to 16 and reeling durations decreasing as the gear setting increased, reflecting progressively higher waterflow speed applied to the sensors.

### 5.3.2 Experimental result

The outputs recorded by each sensor during the experiment are shown in Fig. 5.11. This figure was generated using data from the Pitot-type waterflow sensor, depth sensor, temperature sensor. The Pitot-type sensor contains two pressure sensors (Pitot<sub>com</sub> and Pitot<sub>det</sub>),

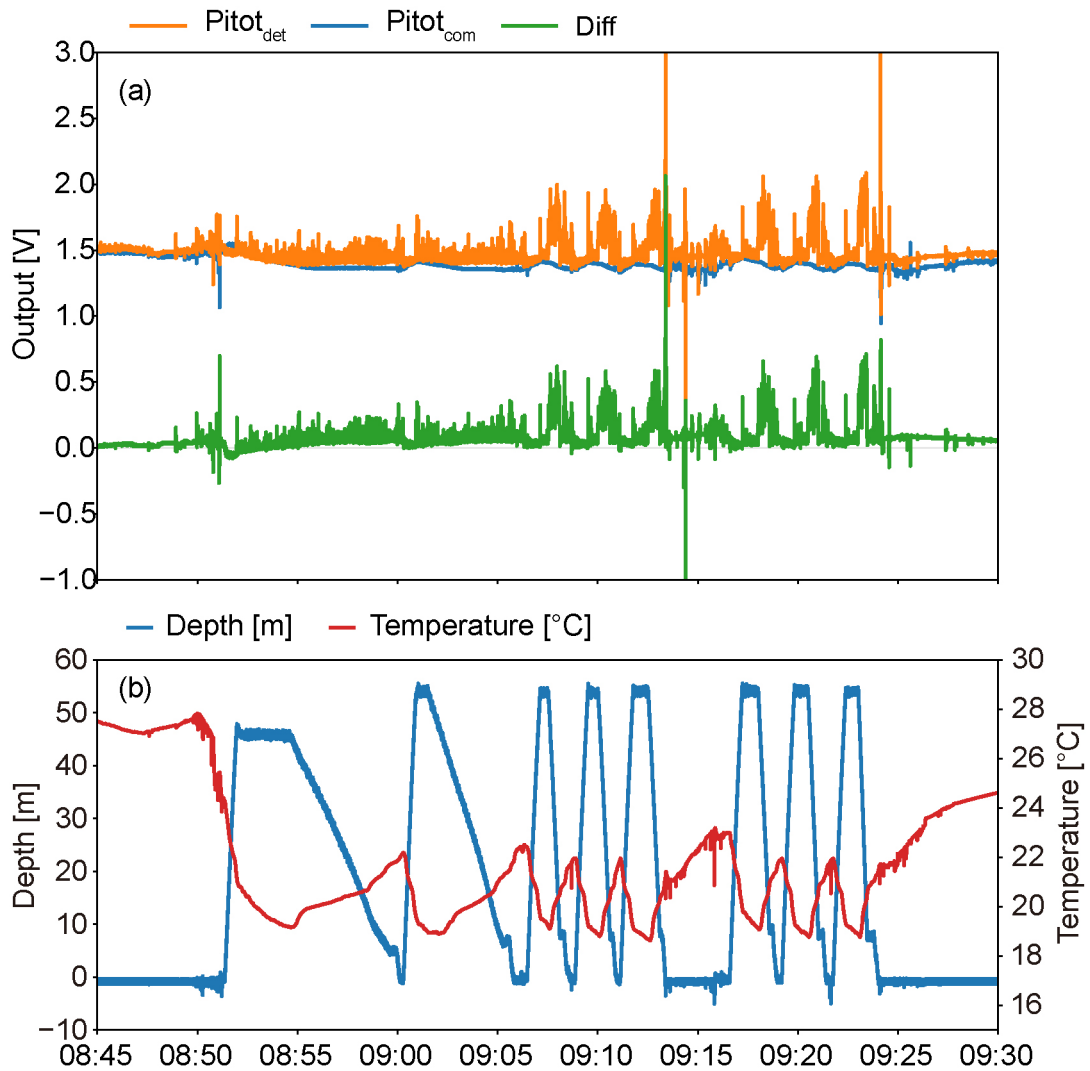


Fig. 5.11 Outputs of (a) the Pitot-type waterflow sensor, (b) the depth sensor, and the water temperature sensor during the experiment.

and the waterflow speed was calculated from the differential pressure between these two sensors. To remove the baseline offset, a 10-s interval from 09:06:00 to 09:06:10 was used as the baseline period. During this interval, the system was confirmed to be on land. The mean output values obtained during this period were subtracted from each sensor signal to perform offset correction. The difference between the two corrected outputs ( $Pitot_{det} - Pitot_{com}$ ) was then calculated and used as the differential pressure signal.

The water depth was derived from the absolute pressure sensor integrated into the

HTR logger. Because the sensor outputs pressure in pascals (Pa), the mean value during the baseline period (09:06:00–09:06:10) was first subtracted to obtain the relative pressure,  $P_{\text{gauge}}$ . The relative pressure was then converted to water depth [m], using the following equation:

$$\text{Depth} = \frac{P_{\text{gauge}}}{\rho g}, \quad (5.2)$$

where  $\rho = 1000 \text{ kg/m}^3$  is the density of seawater and  $g = 9.80 \text{ m/s}^2$  is the gravitational acceleration. Through this conversion, the instantaneous depth was estimated from the relative pressure output of the sensor.

Next, the difference between the two offset-corrected sensor outputs ( $\text{Pitot}_{\text{det}} - \text{Pitot}_{\text{com}}$ ) was calculated and treated as the differential pressure signal. Taking the difference between the two sensors effectively reduced external disturbances such as temperature and hydrostatic pressure change. A fourth-order Butterworth low-pass filter with a cutoff frequency of 5 Hz was then applied to the differential signal to remove high-frequency noise components. Subsequently, additional compensation procedures were implemented to eliminate residual drifts that could not be removed solely by differencing. To correct drift caused by internal temperature variations of the sensor, temperature compensation was performed using the output from the built-in temperature sensor. The experimentally determined temperature-compensation coefficient,

$$A_{\text{TEMP\_BIT}} = -3.486 \text{ bit} / ^\circ\text{C} \quad (5.3)$$

was applied proportionally to the temperature deviation from the baseline period. It should be noted that the Pitot-type sensor used in this experiment differs from that described in Section 3.5. Therefore, a separate calibration coefficient was employed.

To further account for the hydrostatic pressure component associated with changes in depth, a 30 s interval from 08:51:30 to 08:52:00 was defined as the hydrostatic-pressure correction period. This interval corresponded to the section of the experiment during which the fishing reel was operated to lower the sensor vertically into the water. The relationship between the depth data and the differential-pressure signal during this interval was approximated by linear regression, and the resulting slope,

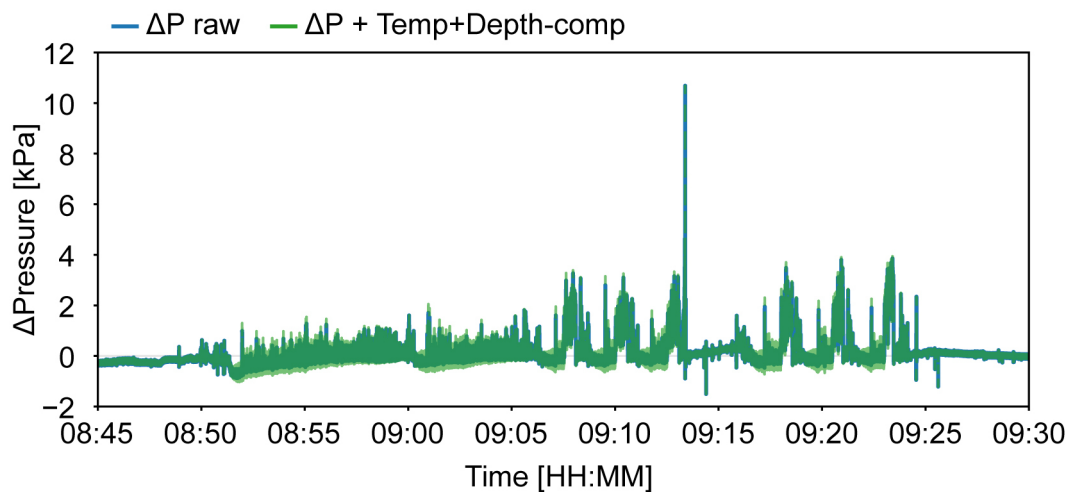


Fig. 5.12 Compensated output of the Pitot-type waterflow sensor after temperature and hydrostatic pressure corrections.

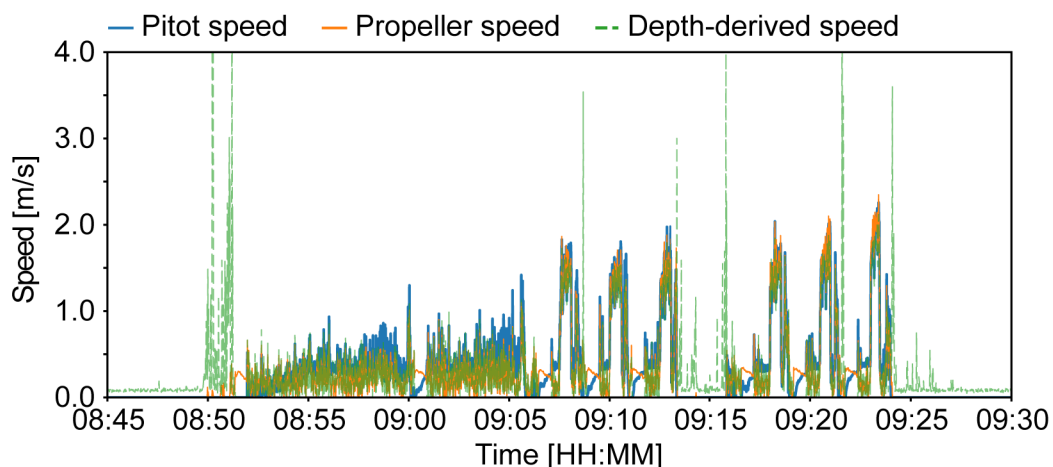


Fig. 5.13 Comparison of flow speeds obtained from the Pitot-type waterflow sensor, propeller logger, and depth-derived vertical speed.

$$a = 3.21 \times 10^{-3} \text{ kPa/m} \quad (5.4)$$

was used to estimate the hydrostatic-pressure effect. This component was then subtracted from the differential pressure signal to remove depth-dependent drift.

After all corrections were applied, the differential-pressure signal was converted into pressure values using the known calibration factor of 1 bit = 1/1666.1 kPa obtained from

pressure calibration experiment. The compensated output of the Pitot-type waterflow sensor is shown in Fig. 5.12. Finally, the waterflow speed was calculated based on the theoretical relationship derived from the water tunnel calibration experiments. The resulting speed data, sampled at 100 Hz, averaged over 1 s intervals to produce the final time-series output.

In contrast, for the propeller logger, the waterflow speed was calculated from the rotational frequency derived from the count data recorded at 1 s intervals. The conversion was performed using a known calibration coefficient of  $0.0205 \text{ m s}^{-1} \text{ rps}^{-1}$ , which relates the propeller's rotation frequency to the corresponding flow speed. Additionally, the vertical velocity component,  $v_{\text{depth}}$  was obtained by differentiating the measured water-depth data with respect to time. Figure 5.13 presents a comparison of the outputs obtained from the Pitot-type waterflow sensor, the propeller logger, and the vertical speed derived from depth. The outputs of the three sensors were generally consistent with each other.

To evaluate the consistency among the three independently derived speeds, a correlation analysis was performed. The analysis used the output of the Pitot-type waterflow sensor, the propeller logger, and the depth-derived speed. All speed time series were temporally synchronized and averaged over 1 s intervals to establish a common time base and to reduce short-term fluctuations. Only data points for which all three speeds were available simultaneously and had positive values were used in the analysis. In addition, to ensure that the correlation analysis reflected only the imposed towing conditions, the comparison data were limited to the time intervals corresponding to each trial listed in Table 5.3. For each trial, the time interval from the start time to the elapsed duration  $\Delta\text{Time}$  was extracted in the analysis. Data recorded during the deployment and stationary phases were excluded because they may be influenced by ambient currents and waterflow disturbances unrelated to the controlled reeling motion.

First, an overview comparison was performed by visualizing the relationship among the three speeds in a three-dimensional space, as shown in Fig. 5.14. Overall, the data points are distributed close to the 1:1:1 reference line across the entire range of measured speeds. This indicates that the three independently derived speeds are generally consistent. Following this qualitative overview, the relationship between the speeds was examined more

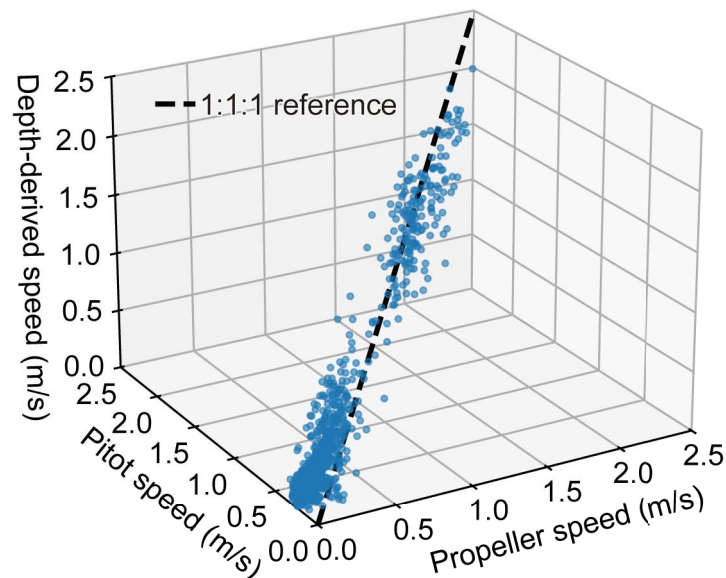


Fig. 5.14 Three-dimensional comparison of waterflow speed measured by the Pitot-type waterflow sensor, the propeller logger, and the depth-derived speed.

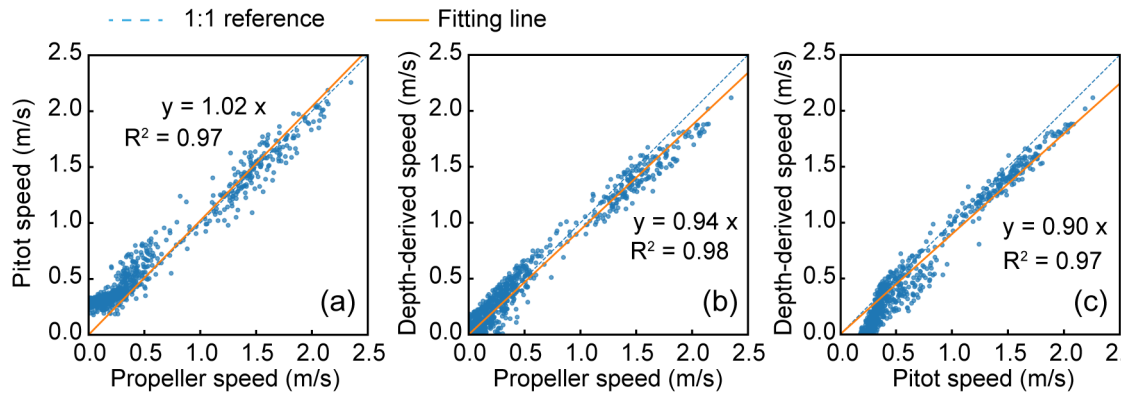


Fig. 5.15 Pairwise comparison of waterflow speed measured by different methods: (a) Pitot-type waterflow sensor versus propeller logger, (b) propeller logger versus depth-derived speed, (c) depth-derived speed versus Pitot-type waterflow sensor.

quantitatively using pairwise comparisons. In each comparison, one derived speed was plotted against another, and a least-squares linear regression constrained to the form  $y = ax$  was used. Figure 5.15 shows the calculated results of each pairwise comparison. As shown in Fig. 5.15 (a), the Pitot-type waterflow sensor and the propeller logger exhibit close



correspondence, with a coefficient of fitting line of 1.02 and coefficient of determination of  $R^2 = 0.97$ .  $R^2$  was calculated using the definition given in

$$R^2 = 1 - \frac{\sum_{i=1}^N (y_i - \hat{y}_i)^2}{\sum_{i=1}^N y_i^2}, \hat{y}_i = ax_i \quad (5.5)$$

This result indicates that both sensors capture nearly the same towing-induced speed. The proposed Pitot-type waterflow sensor provides speed estimates comparable to conventional propeller loggers during controlled strain-line towing in a natural marine environment. When the depth-derived speed is compared with the propeller logger speed (Fig. 5.15 (b)) and the Pitot-type waterflow sensor (Fig. 5.15 (c)), the correlations are also high.  $R^2$  were 0.98 and 0.97, respectively. But the coefficients of the fitting lines are 0.94 and 0.90, which are below unity. This suggests that the depth-derived speed is approximately 6–10% lower than the two sensor measurements.

The depth-derived speed is obtained from the rate of change in depth and represents the vertical component of ground speed. Comparing this quantity with the two waterflow-based sensors assumes that the ambient current is negligible, so that the vertical ground speed is approximately equal to the relative waterflow speed. Therefore, the measurements of the depth-derived speed may be slightly affected by ocean currents. In addition, the depth-derived speed is obtained only from the vertical component of speed. As a result, it is sensitive to deviations from purely vertical towing. Changes in line angle or lateral motions caused by waves and ambient currents can lead to the depth-derived speed being underestimated relative to the actual speed. Accordingly, these combined factors likely explain why the depth-derived speed was lower than the speeds measured by the propeller logger and the Pitot-type waterflow sensor. Despite this limitation, the three independently derived speeds exhibited strong correlations during the controlled reeling intervals, indicating that they consistently tracked the towing-induced speed variations. Overall, these results support the conclusion that the Pitot-type waterflow sensor can measure relative waterflow speed with an output level consistent with a widely used conventional method.

5.4 Setup of a biologging experiment

A biologging experiment was conducted by attaching the developed sensor system to wild loggerhead turtles (*Caretta caretta*) to measure relative waterflow speed. The experiment was carried out under the supervision of the Sato Laboratory at the University of Tokyo, which specializes in biologging research. This experiment was performed in accordance with the guidelines of the Animal Ethics Committee of the University of Tokyo and Keio University and conducted as a part of a ‘tag and release’ program, in which loggerhead sea turtles caught by set net as bycatch in the Sanriku Coast, were turned over by fishermen to researchers. This fieldwork experiment was conducted on 7 August 2025, using a loggerhead turtle designated as L2509. This turtle was incidentally captured by commercial set nets along the Sanriku coast (38°55′–39°40′N, 141°40′–142°05′E) of Japan. This experiment site was a summer-restricted foraging ground for loggerhead turtles [48]. Then the turtle was brought to the Otsuchi Coastal Research Center (OCRC) at the Atmosphere and Ocean Research Institute, The University of Tokyo (39°21′05″N, 141°56′04″E) in Otsuchi town, Iwate prefecture, Japan. The turtle was housed in an outdoor water tank (2×1×1 m, length×width×depth) within the facility of OCRC and was maintained under appropriate daily care and management after the turtles were tagged with metal ID labels.

The basic characteristics of L2509 are summarized in Table 5.4. The body mass of the turtle was 59.2 kg. As shown in Fig. 5.16, the field site was Otsuchi Bay (39°20′N, 141°56′E), located in Otsuchi Town, Iwate Prefecture, Japan. The turtle was released around Otsuchi Bay. Three main devices were used in the biologging experiment, as illustrated in Fig. 5.17. The turtle was equipped with a carapace tag that measured its swimming speed relative to the surrounding water, and a towed tag positioned behind the turtle to continuously

Table 5.4 Basic characteristics of the loggerhead turtle used in the biologging experiment.

| Turtle | Sex | Body mass (BM) | carapace length (SCL) | Girth     | Date of capture |
|--------|-----|----------------|-----------------------|-----------|-----------------|
| L2509  | -   | 59.2 kg        | 77.6 cm               | 137.63 cm | 11/07/2025      |

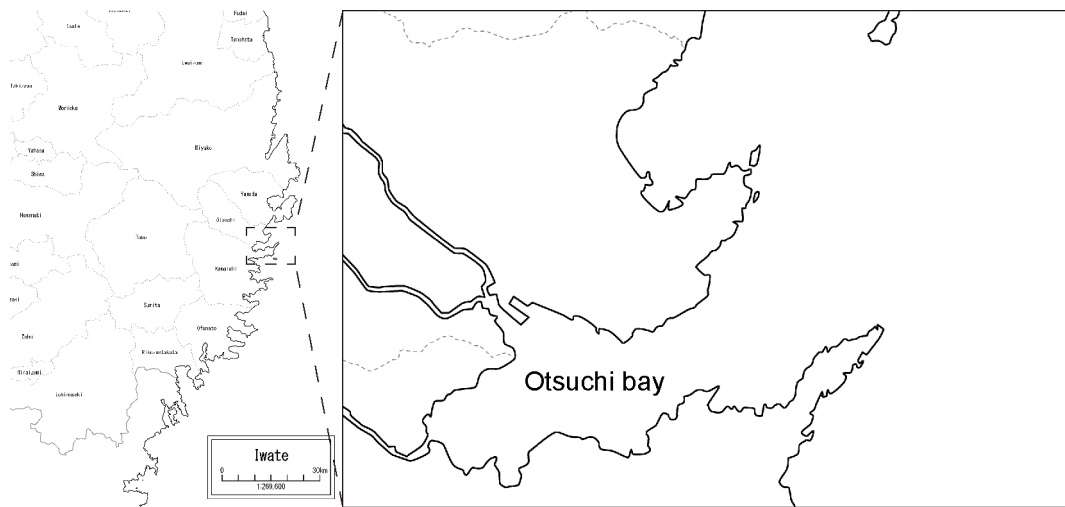


Fig. 5.16 Field site of the biologging experiment. The experiment was conducted in Otsuchi Bay, Iwate Prefecture, using loggerhead turtles incidentally captured in a set net. (Source: Freemap Japan, <https://www.freemap.jp/>)

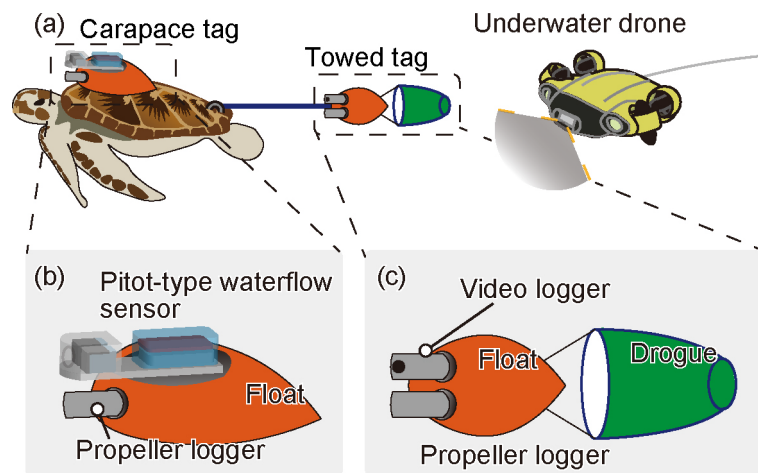


Fig. 5.17 Schematic diagram of the biologging experiment setup: (a) overall setup, (b) carapace tag attached to the turtle's back, and (c) towed tag attached behind the turtle record its rear view. In addition, an underwater drone was employed to capture the turtle's swimming behavior from multiple angles throughout the experiment. The specifications and functions of each device are described below.

#### 5.4.1 Carapace tag

The sensor system was attached to wild loggerhead turtles and deployed in a natural marine environment. Animal-borne sensor systems require the recapture of sensor systems for data retrieval and the recapture of instrumented animals. However, in the case of loggerhead turtles around Sanriku coast, the recaptures of sensor systems and animals are almost impossible. Because the Sanriku Coast serves summer foraging habitats for loggerhead turtles [48] rather than nesting site. Sea turtles do not return to the same location after being released. Exceptions are satellite [115] or cellular network [29] linked telemetry, but its limited data transmission capacity makes it unsuitable for the high-sampling rate Pitot type waterflow sensor proposed in this study. Therefore, to recover the recorded data, a dedicated recovery mechanism was required that could autonomously separate the sensor system from the turtle after measurement and enable its subsequent retrieval. To meet these requirements, a modified float system based on a conventional automatic time-scheduled release system used in biologging studies [91]–[93] was developed, as shown in Fig. 5.18. The system consists of a buoyant body, a weight, a release device, and a transmitter.

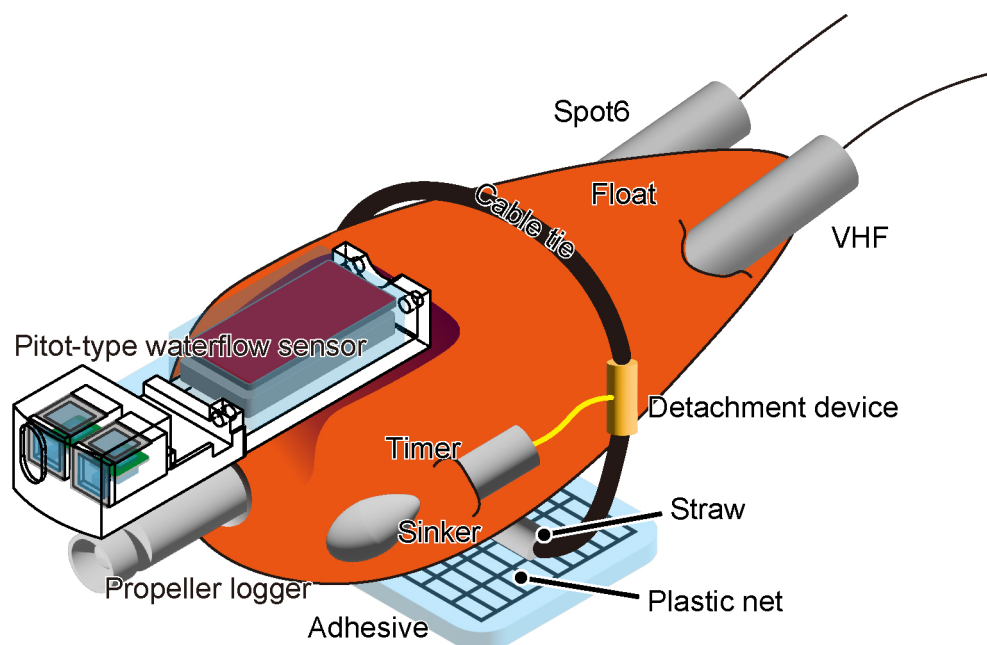


Fig. 5.18 Components of the carapace tag

The main component of the system, the float, was fabricated by mixing glass bubbles (K1, 3M Company, Saint Paul, Minnesota, USA) with epoxy resin and hardener (Aradur, Huntsman International LLC, The Woodlands, Texas, USA). The Pitot-type waterflow sensor and a propeller logger (PD3GT, Little Leonardo Corporation, Tokyo, Japan) were mounted on the float structure. The Pitot-type sensor was attached using a silicone sealant (8060Pro, CEMEDINE Co., Ltd., Tokyo, Japan), while the propeller logger was installed inside a hole made in the float and secured with self-fusing tape. The propeller logger was installed on the float for comparison purposes. To attach the float system to the turtle, a mesh net was bonded to the carapace using an adhesive (Quick5, Konishi Co., Ltd., Osaka, Japan). A straw was inserted between the mesh layers to form a passage, through which a cable tie was threaded to secure the float system to the turtle's body. The cable tie was connected to a biologging release device (RC-300-150, Little Leonardo Corporation, Tokyo, Japan), which was electrically linked to a timer embedded in the float. When the timer reached the preset time, a small pyrotechnic charge within the release device was ignited, cutting the cable tie and releasing the sensor system from the turtle.

After detachment, the sensor system floated to the sea surface due to the buoyancy of the float. Two transmitters, SPOT-6 (Wildlife Computers, Inc., Redmond, Washington, USA) and VHF, were attached to the float. The SPOT-6 transmitter remains inactive while submerged and begins operation only after surfacing, triggered by a seawater detection switch located on its side. In contrast, the VHF transmitter operates continuously, allowing signal reception even during brief surfacing events. Because the antennas must be above the water surface to transmit signals effectively, a fishing weight was attached to the side opposite the transmitters. As shown in Fig. 5.19, the balance between the float and the weight ensured that the transmitter side was always oriented upward when floating on the sea surface.

Once at the surface, the location of the system was determined using two transmitters. The SPOT-6 transmitter operates through the ARGOS satellite system, which is widely used for collecting atmospheric and oceanographic data. It sends signals to observation satellites, enabling estimation of the system's approximate position from the received signal data. In biologging studies, sensors can sometimes be lost or drift away due

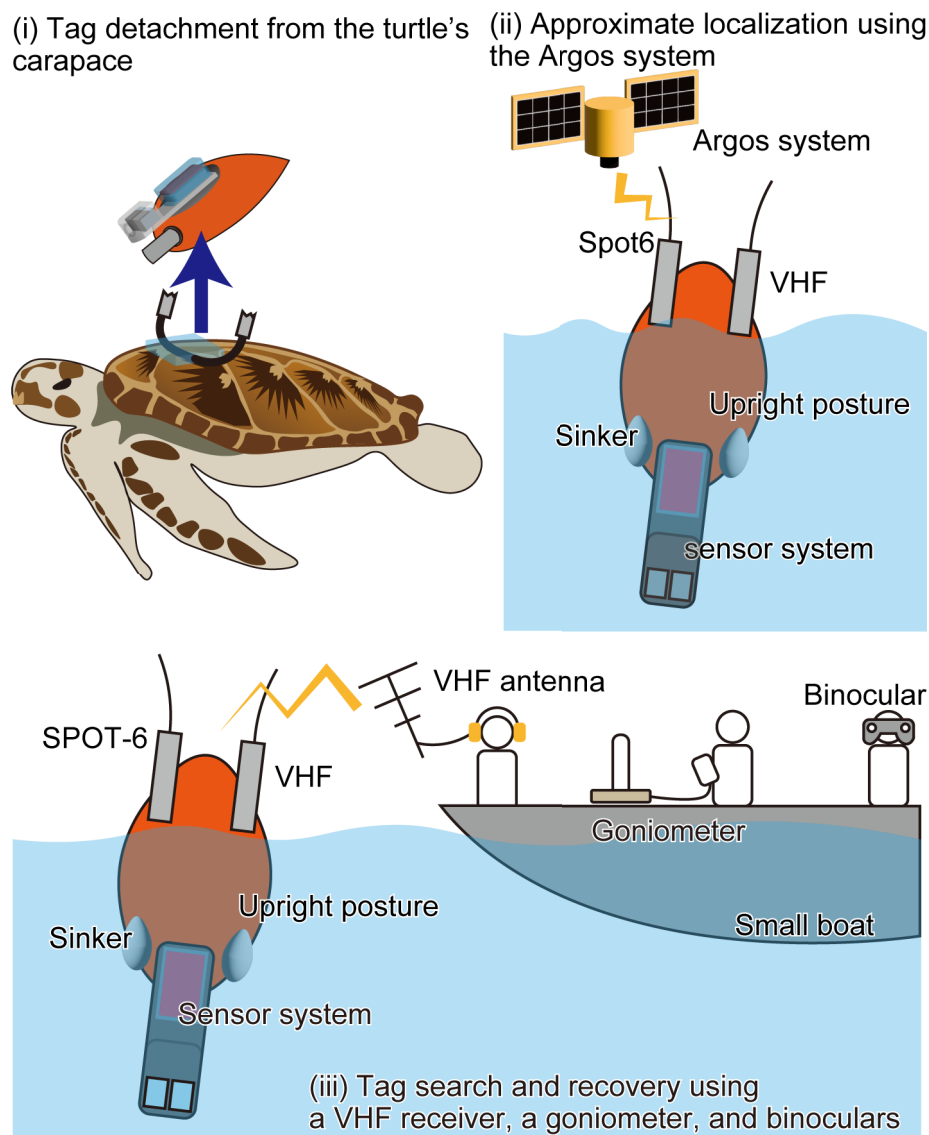


Fig. 5.19 Surfacing behavior and retrieval process of the float system.

to ocean currents or other factors. Therefore, the SPOT-6 transmitter was primarily used to verify that the sensor system had surfaced and to obtain its approximate location before initiating recovery operations.

After obtaining a rough position using SPOT-6, a more precise search was conducted with a goniometer and a VHF transmitter. The goniometer is a device capable of directly receiving satellite signals transmitted from SPOT-6 using an antenna. Although the

ARGOS system can only be accessed when the satellite passes over Japan, the goniometer can receive transmissions from the SPOT-6 every 30 to 45 seconds, as long as the SPOT-6 unit is floating on the sea surface.

The VHF transmitter emits radio waves at a fixed frequency, which are received by a directional Yagi antenna connected to VHF receiver. On the goniometer display, both the signal strength and the direction of the received signal are shown when the SPOT-6 emits signal. By combining these two pieces of information, the position of the floating sensor system can be determined from the research vessel, allowing operators to approach it efficiently. Once the approximate location had been identified, the sea surface was visually scanned with binoculars to locate the float. To facilitate visual detection, the float was spray-painted fluorescent pink to ensure high visibility at sea. Figure 5.20 shows a photograph of the fabricated carapace tag.

#### 5.4.2 Towed tag

To record the swimming behavior of sea turtles and manipulate their swimming speed, a towed tag was developed as part of a collaborative study led by a co-investigator. The components of this system are described here to provide a complete overview of the field experimental configuration. However, except for a video logger used to confirm sea turtle swimming behavior, the data obtained from this tag were not used for analysis or discussion

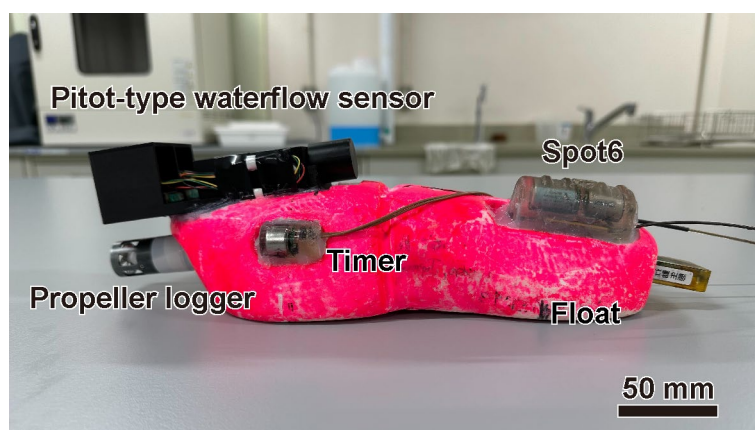


Fig. 5.20 Photograph of the fabricated carapace tag

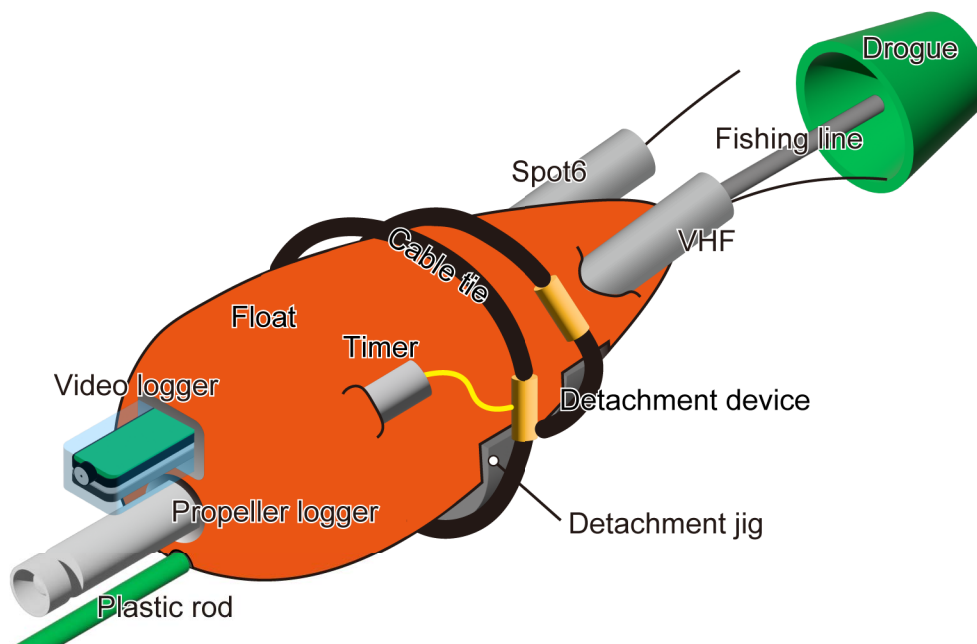


Fig. 5.21 Schematic image of the towed tag.

in this thesis. A schematic of the towed tag is shown in Fig. 5.21. The system consists of a float, a video logger (DVL400M130, Little Leonardo Corporation, Tokyo, Japan), a propeller logger (PD3GT, Little Leonardo Corporation, Tokyo, Japan), a drogue, SPOT-6, VHF and two pairs of release devices. The video logger enables continuous observation of the turtle's swimming behavior, while the drogue increases the hydrodynamic drag acting on the turtle, thereby changing its swimming speed and movement pattern. The drogue was fabricated by modifying a plastic flowerpot. The float was fabricated by mixing glass bubbles with the epoxy resin and hardener, as with the carapace tag.

The towed tag was attached to the turtle using a detachment jig equipped with a plastic rod and cable ties. The float was designed with a recess section to which the detachment jig was mounted. The jig itself was fabricated using a 3D printer (Bambu Lab X1-Carbon, Bambu Lab, Shenzhen, Guangdong, China) and featured a narrow slit. By threading a cable tie along this slit, the float and the rod were securely fixed together. The opposite end of the plastic rod was connected to an pad eye that had been directly bonded to the turtle's carapace with the epoxy adhesive. The float also included another recess section



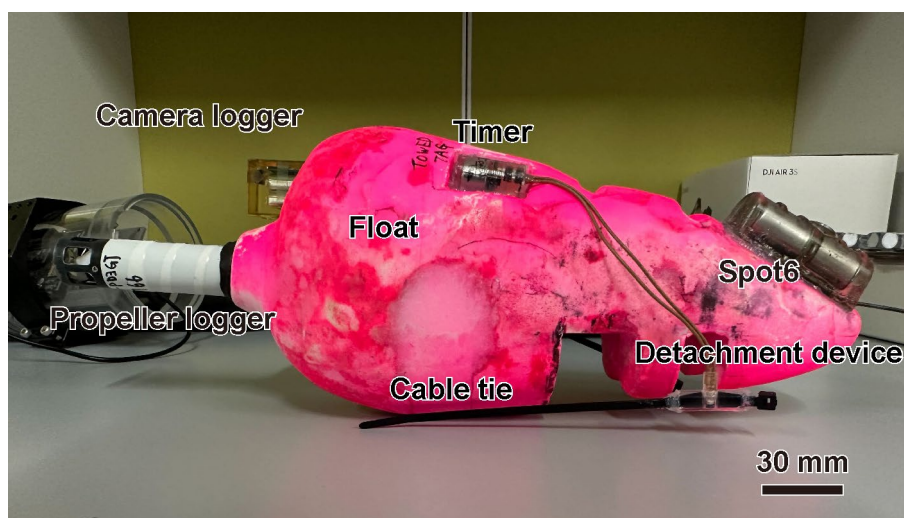


Fig. 5.22 Photograph of the fabricated towed tag

that housed the detachment jig for the drogue. A polyethylene (PE) fishing line was attached to this jig and connected to the drogue. The PE line has low frictional resistance. Therefore, if it becomes entangled with underwater objects, it is designed to break naturally as the turtle struggles, allowing the animal to free itself without external assistance. Separate timers were installed on the detachment devices for the drogue and the plastic rod, allowing independent release at different times. During the experiment, the drogue-side device was activated first to release the drogue. This was followed by the activation of the plastic-rod-side device, which detached the entire towed tag from the turtle. A photograph of the fabricated towed tag is shown in Fig. 5.22. Similar to the carapace tag, the towed tag was spray-painted fluorescent pink to enhance its visibility underwater.

#### 5.4.3 Timeline of the experiment and release of the sea turtle

A photograph of the turtle equipped with the carapace tag is shown in Fig. 5.23. The carapace tag was mounted on the carapace using an alignment procedure to ensure consistent orientation among individuals. First, a straight reference line was written along the longitudinal body axis by connecting the anterior and posterior tips of the carapace. The tag was then placed so that the Pitot-type waterflow sensor's sensing axis was parallel to this reference line, and the alignment was visually confirmed before fixation. To prevent rotation

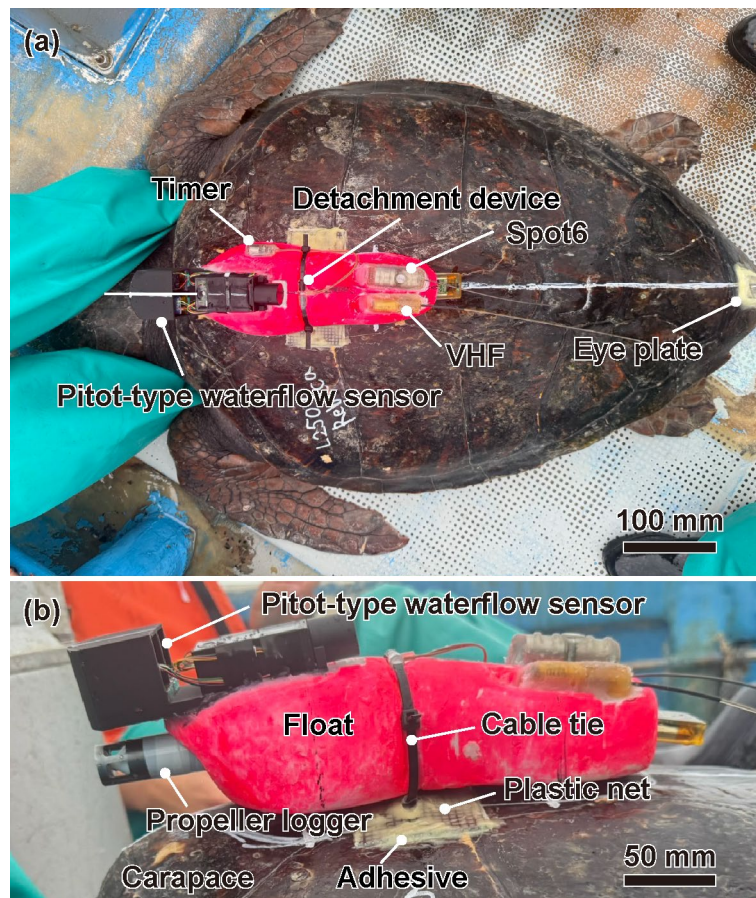


Fig. 5.23 A photograph of the loggerhead turtle equipped with the carapace tag.

or translation during the biologging experiment, a positioning jig was attached to the carapace. The jig was fabricated from wooden rods (chopsticks) and the metal epoxy putty and functioned as a mechanical guide to maintain the sensor orientation during the experiment. The jigs were then fixed to the carapace using epoxy adhesive, providing a more rigid fixation of the carapace tag.

The propeller loggers were scheduled to activate at 04:20:00. These loggers are equipped with a delay function, which allows them to start recording after a preset delay period. By setting the activation time to 16:20:00 on the previous day with a 12-hour delay, the logger could be activated early in the morning. The propeller logger measured waterflow speed (8 Hz), tri-axis acceleration (32 Hz), depth (1 Hz), and water temperature (1 Hz). The Pitot-type waterflow sensor was set to start at 05:14:00. High Time Resolution (HTR) loggers

were used for these devices. Since the HTR loggers do not have a delay function, they were manually activated at the designated time. The HTR logger measured waterflow speed (100 Hz), tri-axis acceleration (100 Hz), tri-axis magnetism (100 Hz), depth (100 Hz), and water temperature (100 Hz).

Sea turtles swim by flapping their flippers, and the flipper-stroke frequencies are on the order of a sub second hertz [95]. Even when non-sinusoidal motion is considered, speed fluctuations induced by flipper motion are expected to occur at frequencies on the order of a few hertz. Therefore, to measure these fluctuations accurately, the sampling rate of the Pitot-type waterflow sensor must be several times higher than the frequency. Based on the dynamic response evaluation presented in Section 3.4, the fabricated sensor exhibited a 10–90% rise time of 3.9 ms. This rise time corresponds to an equivalent temporal resolution on the order of several hundred hertz (approximately 250 Hz). To avoid loss of physically meaningful information while maintaining a sufficient temporal margin relative to both the expected behavioral frequencies and the sensor's response capability, the sampling rate of 100 Hz was adopted in this study. This rate is more than an order of magnitude higher than the characteristic behavioral frequency and therefore allows rapid speed fluctuations to be captured without aliasing. And at the same time, it is well below the sensor's effective response limit, providing a practical balance between temporal resolution, data volume, and power consumption. Sampling rate of 100 Hz also enables flexible post-processing, such as filtering and downsampling.

The timer attached to the drogue of the towed tag was set to activate at 07:45, whereas the timers connected to the plastic rods of the carapace tag and the towed tag were programmed to activate at 08:30. When these timers were connected to the detachment devices, power was supplied, and the devices were configured to trigger 24 hours later. Accordingly, the timers and detachment devices were initiated at 7:45 and 8:30 on the previous day, respectively. To ensure waterproofing, the junctions between the detachment devices and the timers were sealed with epoxy resin. After powering on the timers, each device was attached to the float using the silicone sealant.

Before the biologging measurement, loggers of both tags were activated, and

accelerometer calibration was performed between 5:23 and 5:26. The accelerometer installed in the propeller logger does not directly output acceleration in physical units; instead, it provides integer counts proportional to the applied acceleration. To calibrate this output, a sequence of controlled maneuvers was conducted to apply known gravitational accelerations along each sensor axis. The tag was first gently shaken for 30 s to activate the accelerometer, then placed horizontally at rest for 30 s to record a baseline. It was shaken again for 30 s, positioned with the propeller and Pitot-type sensor facing downward for 30 s, shaken once more for 30 s, and finally placed sideways for another 30 s. This sequence ensured that approximately 1 g of gravitational acceleration was applied successively along the x-, y-, and z-axes. Using these data, the raw integer counts were calibrated against the corresponding gravitational acceleration values, enabling accurate conversion of the propeller logger's accelerometer output into physical acceleration units.

The transportation of the turtle began at 06:00. The turtle was loaded onto a research vessel operated by the Otsuchi Coastal Research Center of the Atmosphere and Ocean Research Institute, the University of Tokyo, and transported to the mouth of the Otsuchi Bay. This location was chosen because numerous set nets are installed within the bay, and releasing the turtle inside the bay could lead to entanglement. To minimize this risk, the release was conducted at the bay mouth, allowing the turtle to swim along a trajectory free from fishing gear.

To prevent sensor damage caused by the turtle's movement, the cable ties and tags were attached only after the vessel reached the release site. The release took place at approximately 06:40. Consequently, the sensor system was expected to record about 65 minutes of swimming with the drogue attached, followed by approximately 45 minutes of swimming without it. Because the timers connected to the detachment devices may exhibit slight deviations, these durations are considered approximate.

When the turtle was released, an underwater drone (V-EVO, Shenzhen QYSEA Tech Co., Ltd., Shenzhen, Guangdong, China) was deployed beside the vessel and positioned in the water to observe the turtle's movement. Using this drone, the turtle's swimming behavior was recorded from multiple angles as it swam away. The drone continuously



Fig. 5.24 Swimming behavior of the loggerhead turtle during the experiment, recorded by the underwater drone.

followed the turtle, capturing approximately 15 minutes of footage until it reached the limit of its cable length and could no longer pursue the animal. A side-view photograph of the swimming turtle, captured by the underwater drone, is shown in Fig. 5.24.

#### 5.4.4 Recovery of the sensor system

After the turtle was released, the research team remained onshore for a short period before resuming operations. At 08:30, when the two tags were expected to detach, the research vessel was redeployed to begin the recovery process. The approximate locations of the tags were first estimated using the Argos satellite system, and the vessel then navigated toward the identified area. Subsequently, a goniometer and a VHF antenna were used to locate the tags more precisely. These two instruments provided information on the approximate distance and direction of the tags relative to the vessel.

However, both instruments were susceptible to errors caused by radio wave reflections from surrounding terrain and fluctuations of the ocean surface. Therefore, the search was carried out cautiously by comparing the readings from both devices while gradually approaching the estimated location. Once the signals indicated proximity to the



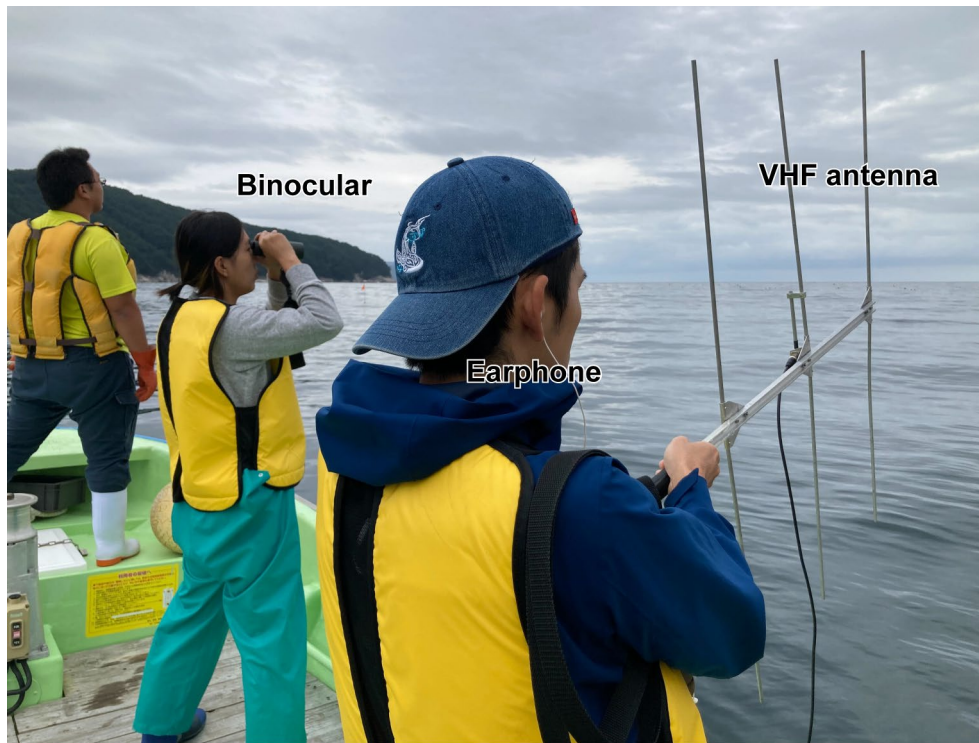


Fig. 5.25 Photograph of tag recovery operation.

tags, visual observations were conducted using binoculars. A photograph showing the tag recovery operation is presented in Fig. 5.25.

The carapace tag was successfully recovered at 09:40 on August 7 at a position of 39°21'29" N, 141°58'51" E, confirming that the turtle had moved after release. However, the recovery of the towed tag was challenging. It was eventually retrieved at 09:55 on August 9 at a position of 39°23'58.9" N, 141°57'17.0" E. This issue occurred because the detachment device connected to the plastic rod failed to activate. As a result, the towed tag remained attached to the turtle and was continuously dragged throughout its swimming. The tag was eventually recovered when the turtle was directly captured from the vessel.

## 5.5 Results of the biologging experiment

### 5.5.1 Outputs of the various sensors

After the tag was recovered from the sea turtle, the sensor system, propeller logger, and other devices were rinsed with fresh water to remove residual salt. Subsequently, the SD card was removed from the HTR logger, and the recorded data were extracted using dedicated software, which generated CSV files containing the logged sensor data.

The data recorded by the HTR logger during the experiment are shown in Fig. 5.26. The logger simultaneously recorded outputs from multiple sensors, including the Pitot-type waterflow sensor, acceleration sensor, gyroscope, geomagnetic sensor, and water pressure–temperature sensor. The CSV files contained timestamped raw data from all sensors integrated into the HTR logger. Each row corresponded to a single sampling point at a rate of 100 Hz, while the header line defined the signal channels (e.g., “BlockIndex,” “Date\_Time,” “SampleIndex,” and individual sensor outputs). The measurement start time was obtained from the timestamp embedded in the first data block, and a continuous time index was generated based on the known sampling rate (100 Hz). This time axis enabled synchronization of all sensor channels.

For the Pitot-type waterflow sensor, which consisted of two units (Pitot<sub>det</sub> and Pitot<sub>com</sub>), baseline correction was applied to eliminate offset drift before calculating differential signals. A one-minute time window (08:40–08:41 a.m.), corresponding to the period when the tag had detached and was floating near the sea surface, was selected, and the mean output during this interval was defined as the zero reference. The raw bit values were then baseline-corrected by subtracting this mean and subsequently converted into voltages using Eq. (2.90). Finally, to suppress high-frequency noise caused by vibration or vortex shedding, a fourth-order Butterworth low-pass filter with a 5 Hz cutoff frequency was applied to both Pitot<sub>det</sub> and Pitot<sub>com</sub> signals.

The pressure–temperature sensor (MS5803) measured absolute pressure values. These were converted into gauge pressure by subtracting the mean atmospheric pressure measured during the air-exposed period (5:50–6:00 a.m.). The hydrostatic depth was then

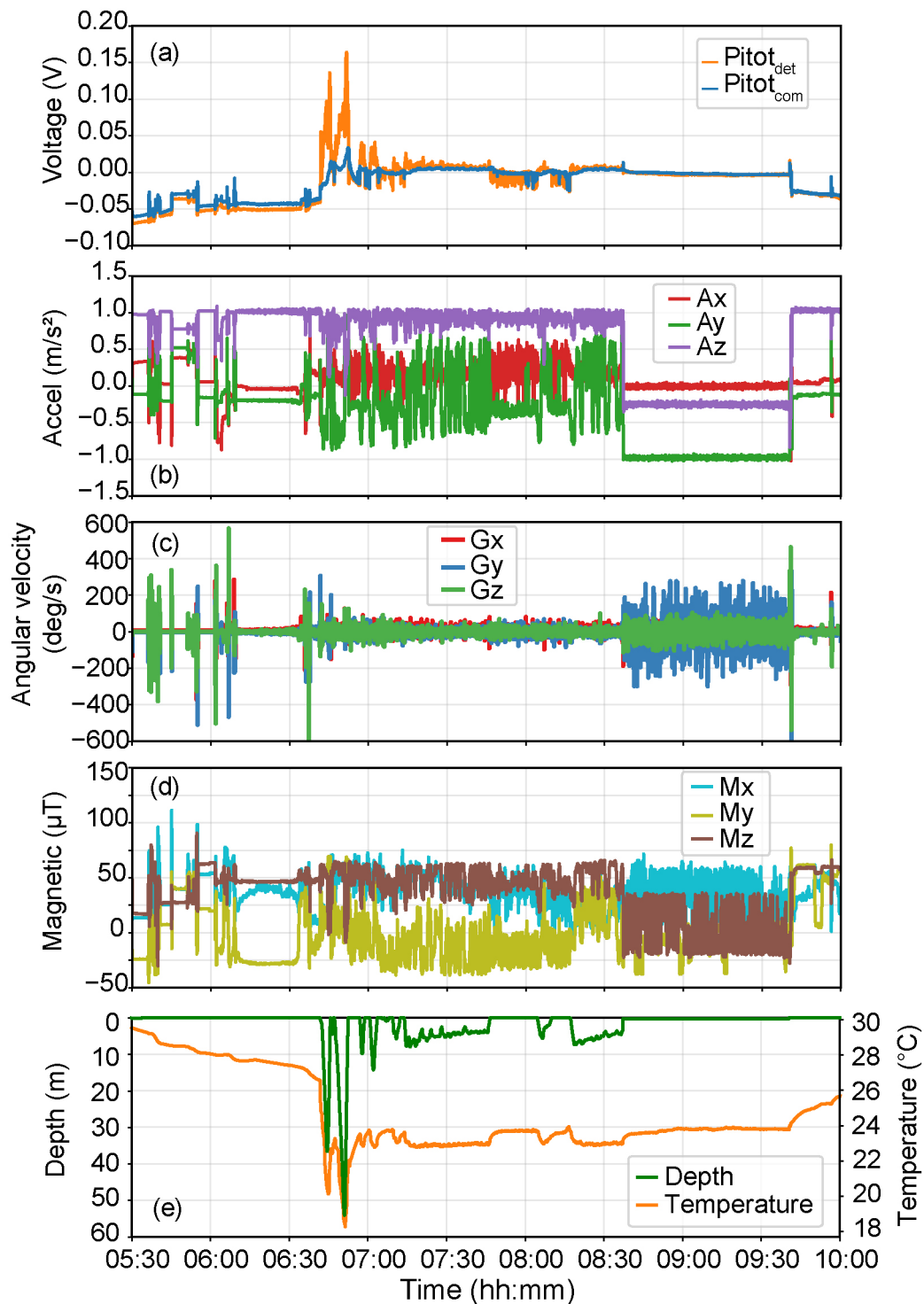


Fig. 5.26 Outputs from various sensors during the experiment: (a) Pitot-type waterflow sensor, (b) acceleration sensor, (c) angular velocity sensor, (d) geomagnetic sensor, and (e) depth sensor.



calculated using

$$Depth = \frac{P_{\text{gauge}}}{\rho g}, \quad (5.6)$$

where  $\rho = 1000 \text{ kg/m}^3$  and  $g = 9.8 \text{ m/s}^2$ . Each tri-axial component of the acceleration, gyroscope, and magnetic field data was plotted separately ( $A_x, A_y, A_z; G_x, G_y, G_z; M_x, M_y, M_z$ ). To enhance readability while preserving essential signal characteristics, the data were downsampled by averaging every 2 s. Finally, all channels were plotted together in a stacked configuration: (a)  $P_{\text{det}}$  and  $P_{\text{com}}$  voltages, (b) accelerations, (c) angular velocities, (d) magnetic fields, and (e) depth and temperature.

When examining the outputs of each sensor recorded by the HTR logger, a distinct change was observed around 6:45, corresponding to the moment when the sea turtle was released. At this time, the signals from the Pitot-type waterflow sensor, water temperature sensor, and pressure sensor exhibited large fluctuations, reflecting the start of active swimming. Around 8:40, the acceleration values became nearly constant, while the angular velocity and geomagnetic signals began to fluctuate strongly, and the measured depth approached zero. Once the tag is expected to surface, it would likely float with the SPOT-6 and other transmitters oriented upward. In this state, the acceleration data should stabilize, with the Y-axis expected to indicate approximately  $-1 g$ , reflecting the tag's static posture on the water surface. Meanwhile, because the tag would be gently oscillating with the surface waves, the angular velocity would be expected to fluctuate significantly. The sensor outputs observed after approximately 8:40 are consistent with these anticipated behaviors, suggesting that the tag likely surfaced and floated stably on the sea surface. This timing corresponds closely to the preset detachment time of 8:30, suggesting that the tag was successfully released from the turtle as scheduled. These results indicate that the sensor system successfully captured the characteristic signal variations associated with both the turtle's swimming behavior and the autonomous detachment of the tag.

The raw data obtained from the propeller logger were processed to derive the propeller rotation number per second, acceleration, water temperature, and depth, as summarized in Fig. 5.27. Each sensor module of the PD3GT logger outputs an independent

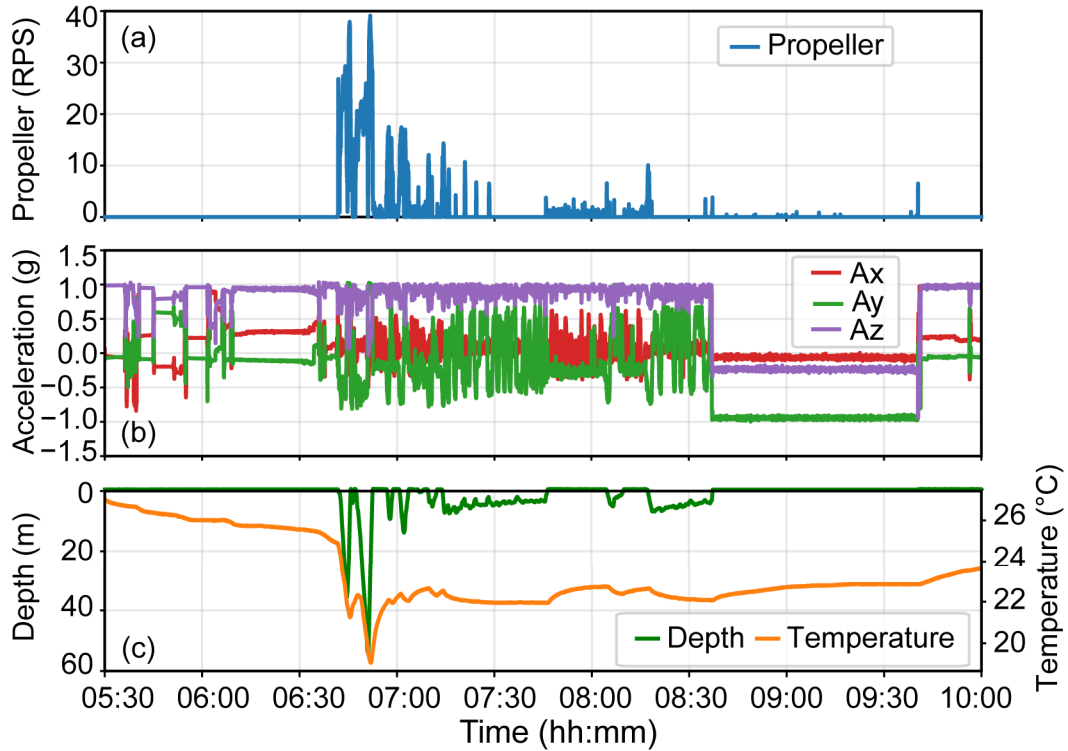


Fig. 5.27 Outputs from various sensors during the experiment: (a) Propeller-type waterflow sensor, (b) acceleration sensor, and (c) depth-temperature sensor.

time series in CSV format, including metadata that specify the recording start time and sampling interval. These metadata were first parsed to reconstruct the absolute timestamps of each data series, allowing all channels to be synchronized to a common time axis.

The propeller channel records counts corresponding to 1/8-s intervals (8 Hz sampling). To obtain the propeller's rotational number per second, the number of rotations over eight consecutive samples (corresponding to a 1-s window) was summed and converted to the equivalent rotation rate per second:

$$f_{\text{prop}}(t) = \sum_{i=-3}^4 C(t + i\Delta t), \quad (5.7)$$

Where  $C(t)$  denotes the raw propeller count at time  $t$ .

The three-axis accelerometer data were recorded as raw integer counts and subsequently converted to physical acceleration in units of  $g$  using the calibration

coefficients experimentally obtained from the pre-deployment calibration procedure described earlier. During this calibration, each sensor axis was sequentially oriented to experience approximately 1 g of gravitational acceleration, allowing the relationship between the raw output counts and true acceleration to be determined through linear regression. The resulting calibration coefficients for each axis were as follows:

$$a_x = -0.0204(x - 2013.8), \quad (5.8)$$

$$a_y = -0.0212(y - 2032.4), \quad (5.9)$$

$$a_z = -0.0214(z - 2052.4), \quad (5.10)$$

and the values were normalized by the gravitational constant  $g_0 = 9.80665 \text{ m/s}^2$ . These coefficients, derived from the calibration experiment, were then applied to convert the logger's accelerometer outputs into physical acceleration units. The resulting acceleration data were resampled to 1-s intervals and averaged to suppress high-frequency noise.

The values recorded by the propeller logger also began to fluctuate around 6:45, corresponding to the release of the sea turtle, and stabilized around 8:40, when the tag was detached. These results indicate that the propeller logger successfully captured the characteristic signal variations associated with both the initiation of the turtle's swimming activity and the detachment of the tag, consistent with the data obtained from the Pitot-type sensor system.

### 5.5.2 Preprocessing of Sensor Data

The waterflow speed was calculated from the outputs of the two Pitot-type sensors (Pitot<sub>det</sub> and Pitot<sub>com</sub>). A summary of the signal-processing steps applied to these outputs is shown in Fig. 5.28. Panel (a) presents the raw voltages of Pitot<sub>det</sub> and Pitot<sub>com</sub>, obtained by converting the 15-bit digital output of each channel into voltage using Eq. (2.90). In panel (b), the differential voltage between Pitot<sub>det</sub> and Pitot<sub>com</sub> is computed to isolate the dynamic-pressure component associated with waterflow. This uncorrected differential signal,

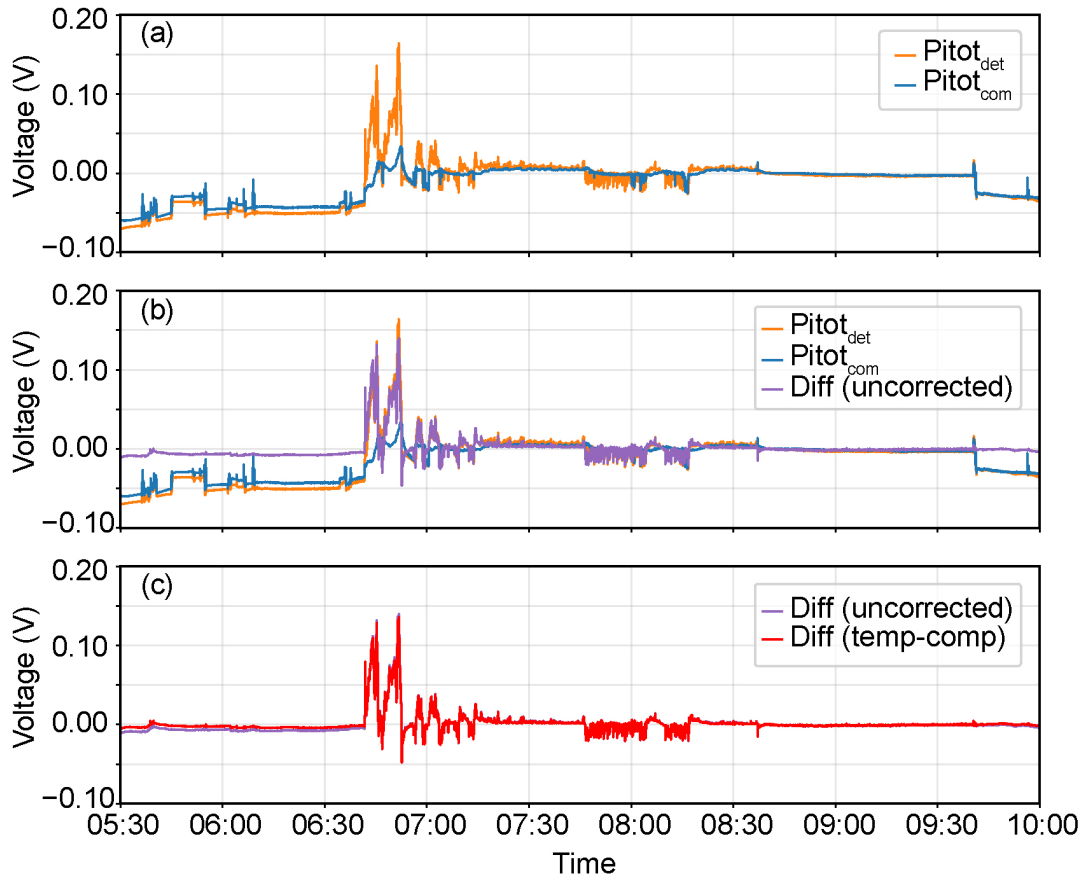


Fig. 5.28 Outputs of the Pitot-type waterflow sensor during the biologging experiment: (a) uncorrected data, (b) differential signal between the two Pitot sensors, and (c) temperature-compensated data.

$$\Delta V_{\text{uncorr}} = V_{\text{det}} - V_{\text{com}} \quad (5.11)$$

still contain temperature-dependent drift that was not completely eliminated by taking the difference between the two sensor outputs. Panel (c) shows the temperature-compensated differential voltage. The internal temperature sensor was used to estimate the temperature deviation  $\Delta T$  from a baseline period when the tags were detached. The thermal correction was performed according to the experimentally determined slope  $A_{\text{slope}}$ :

$$\Delta V_{\text{temp-comp}} = \Delta V_{\text{uncorr}} - (A_{\text{slope}} \times \Delta T) \quad (5.12)$$

where  $A_{\text{slope}} = -9.37 \text{ bit} / ^\circ\text{C}$  from the temperature calibration experiment. This compensation removed gradual drifts due to temperature changes. After obtaining the differential output

between the two sensors and applying temperature compensation, it was still necessary to correct for the influence of hydrostatic pressure. Although the sensor's differential configuration inherently reduces the effect of ambient pressure, in practice, residual dependence on hydrostatic pressure remains due to factors such as the slight compressibility of the internal silicone oil and mechanical deformation of the sensor housing. According to the theoretical model on Eq. (2.55), the influence of hydrostatic pressure  $P$  on the sensor output is expected to exhibit a linear relationship of the form

$$\Delta P = a P \quad (5.13)$$

where  $a$  is a proportionality coefficient representing pressure sensitivity. Because the correction coefficient for hydrostatic pressure was not determined experimentally beforehand, it was derived from the sensor data obtained during the field experiment.

We first estimate the turtle's body attitude; specifically, the pitch angle is derived from the tri-axial accelerometer signals [54], [116]. The accelerations derived from the propeller logger, calculated using Eqs. (5.6)–(5.8), correspond to the following motion components: the  $x$ -axis represents lateral sway, the  $y$ -axis corresponds to the longitudinal surge, and the  $z$ -axis represents vertical heave. Therefore, the pitch angle can be estimated from the surge component, which reflects the forward–backward motion of the turtle relative to gravity. Given the gravitational constant  $g = 9.80665 \text{ m/s}^2$ , the instantaneous body pitch angle  $\phi(t)$  is obtained from the specific force along the surge axis as

$$\phi(t) = \arcsin\left(\frac{g_0}{a_{\text{surge}}(t)}\right) [\text{rad}], \quad (5.14)$$

And expressed in degrees for visualization. For numerical stability, the argument of the  $\arcsin(\cdot)$  function is clipped to the range  $[-1, 1]$ . Although this method inherently includes a small amount of dynamic acceleration due to flipper strokes and body motion, it provides a reasonable approximation of the turtle's body inclination during swimming. The resulting pitch angle calculated from the accelerometer data of the propeller logger is shown in Fig. 5.29.

Inspection of these outputs revealed two distinct upward movements: 06:44:30–06:45:30 and 06:51:00–06:52:15. These ascending phases were also captured by the

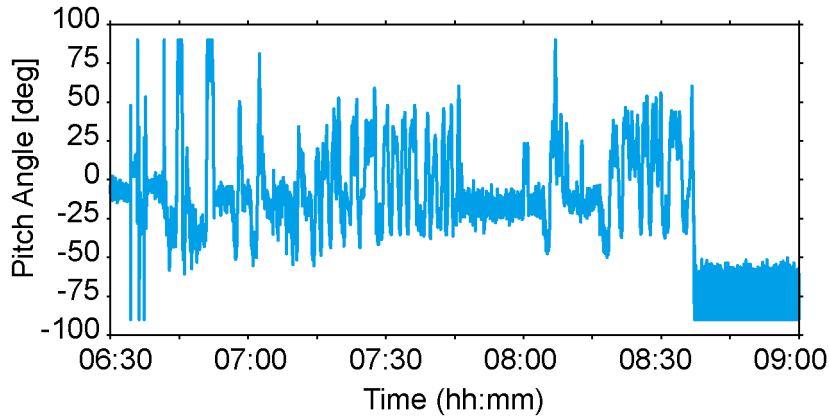


Fig. 5.29 Estimated pitch angle of the turtle during the experiment.

underwater drone, and the video agreed well with the pitch estimated from the accelerometer. To quantify hydrostatic effect, a dedicated correction procedure was implemented using the period when the turtle ascended vertically (06:51:30–06:52:15), during which both the Pitot-based speed and the rate of depth change could be compared directly. When the turtle swims nearly vertically and the surrounding current is sufficiently small, the variation in depth can be regarded as a direct measure of the turtle's true relative waterflow speed. In such conditions, the depth-derived speed  $v_{\text{depth}}(t)$  represents the true flow speed  $v_{\text{true}}(t)$ , providing a reliable reference for evaluating the Pitot-based measurements. Before applying the correction, the output of the Pitot-type differential pressure sensor can be expressed as

$$P_{\text{pitot}}(t) = aP + Kv_{\text{true}}^2 = Kv_{\text{pitot}}^2 \quad (5.15)$$

where  $a$  is a proportionality coefficient that describes the residual sensitivity of the differential pressure output to the ambient hydrostatic pressure  $P$  and  $K = 676.5 \text{ Pa}/(\text{m/s})^2$  is the calibration constant derived from the waterflow calibration experiment. During the vertical swimming period, the true flow velocity can be approximated by the rate of change in depth, i.e.,

$$v_{\text{true}}(t) \approx v_{\text{depth}}(t). \quad (5.16)$$

Substituting this relation into Eq. (5.15) yields

$$P_{\text{pitot}}(t) = aP + Kv_{\text{depth}}^2(t). \quad (5.17)$$

Therefore, by comparing the Pitot-derived pressure  $P_{\text{pitot}}(t)$  with the pressure corresponding to the depth-derived speed  $P_{\text{pitot}}(t) = Kv_{\text{depth}}^2(t)$ , the residual component  $aP$  can be isolated. Taking their difference gives

$$\Delta P(t) = P_{\text{pitot}}(t) - P_{\text{depth}}(t) = aP, \quad (5.18)$$

which allows the coefficient  $a$  to be estimated empirically from the slope of the relationship between  $\Delta P$  and  $P$  (or equivalently, between  $\Delta P$  and depth). This procedure thus provides a physically consistent method for quantifying and compensating for the hydrostatic pressure dependence on the Pitot-type waterflow sensor output.

The raw 100 Hz data were processed to obtain the depth-derived vertical speed  $v_{\text{depth}}(t)$  by computing the local slope of the depth signal within a 1 s centered window. This was achieved using a locally weighted linear regression expressed as

$$v_{\text{depth}}(t) = -\frac{d}{dt}\text{Depth}(t) \quad (5.19)$$

where the negative sign indicates upward motion [51]. The Pitot-estimated speed  $v_{\text{pitot}}(t)$  was then compared with this depth-derived value to evaluate their correspondence during ascent.

To quantify the effect of hydrostatic pressure on the Pitot sensor output, a comparison was made between the speed derived from the Pitot sensor (after applying temperature compensation only) and the speed calculated from the depth sensor during a period of vertical ascent. The results are shown in Fig. 5.30. As the turtle ascended vertically, the difference between the two speeds gradually decreased, indicating that the Pitot-derived signal was influenced by the hydrostatic pressure acting on the sensor.

Both the Pitot-derived and depth-derived speeds were subsequently converted into equivalent dynamic pressures using the calibration coefficient  $K = 676.5 \text{ Pa}/(\text{m/s})^2$ . The differential pressure  $\Delta P$  between the Pitot-derived and depth-derived estimates was calculated for the period of vertical ascent (06:51:30–06:52:15) via Eq. (5.19) and its dependence on depth  $h$  was examined (Fig. 5.31). Fitting a line constrained through the origin yielded

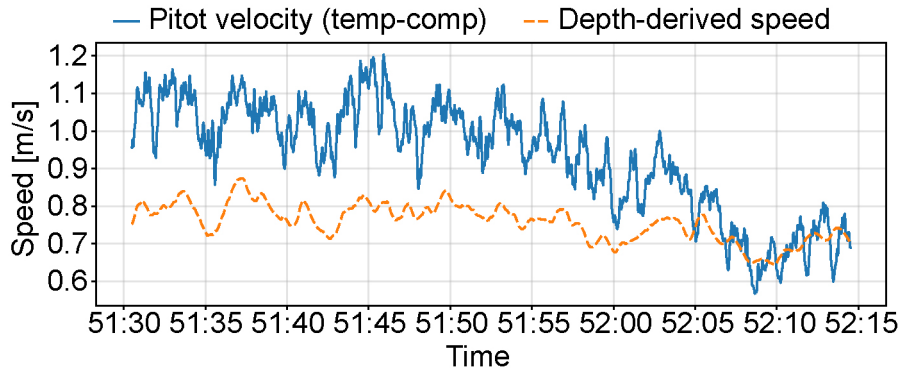


Fig. 5.30 Comparison between the flow velocity obtained from the temperature-compensated Pitot-type waterflow sensor and that derived from depth.

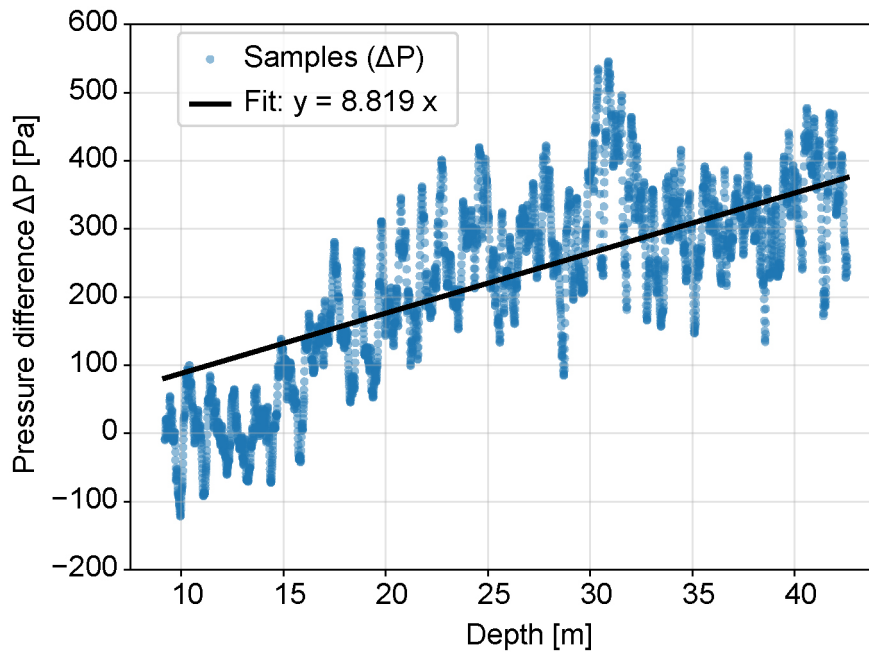


Fig. 5.31 Relationship between the differential pressure calculated from the outputs of the Pitot-type waterflow sensor and the pressure sensor, and depth.

$$\Delta P \approx a_h h, \quad a_h = 8.819 \text{ Pa/m}, \quad (5.20)$$

which indicates that the residual bias grows linearly with depth. Because the hydrostatic pressure  $P$  is  $P = \rho gh$ , this result means  $\Delta P = aP = a\rho gh$ . Therefore, the dimensionless pressure sensitivity coefficient  $a$  is given by



$$a = \frac{a_h}{\rho g} = \frac{8.819 \text{ Pa/m}}{(1000 \text{ kg/m}^3)(9.8 \text{ m/s}^2)} \approx 9.00 \times 10^{-4}. \quad (5.21)$$

In subsequent processing, the depth-based coefficient  $a_h$  was used as the correction factor to remove the depth-related (hydrostatic) bias from the Pitot-type waterflow sensor output.

After determining the coefficient  $a_h = 8.819 \text{ Pa/m}$ , this value was used for the signal-processing to correct the Pitot-type sensor outputs for residual hydrostatic pressure effects. The pressure-dependent bias component was then estimated as  $a_h h(t)$ , corresponding to the hydrostatic influence identified during the vertical-swimming calibration. This component was subtracted from the temperature-compensated differential signal to obtain the corrected differential voltage  $\Delta V_{\text{water-comp}}(t)$ , expressed as

$$\Delta V_{\text{water-comp}}(t) = \Delta V_{\text{temp-comp}}(t) - a_h h(t) \quad (5.22)$$

where  $\Delta V_{\text{temp-comp}}(t)$  represents the differential voltage after temperature compensation. This correction effectively reduces the depth-dependent offset caused by hydrostatic compression. The sensor outputs after hydrostatic-pressure-compensation are shown in Fig. 5.32 (a).

After applying the hydrostatic-pressure correction, intermittent noise remained in certain segments of the data, most notably around 08:00. Inspection of the corresponding depth records and video footage revealed that these fluctuations occurred when the sensor intermittently emerged from the water surface. The noise was therefore attributed to partial exposure of the Pitot type waterflow sensor, causing unstable differential pressure as the sensor alternated between air and water.

To further suppress these noises, a masking process was applied to exclude data recorded near the water surface. Specifically, data obtained at depths shallower than 0.1 m were excluded by assigning a zero value to the corrected differential signal:

$$\Delta V_{\text{masked}}(t) = \begin{cases} \Delta V_{\text{water-comp}}(t), & \text{if } h(t) > 0.1\text{m}, \\ 0, & \text{otherwise.} \end{cases} \quad (5.23)$$

This masking ensured that only data collected under stable submersion conditions were retained for subsequent analysis. Figure 5.32 (b) shows masked sensor data. After applying the masking procedure, the intermittent noise was effectively removed, particularly around 08:00, where fluctuations had previously appeared due to the sensor's intermittent exposure

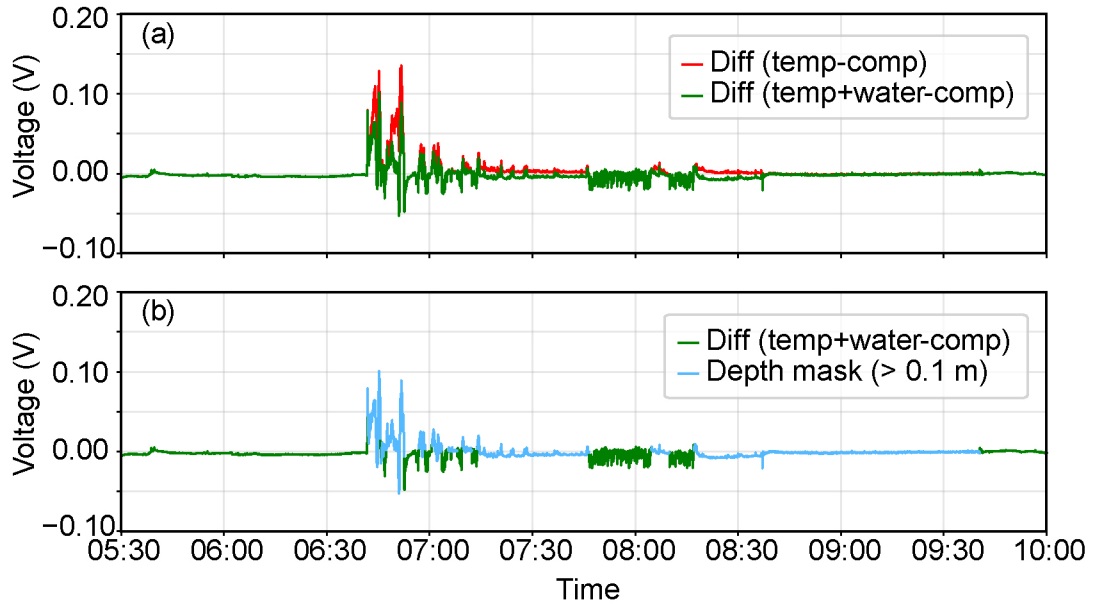


Fig. 5.32 Outputs of the Pitot-type waterflow sensor during the biologging experiment after temperature compensation: (a) hydrostatic-pressure-compensated data and (b) signal after masking process.

to air.

### 5.5.3 Calculation of the waterflow speed

After applying the depth-based masking, the differential pressure signal from the Pitot-type waterflow sensor was converted to waterflow speed using the following relationship:

$$v_{\text{Pitot}}(t) = \sqrt{3.3 \times \frac{1}{127.1} \max(V(t), 0)}. \quad (5.24)$$

This equation was established from calibration experiments conducted in the water tunnel. In parallel, the propeller logger data were converted to waterflow speed using liner relationship

$$v_{\text{Prop}}(t) = k f_{\text{Prop}}(t) \quad (5.25)$$

where  $f_{\text{Prop}}(t)$  is the propeller rotation number per second and  $k = 0.0205$  is the calibration coefficient determined experimentally using a fishing-rod-based towing calibration setup. A

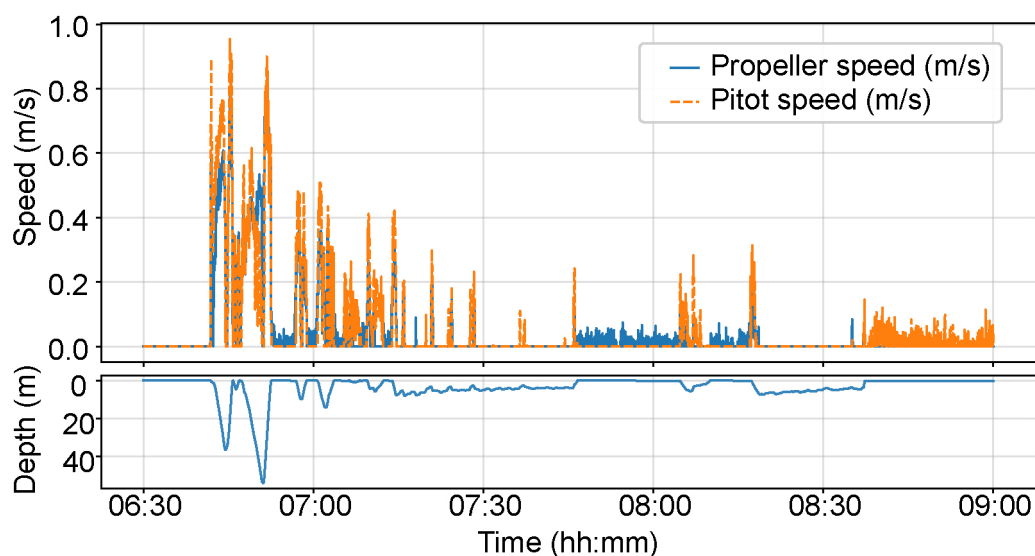


Fig. 5.33 Calculated speed from the propeller and the Pitot-type waterflow sensor.

comparison of the flow speeds estimated by the Pitot-type sensor and by the propeller logger is presented in Fig. 5.33.

The outputs of the Pitot-type sensor and the propeller logger were generally consistent, and both sensor systems exhibited similar responses during periods when the turtle was swimming while changing its depth. Figure 5.34 shows the waterflow speed derived from the Pitot-type sensor and the propeller logger during several of the initial dives. The two sensors exhibited nearly identical outputs, indicating that the Pitot-type waterflow sensor accurately captured the turtle's relative waterflow speed. Notably, in certain periods such as those after 07:07 and 07:11, the Pitot-type sensor still recorded speeds of approximately 0.2 m/s, whereas the propeller logger showed no output. This discrepancy arises because the propeller becomes unresponsive at low speeds (below approximately 0.2 m/s), a range known as the stall speed at which the propeller ceases to rotate. Figure 5.35 shows sequential images captured by the towed tag around 7:10:45, showing the turtle's behavior at one-second intervals. As the images clearly confirm active swimming during this period, the results demonstrate that the proposed Pitot-type waterflow sensor successfully measured low-speed ranges that were difficult to detect using conventional propeller logger.

In addition, the underwater drone footage revealed two distinct types of swimming

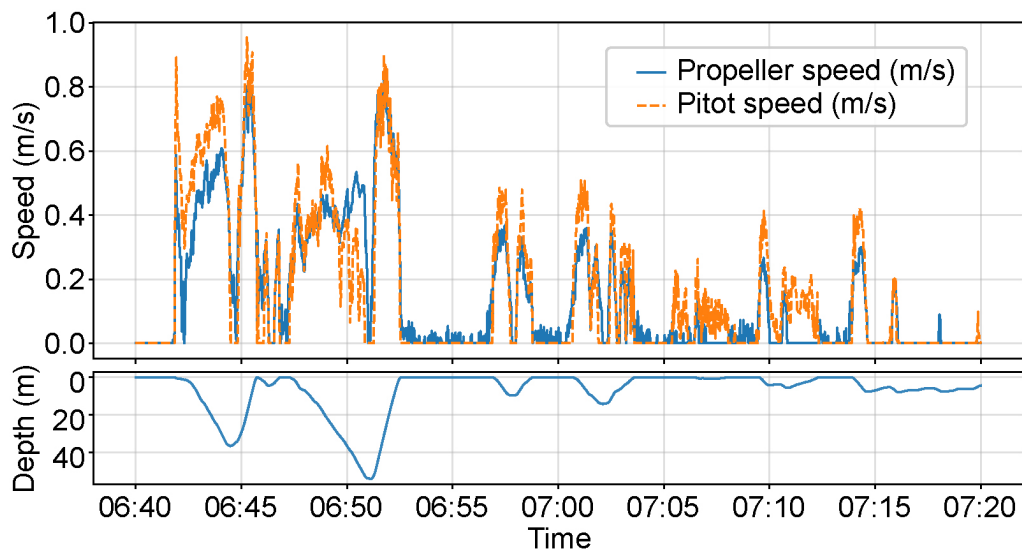


Fig. 5.34 Calculated speed from the propeller and the Pitot-type waterflow sensor during a diving event.

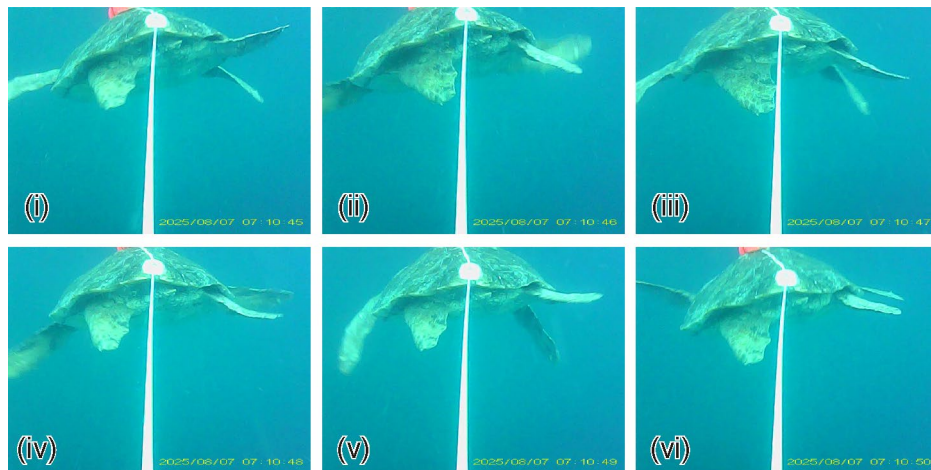


Fig. 5.35 One-second interval images recorded by the towed tag between 7:45:00 and 7:45:05, showing the turtle's active swimming behavior.

behavior. One was gliding, in which the turtle moved forward without flapping its flippers, and the other was flapping, characterized by active flipper strokes. These two modes of locomotion were clearly distinguishable in the recorded video sequences. Figure 5.36 shows a sequence of images illustrating the turtle's swimming behavior during a gliding event. The images were extracted from underwater drone footage recorded between 06:49:30 and 06:49:36 at 0.5 s intervals. As seen in the photographs, the turtle advanced forward without

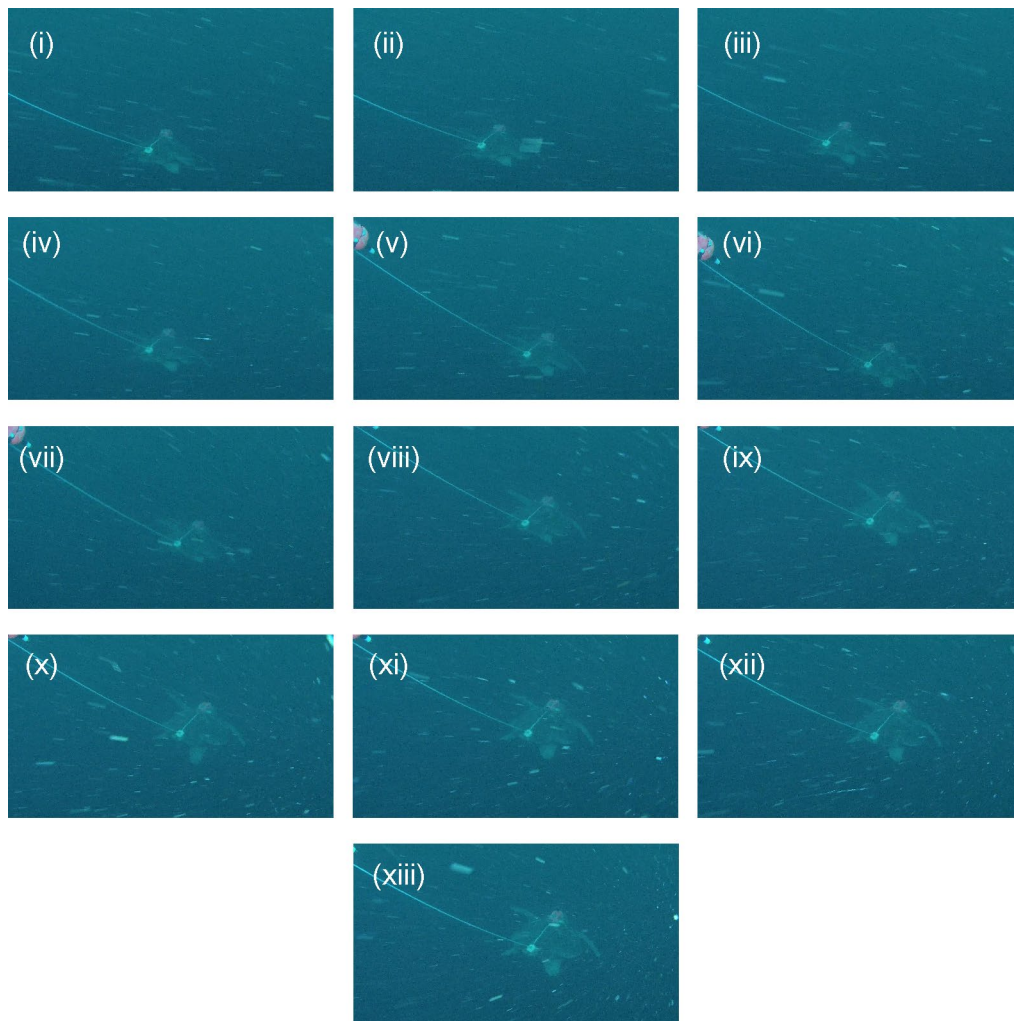


Fig. 5.36 Sequential images of the turtle during a gliding event. Frames were extracted from underwater-drone footage recorded between 06:49:30 and 06:49:36 at 0.5-s intervals, showing the turtle moving forward without flapping its flippers.

flapping its flippers, confirming a gliding mode of locomotion. Figure 5.37 presents the turtle's swimming behavior during a flapping event accompanied by vertical motion. The images were extracted from underwater drone footage recorded between 06:52:08 and 06:52:14, at 0.5 s intervals. In this sequence, the turtle's flippers were actively moving, indicating a flapping-type swimming motion.

Figure 5.38 shows the outputs of the Pitot-type waterflow sensor, the propeller logger, and the z-axis acceleration of the HTR logger's built-in accelerometer during two 6-

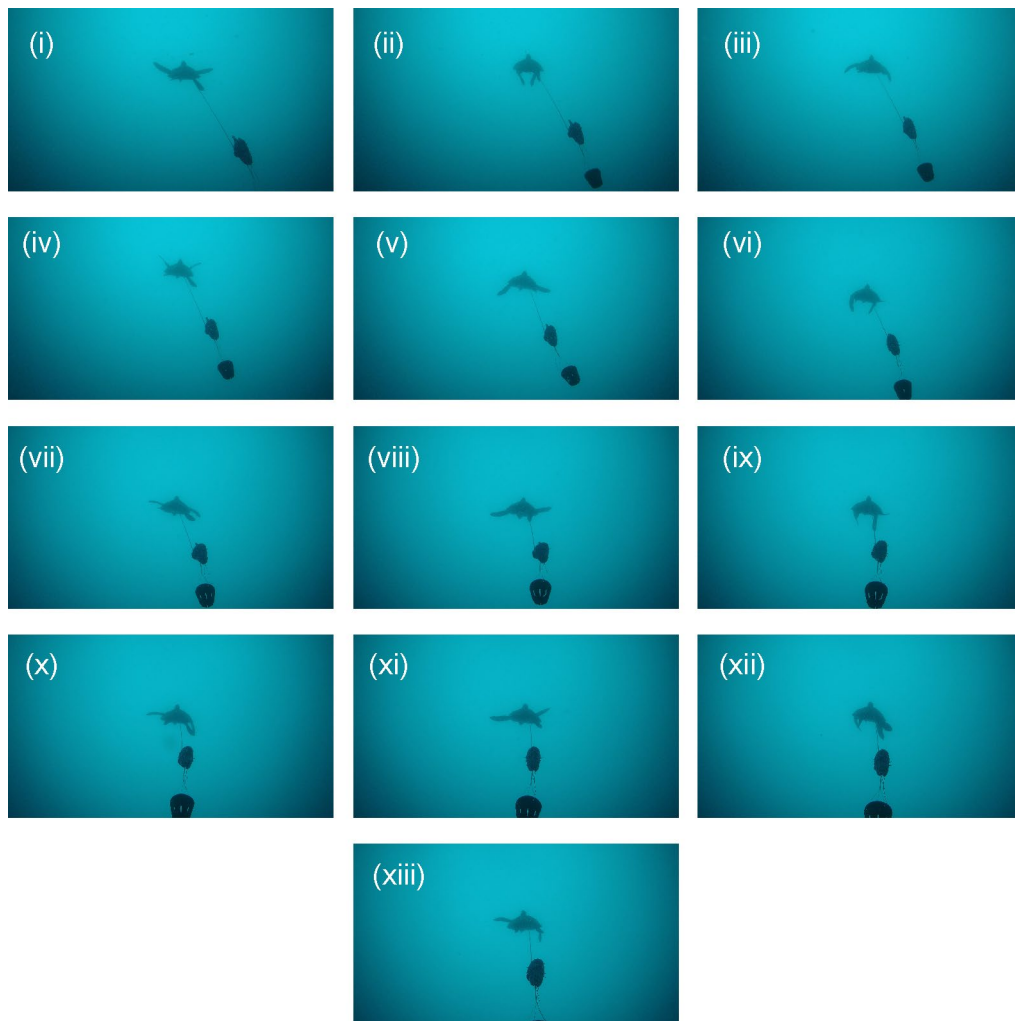


Fig. 5.37 Sequential images of the turtle during a flapping event. Frames were taken from underwater-drone footage recorded between 06:52:08 and 06:52:14 at 0.5-s intervals, showing active flipper motion associated with vertical swimming.

s intervals corresponding to gliding and flapping behaviors. Panel (a) represents the gliding period, and panel (b) corresponds to the flapping period. During gliding, both the Pitot-type sensor and the propeller logger exhibited nearly constant outputs, indicating steady forward motion without significant speed fluctuations. In contrast, during flapping, the propeller logger maintained a relatively stable output, whereas the Pitot-type sensor displayed small oscillations synchronized with the flipper strokes captured in the drone footage.

The acceleration data shown in the graph were high-pass filtered at 0.3 Hz to



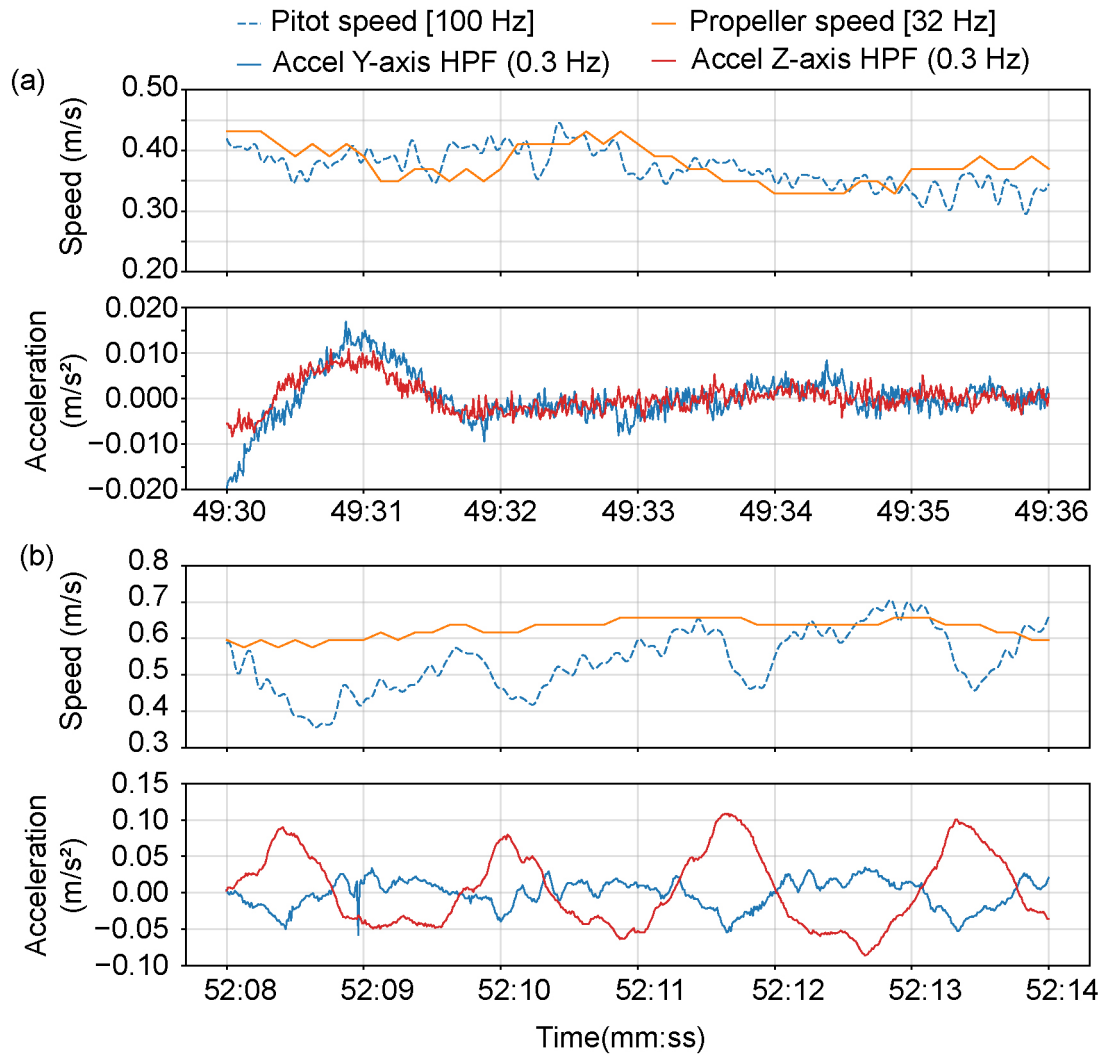


Fig. 5.38 Comparison of sensor outputs during gliding and flapping.  
:(a) Gliding period (06:49:30–06:49:36). (b) Flapping period (06:52:08–06:52:14).

remove static components such as gravity and low-frequency drift. The surge (y-axis) component represents the forward acceleration along the turtle's swimming direction, whereas the heave (z-axis) component corresponds to the vertical acceleration. Accordingly, the surge axis indicates forward acceleration and deceleration, while the heave axis reflects vertical oscillations induced by flipper strokes, providing a quantitative measure of flapping motion. During the gliding period, when no flipper strokes were performed, the acceleration remained nearly constant. In contrast, during the flapping period, both the surge (y-axis) and

heave (z-axis) accelerations exhibited periodic variations. The heave acceleration displayed a waveform resembling a sine wave, with each positive peak corresponding to the downward stroke of the flippers. The surge acceleration, representing forward acceleration and deceleration, reflected the turtle's propulsion dynamics, and its fluctuations closely matched the fine-scale variations detected by the Pitot-type waterflow sensor. These observations indicate that the speed fluctuations captured by the Pitot-type sensor correspond to the cyclic increases and decreases in swimming speed associated with flipper strokes. Specifically, the turtle's forward speed decreased during the upstroke and increased during the downstroke. This sequence of motion was successfully detected by the proposed sensor system, and the observed patterns are consistent with the swimming kinematics reported in previous studies [85].

The propeller logger contains a rotating mechanical element whose motion is influenced by inertia. Because the waterflow speed is derived from the propeller's rotation number per second, the estimated speed represents a temporally averaged response that inherently includes a delay associated with the rotational period and mechanical inertia. In contrast, the Pitot-type waterflow sensor has no moving parts and employs a highly responsive pressure sensor element. This configuration enables the instantaneous computation of waterflow speed from the differential pressure at each sampling moment, without mechanical lag or averaging effects. Consequently, the proposed sensor provides superior temporal responsiveness and higher time resolution than the propeller logger.

Given that the flipper-beat frequency of sea turtles is typically on the order of a few hertz, the propeller logger struggles to accurately capture such rapid velocity fluctuations. The inertia of the rotating element and the averaging process used to convert rotation number into flow speed act as a low-pass filter, attenuating high-frequency components in the measured signal. In contrast, the Pitot-type waterflow sensor directly measures instantaneous differential pressure, enabling a much faster dynamic response. Therefore, the proposed sensor can detect the several-hertz variations in swimming speed associated with flipper strokes. Such rapid fluctuations are difficult to capture with the propeller logger due to its limited temporal response. These results confirm that the Pitot-type sensor successfully



captured the short-term speed fluctuations linked to flipper strokes, which were undetectable with the slower response of the propeller logger.

#### 5.5.4 Results from the other three biologging trials

In addition to L2509, biologging experiments were conducted using three other loggerhead turtles designated as L2536, L2545, and L2556. All experiments followed the same ‘tag-and-release’ program as those used for L2509. Specifically, loggerhead turtles incidentally captured in set nets along the Sanriku coast were provided to the researchers by fishermen, instrumented, and released. Table 5.5 summarizes the basic characteristics of all sea turtles used for biologging experiments. The sexes were not determined. Including L2509, the mean $\pm$ s.d. body mass of the turtles was 103.6 $\pm$ 43.4 kg (59.2–143.6 kg). The capture and experimental procedures were generally identical for all individuals. The experiments for L2536, L2545, and L2556 were conducted on 9 September 2025, 16 September 2025, and 19 September 2025. For L2536 and L2545, both the carapace tag and the towed tag were attached to turtles. For L2556, measurements were conducted using the carapace tag only. For L2536, L2545, and L2556, measurements were conducted for approximately 3 h. For L2536 and L2545, the experiments were configured so that the drogue was released about 1.5 h after the turtle's release.

Between the measurement of L2509 and L2536, the carapace tag including the Pitot-type waterflow sensor and the propeller logger used for L2509 was lost during a biologging experiment. Therefore, the Pitot-type waterflow sensor system and the propeller logger used

Table 5.5 Basic characteristics of the loggerhead turtle used in all biologging experiments.

| Turtle | Sex | Body mass (BM) | carapace length (SCL) | Girth    | Date of capture | Date of experiment |
|--------|-----|----------------|-----------------------|----------|-----------------|--------------------|
| L2509  | -   | 59.2 kg        | 77.6 cm               | 137.6 cm | 11/07/2025      | 07/08/2025         |
| L2536  | -   | 143.6 kg       | 73.8 cm               | 147.1 cm | 01/08/2025      | 09/09/2025         |
| L2545  | -   | 140.7 kg       | 81.5 cm               | 143.5 cm | 07/08/2025      | 16/09/2025         |
| L2568  | -   | 70.9 kg        | 80.5 cm               | 142.3 cm | 30/08/2025      | 19/09/2025         |

for the measurements of L2536, L2545, and L2556 were different units from those used for L2509. The calibration and correction coefficients differ from the L2509 measurement in those measurements. The temperature correlation coefficient was recalibrated by conducting the temperature calibration experiment again. The resulting coefficient was obtained as

$$\Delta E = -3.51 \times 10^{-4} \Delta T. \quad (5.26)$$

Because there were few periods during which the sea turtles swam in a strictly vertical orientation, the in-situ calibration of the hydrostatic pressure effect was not feasible. However, since the sensor was successfully recovered after the experiments, a hydrostatic pressure calibration experiment was conducted using a pressure application device. The calibration results indicate that the Pitot-type waterflow sensor units used for L2536, L2545, and L2556 effectively suppressed the influence of hydrostatic pressure through the differential configuration. The hydrostatic pressure correction coefficient for the differential output was determined as

$$\Delta P \approx a_h h, \quad a_h = -0.24 \text{ Pa/m}. \quad (5.27)$$

In addition, because a different propeller logger was used in L2536, L2545, and L2556 measurements, the rotation number of the propeller was converted to waterflow speed using the Eq. 5.25 with  $k = 0.0232$ . All other data processing steps of the Pitot-type waterflow sensor and the propeller logger, except for these calibration coefficients, were identical to those applied in the measurement of L2509. All sensors in the Pitot-type waterflow sensor system were sampled at 100 Hz, whereas the propeller logger record propeller rotation number at 1 Hz. In trials of L2536, L2545, and L2556, underwater drone imaging was attempted. However, the sea turtles were lost from underwater drone view after a short time, and video recording was unsuccessful.

Figure 5.39 shows the waterflow speed, depth, and temperature measured during the experiment of L2536. The waterflow speeds were measured by both the Pitot-type waterflow sensor and the propeller logger, while depth and temperature in the figure were measured from the temperature and pressure sensors integrated into the Pitot-type waterflow sensor system. Multiple depth changes were observed, indicating active diving behavior.

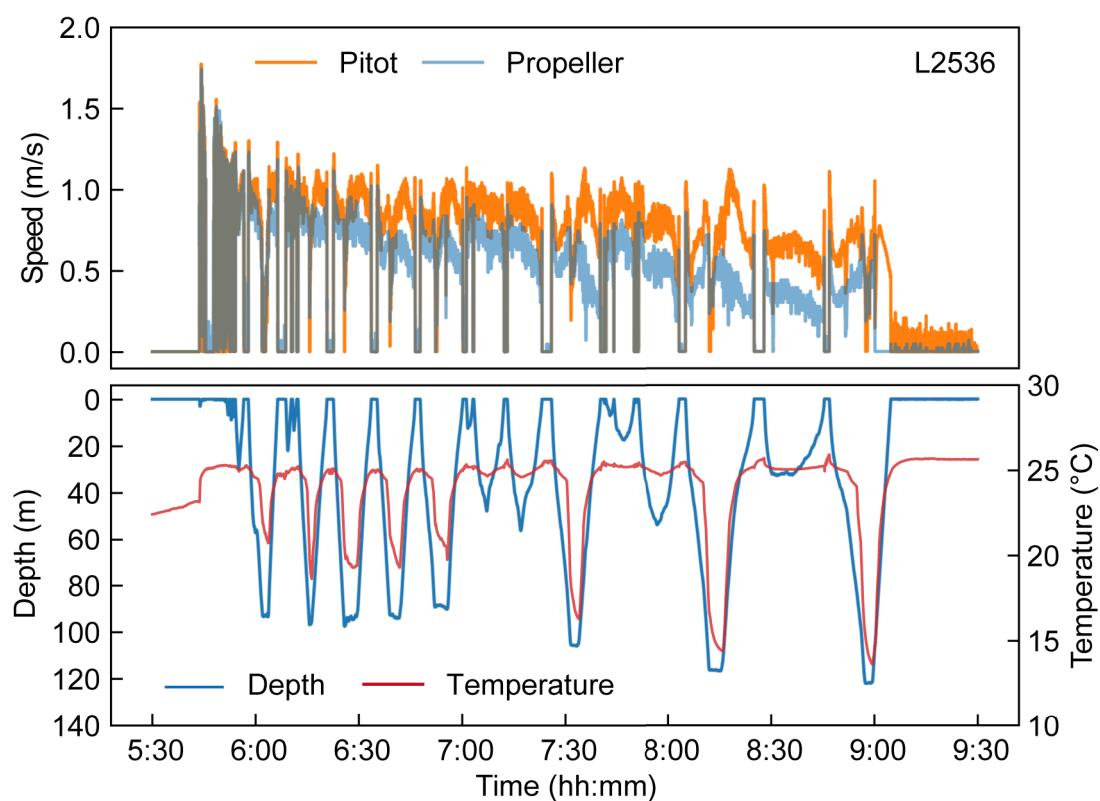


Fig. 5.39 Measured waterflow speed, temperature, and depth during the biologging experiment of L2536.

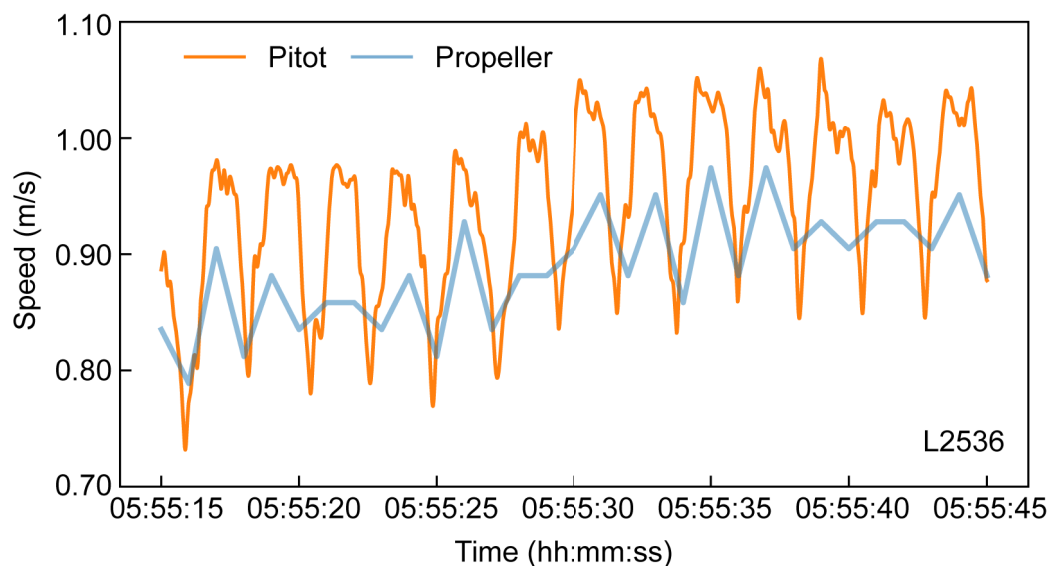


Fig. 5.40 Waterflow speeds measured by the Pitot-type waterflow sensor and the propeller logger during a 30-s interval (05:55:15–05:55:45) in the L2536 experiment.

Both the Pitot-type waterflow sensor and the propeller logger continued to record waterflow speed until the sensors were detached from the sea turtle at 9:00. The Pitot-type waterflow sensor generally showed higher speed values than the propeller logger. Nevertheless, both sensors captured synchronous temporal variations, showing similar patterns of speed increases and decreases. Figure 5.40 shows the measured waterflow speed from the Pitot-type waterflow sensor and the propeller logger during the 30 s interval from 5:55:15 to 5:55:45. Both sensors recorded slow-speed fluctuations that occurred at the same time. However, because the propeller logger has a lower temporal resolution, its output was effectively time-averaged, and distinct fluctuation peaks were not measured. In contrast, the Pitot-type waterflow sensor which has a higher temporal resolution measured speed fluctuations in the sub-hertz range, similar to those for L2509. These observations suggest that the Pitot-type waterflow sensor can capture rapid speed variations that are likely

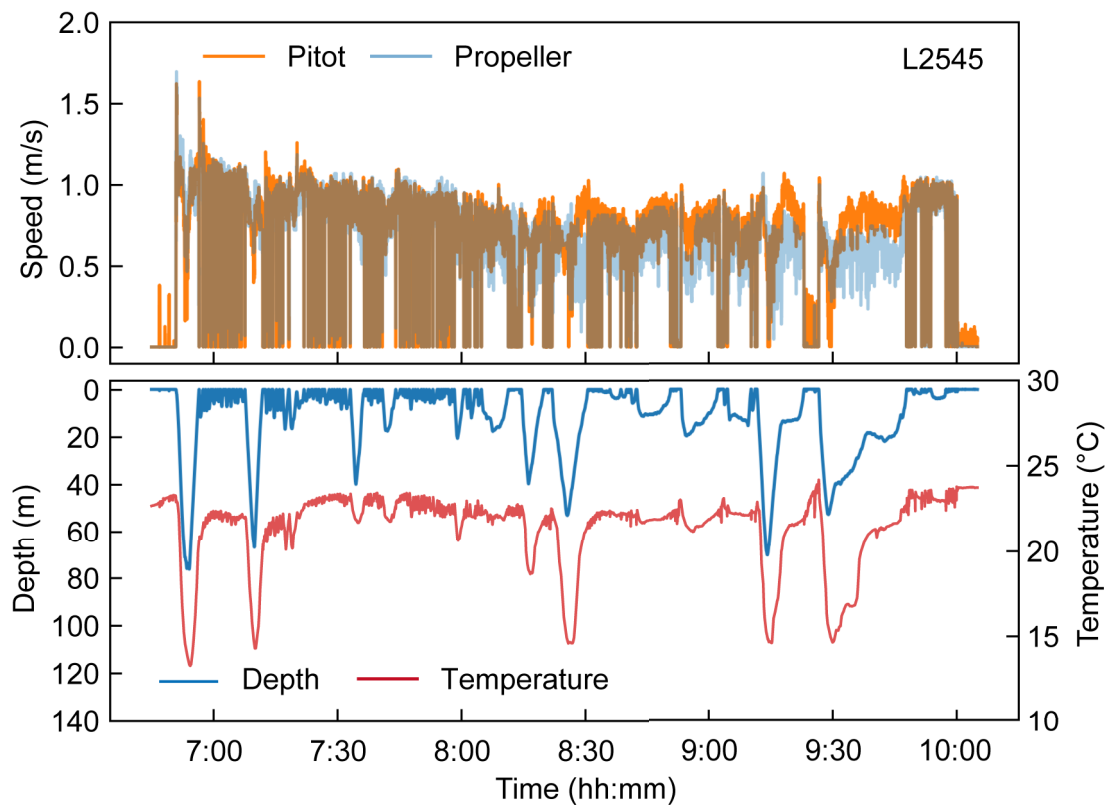


Fig. 5.41 Measured waterflow speed, temperature, and depth during the biologging experiment of L2545.

associated with flipper flapping in sea turtles.

Figure 5.41 shows the waterflow speed, depth, and temperature measured during the experiment of L2545. The Pitot-type waterflow sensor and the propeller logger successfully recorded data until the carapace tag was detached from the sea turtle at 10:00. Several dive events were observed, indicating active swimming behavior of the sea turtle. Throughout the experiment, the Pitot-type waterflow sensor and the propeller logger showed similar waterflow speed and captured synchronous increases and decreases in waterflow speed. Figure 5.42 shows the measured waterflow speed from the Pitot-type waterflow sensor and the propeller logger during the 30 s interval from 8:05:30 to 8:06:00. The two sensors showed generally similar outputs, but the Pitot-type waterflow sensor measured sub-hertz range speed fluctuations that were not clearly observed in the propeller logger output and are likely related to flipper flapping.

Figure 5.43 shows the waterflow speed, depth, and temperature measured during the experiment of L2568. The Pitot-type waterflow sensor and the propeller logger successfully recorded data until the carapace tag was detached from the sea turtle at 8:00. A lot of dive events were observed, indicating active swimming behavior of the sea turtle. In the L2568 trial, the sea turtle was released inside Otsuchi Bay, and the dive depth was shallower

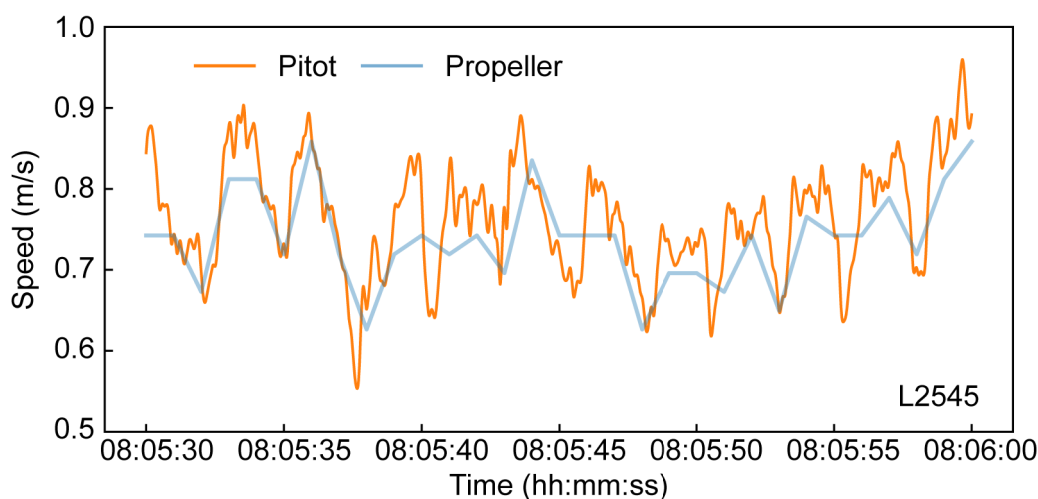


Fig. 5.42 Waterflow speeds measured by the Pitot-type waterflow sensor and the propeller logger during a 30-s interval (08:05:30–05:06:00) in the L2545 experiment.

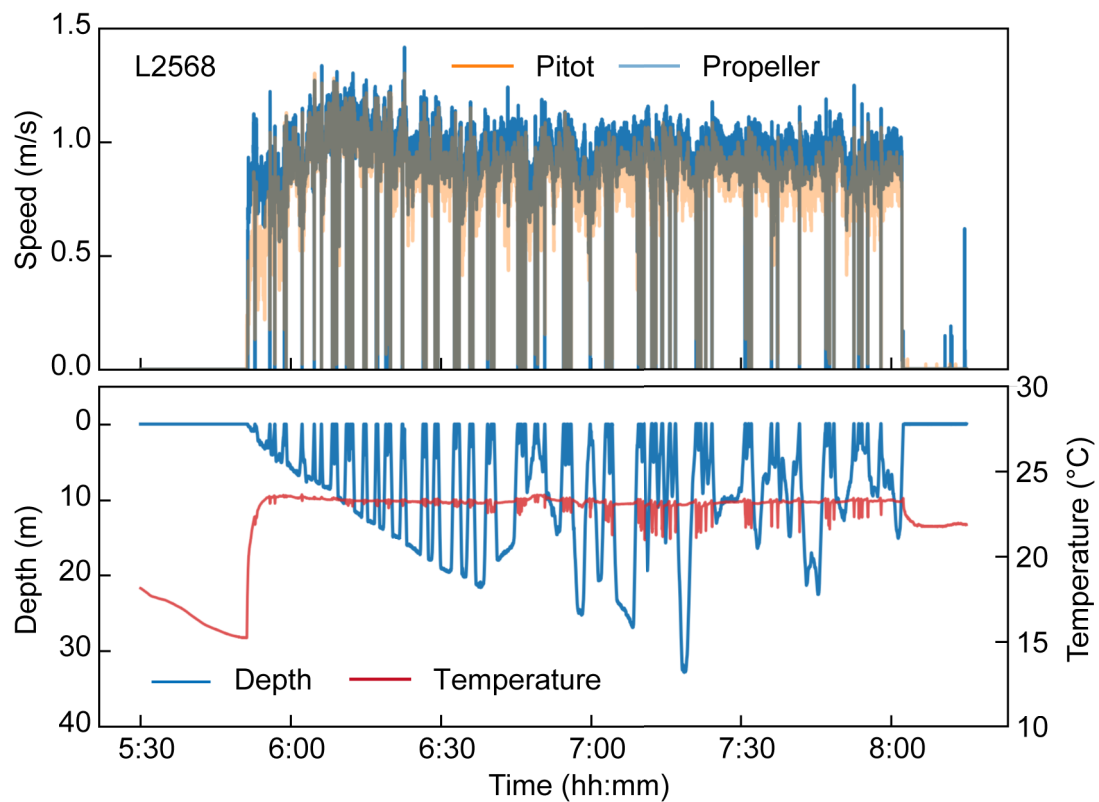


Fig. 5.43 Measured waterflow speed, temperature, and depth during the biologging experiment of L2568.

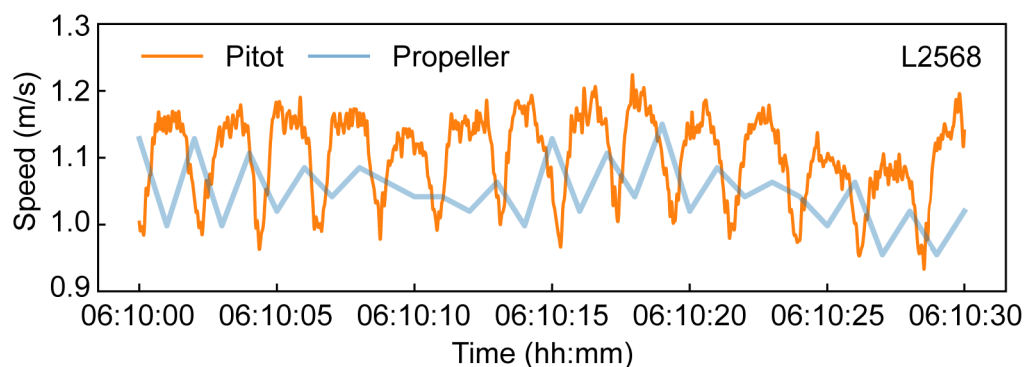


Fig. 5.44 Waterflow speeds measured by the Pitot-type waterflow sensor and the propeller logger during a 30-s interval (06:10:00–06:10:30) in the L2568 experiment.

compared with the other trials. The Pitot-type waterflow sensor and the propeller logger showed closely matching waterflow speed output and captured acceleration and deceleration

events at similar times. Figure 5.44 shows the measured waterflow speed from the Pitot-type waterflow sensor and the propeller logger during the 30 s interval from 6:10:00 to 6:10:30. The two sensors showed generally similar outputs. The Pitot-type waterflow sensor measured sub-hertz range speed fluctuations that were not clearly observed in the propeller logger output and are likely related to flipper flapping.

Across all four trials, the Pitot-type waterflow sensor captured fine-scale speed fluctuations that were not measured by the propeller logger. These results indicate that the Pitot-type waterflow sensor's fast dynamic response enables high frequency waterflow measurement and allows evaluation of sea turtle movement in frequency ranges that are difficult to evaluate using conventional methods.

Furthermore, the Pitot-type waterflow sensor exhibited stable performance throughout all biologging trials without any signs of debris accumulation or biofouling. Owing to its lack of moving parts, the sensor is structurally less susceptible to malfunction caused by clogging or biological attachment, demonstrating high durability while maintaining reliable speed measurements.

### 5.5.5 Cross-validation of the Pitot-type waterflow sensor against the Propeller logger using multiple sea turtle biologging trials

To evaluate the validity of the proposed Pitot-type waterflow sensor, a correlation analysis was performed between its output and the propeller logger output. Before the analysis, the outputs of both sensors were synchronized using their time stamps. To account for differences in temporal resolution, the Pitot-type waterflow sensor data were averaged over 1-s intervals to generate a comparable sensor dataset. Because both sensors ideally provide zero output at zero waterflow speed, a zero-intercept linear regression ( $y = ax$ ) was applied. The regression coefficient  $a$  was estimated by least squares, and  $R^2$  was calculated using Eq. (5.5). In addition, the Pearson product-moment correlation coefficient was calculated as a reference metric to quantify the strength of the linear relationship between the two sensors' outputs.

Figure 5.45 shows the results of the origin-constrained linear regression between

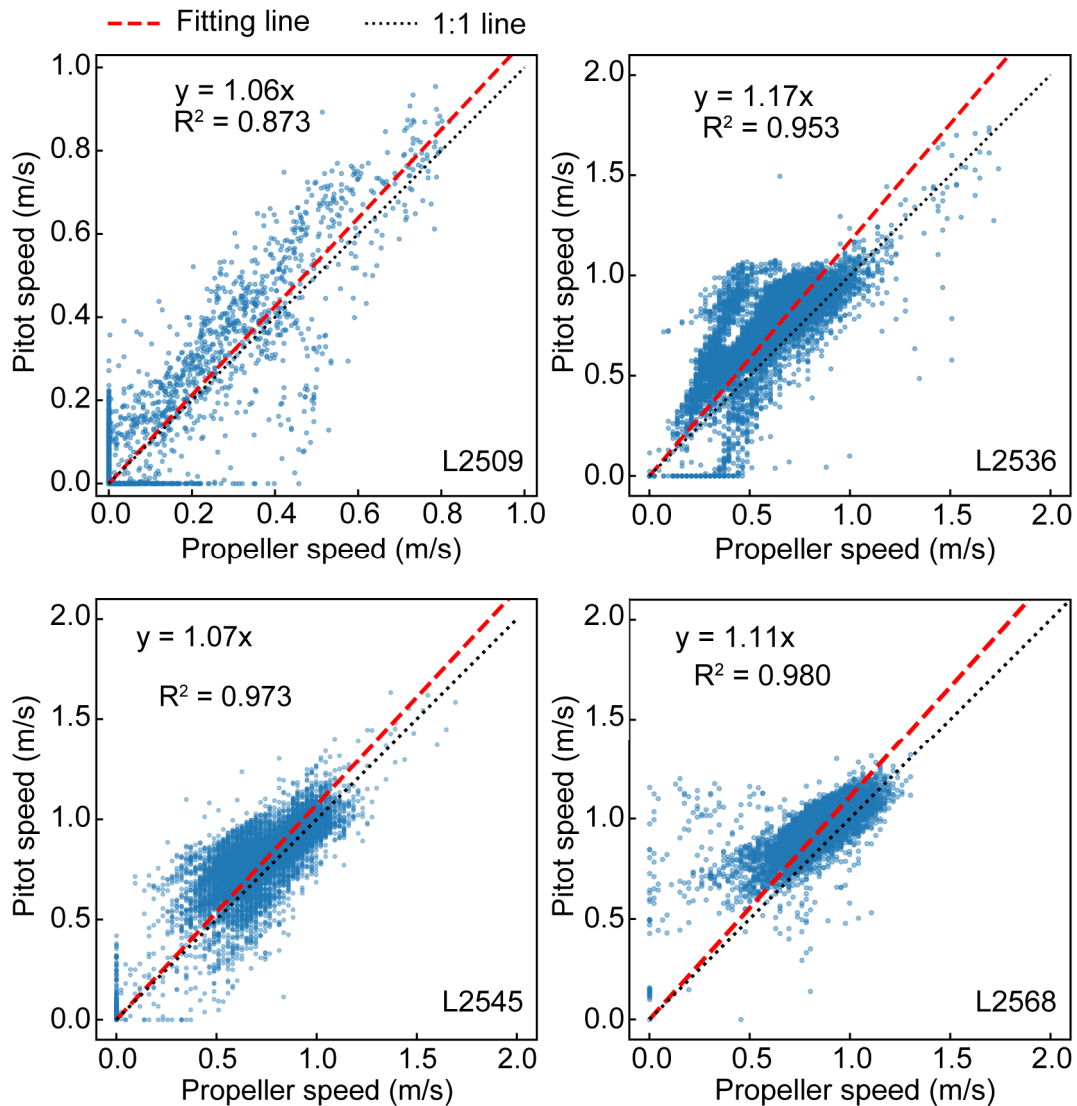


Fig. 5.45 The results of the correlation analysis between the Pitot-type waterflow sensor and the propeller logger outputs across all trials.

the Pitot-type waterflow sensor and the propeller logger across all biologging trials. Across all trials, a strong correlation was observed between the swimming speeds measured by the Pitot-type waterflow sensor and those measured by the propeller logger. The regression coefficients  $a$  obtained were close to 1 for all trials, but consistently slightly greater than 1. This result indicates that the Pitot-type waterflow sensor tended to estimate relative waterflow speed slightly higher than that measured by the propeller logger. In the electric



fishing reel experiment described in Section 5.3, the regression coefficient between the Pitot-type waterflow sensor and the propeller logger was approximately 1.02, indicating closer agreement between the two sensors. In contrast, the regression coefficients from the biologging experiments were consistently slightly larger. These differences could be influenced by environmental disturbances acting on the Pitot-type waterflow sensor. However, in the electric fishing reel experiment conducted in the same marine environment, the Pitot-type waterflow sensor and the propeller logger showed close agreement. This comparison suggests that environmental effects alone cannot explain the observed difference. Instead, the differences are most likely attributed to differences in sensor orientation relative to the incoming waterflow, particularly variations in pitch angle arising from the mounting configuration on the turtle.

In the electric fishing reel experiment, both sensors were mounted on the PVC pipe with sufficient separation and stabilized by the attached weight, leaving sufficient space between them. This configuration ensured that the Pitot-type waterflow sensor and the propeller logger were oriented nearly perpendicular to the incoming waterflow and exposed to a relatively uniform and undisturbed waterflow. Under these conditions, hydrodynamic interference between the sensors was minimized, resulting in closely matched speed estimates.

In contrast, during the biologging experiments, the sensors were mounted vertically on the turtle's carapace via the carapace tag. Therefore, the propeller logger was positioned between the Pitot-type waterflow sensor and the carapace. Although both sensors were mounted to be as parallel as possible to the turtle's longitudinal body axis, this alignment was established under static conditions on land, with the turtle positioned horizontally. Consequently, this setup does not guarantee that the sensors remain parallel to the swimming direction during active swimming in the water. In addition, the pitch angle of the turtle's longitudinal body axis relative to the swimming direction can vary dynamically during swimming. When the turtle swam with its body pitched downward relative to the swimming direction, the upstream Pitot-type waterflow sensor could partially shield the propeller logger, potentially affecting the waterflow field incident on the propeller logger. As a result, the

propeller logger may have experienced a reduced waterflow speed, leading to a slightly lower speed estimate than that obtained from the Pitot-type waterflow sensor.

Although differences between the Pitot-type waterflow sensor and the propeller logger were observed, the regression coefficient  $a$  ranged from 1.06 to 1.17. The fact that  $a$  remained close to unity in all trials suggests that the Pitot-type waterflow sensor preserved an approximately linear response to the propeller logger in situ. The coefficient of determination for the zero-intercept model was high in all trials (0.873-0.9801), demonstrating that a single proportional model ( $y = ax$ ) explained most of the variance in the speed derived from the Pitot-type waterflow sensor relative to the speed derived from the propeller logger. These values showed a strong correlation between these two sensors.

In addition to the origin-constrained linear regression, the Pearson correlation coefficient was calculated to quantify the linear covariation between the outputs of the two sensors. Table 5.6 shows the summary of correlation analysis between the Pitot-type waterflow sensor and the propeller logger across all trials. The Pearson correlation coefficient  $r$  is a dimensionless metric that quantifies the strength and direction of the linear relationship between two continuous variables  $x$  and  $y$ . It is defined as the covariance of the deviations of each variable from its mean, normalized by the product of their standard deviations. The Pearson correlation coefficient is expressed as

$$r = \frac{\sum_{i=1}^N (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^N (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^N (y_i - \bar{y})^2}} \quad (5.28)$$

Here,  $x_i$  and  $y_i$  are the waterflow speed measured by the propeller logger and the Pitot-type

Table 5.5 Summary of correlation analysis between the Pitot-type waterflow sensor and the propeller logger

| Turtle                 | L2509                 | L2536                 | L2545                 | L2568                 |
|------------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Regression coefficient | 1.06                  | 1.17                  | 1.07                  | 1.11                  |
| $R^2$ (zero-intercept) | 0.873                 | 0.953                 | 0.9729                | 0.9801                |
| Pearson $r$            | 0.9244                | 0.7679                | 0.8285                | 0.6718                |
| P-value                | $< 1 \times 10^{-16}$ | $< 1 \times 10^{-16}$ | $< 1 \times 10^{-16}$ | $< 1 \times 10^{-16}$ |

waterflow sensor, respectively.  $\bar{x}$  and  $\bar{y}$  are their corresponding mean values.  $N$  is the number of data points used in the analysis. The Pearson correlation coefficient is independent of the absolute scale and offset of the sensor outputs. Instead, it evaluates the degree to which temporal speed fluctuations measured by the two sensors covary. It provides a measure of how consistently the two methods capture synchronized variations in measured waterflow speed. In contrast, the regression coefficient and the coefficient of determination  $R^2$  were used to evaluate how consistently the two sensors measured the same physical speed on a common scale. The p-value associated with the Pearson correlation coefficient represents the probability that a correlation equal to or larger than the observed value occurs by chance.

The p-value associated with the Pearson correlation coefficient represents the probability of obtaining a correlation coefficient equal to or greater than the observed value by chance, under the null hypothesis that the true correlation is zero. In this study, the p-value was calculated using the following t statistic:

$$t = \frac{r\sqrt{N-2}}{\sqrt{1-r^2}} \quad (5.29)$$

The t value was assumed to follow a t distribution with  $N - 2$  degrees of freedom, and the p-value was obtained as the corresponding two-sided probability.

The Pearson correlation coefficient  $r$  and p-value were calculated using the same dataset as for the origin-constrained linear regression. Across all trials, the Pearson correlation coefficients showed a consistently strong positive linear relationship between the waterflow speed measured by the Pitot-type sensor and that measured by the propeller logger. The  $r$  ranged from 0.67 to 0.92, indicating that temporal speed fluctuations measured by the two sensors generally changed in the same direction. The highest correlation was observed in L2509 ( $r = 0.944$ ), which showed highly synchronized speed variations between the two sensors. In contrast, L2568 showed a lower correlation ( $r = 0.672$ ). This lower value is likely attributed to the narrower range of swimming speeds in this trial, with most data points concentrated between approximately 0.4 and 1.0 m/s. Because Pearson's correlation coefficients are sensitive to the dynamic range of data, a restricted speed range can lead to reduced  $r$  values even when the two sensors capture temporally synchronized fluctuations.

Therefore, the lower  $r$  in 2568 does not necessarily indicate poor agreement between the two sensors. Even this lowest value still represents a substantial positive correlation.

For all trials, the associated p-value was smaller than  $1 \times 10^{-16}$ , indicating that the observed correlations are statistically significant and extremely unlikely to arise by chance under the null hypothesis of zero correlation. Because a large number of data points were used, these very small p-values mainly reflect the robustness of the detected linear relationships rather than the magnitude of the correlation itself. Therefore, Pearson correlation showed that the Pitot-type waterflow sensor captured temporal variations in measured waterflow speed that were strongly synchronized with those measured by the propeller logger among all trials.

Based on the correlation analyses presented above, all biologging trials demonstrate a consistently strong relationship between the swimming speeds measured by the Pitot-type waterflow sensor and the propeller logger. The origin-constrained regression shows that the Pitot-type waterflow sensor maintains a linear proportional relationship with the propeller logger with small regression coefficients. In addition, the Pearson correlation analysis indicates that the Pitot-type waterflow sensor captures temporal variations in waterflow speed that are synchronized with those measured by the in-situ propeller logger. The measured speeds from the two sensors showed close agreement. These results indicate that the proposed Pitot-type waterflow sensor provides relative waterflow speed estimates comparable to those obtained using conventional propeller-based methods. Therefore, the Pitot-type waterflow sensor is an effective tool for measuring relative waterflow speed in sea turtle biologging applications under natural swimming conditions.

## 5.6 Conclusion

---

In this chapter, measurement experiments using the Pitot-type waterflow sensor system developed in Chapter 2 were presented. Three types of experiments were conducted: a captive experiment with sea turtles in an aquarium, a calibration experiment using a motorized fishing rod, and a biologging experiment with wild loggerhead turtle.

For both the aquarium and field experiments, complete experimental setups were constructed to enable in-water data acquisition. The sensor system was directly attached to the carapace of green turtles (*Chelonia mydas*), allowing verification of its performance under realistic swimming conditions. The results demonstrated that the sensor output reflected the turtle's swimming-induced speed changes, confirming that the system functioned reliably when deployed on alive turtles in water.

A calibration test was subsequently conducted using a motorized fishing rod to compare the outputs of the propeller logger and the proposed Pitot-type waterflow sensor. When the line was retrieved at a constant speed, the velocities obtained from both sensors showed close agreement, confirming that the proposed system can accurately measure waterflow velocity under controlled conditions.

Finally, a biologging experiment was performed in Otsuchi Bay, Iwate Prefecture, by attaching the sensor system to wild loggerhead turtles (*Caretta caretta*) that had been incidentally captured in set nets and later released. To enable autonomous recovery, a biologging system was developed that allowed automatic detachment, surfacing, and radio-based localization from the sea surface. The lightest loggerhead turtle used in the experiments had a body mass of 59.2 kg and a SCL of 77.6 cm. Even under this conservative condition, the sensor system with a total mass of 168 g and a projected frontal area of 18 cm<sup>2</sup>, satisfied the design requirements for biologging of loggerhead turtle. During the experiment, a drogue plate was attached to the turtle's carapace to increase hydrodynamic drag; data were recorded for approximately 45 minutes with the drogue attached and another 45 minutes without it. The turtle's swimming behavior was also recorded using an underwater drone that captured its movements from multiple angles.

The waterflow speed measured by the Pitot-type sensor were consistent with those obtained from the propeller logger and corresponded closely to the swimming behavior observed in the drone footage. Notably, the Pitot-type sensor responded to swimming speeds below 0.2 m/s (a range in which the propeller logger failed to produce any output). Video data from the towed camera tag confirmed that the turtle was actively swimming during these low-speed periods, demonstrating that the proposed sensor successfully captured slow

swimming that conventional propeller loggers could not measure.

A comparison between the gliding and flapping periods further revealed that the Pitot-type sensor detected periodic speed fluctuations associated with flipper strokes, whereas the propeller logger did not. These findings indicate that the proposed sensor achieved high temporal resolution and could detect rapid speed variations such as those produced by flapping motions. By contrast, conventional propeller-based sensors lack sufficient temporal responsiveness to capture these fluctuations. In addition to its high responsiveness, the Pitot-type sensor demonstrated excellent robustness, as it contains no moving parts that could be obstructed by debris or biofouling.

Furthermore, three more biologging trials were conducted, resulting in a total of four loggerhead sea turtle trials. Both origin-constrained linear regression and Pearson correlation analyses were then performed using all trial output. Across all biologging trials, the proposed Pitot-type waterflow sensor showed a strong and consistent relationship with the propeller logger. Origin-constrained regression demonstrated a stable linear proportionality with regression coefficients close to unity, while Pearson correlation analysis confirmed that temporal variations in measured waterflow speed were strongly synchronized between the two sensors. Overall, these results indicate that the Pitot-type waterflow sensor provides reliable relative waterflow speed measurements comparable to those obtained from conventional propeller-based methods under natural marine conditions.

In summary, the experimental results confirmed that the proposed Pitot-type waterflow sensor system showed a strong correlation with the conventional propeller-based measurement and provides three major advantages over the conventional propeller logger.

- (1) reliable measurement at low speeds
- (2) high temporal resolution capable of capturing rapid flow variations, and
- (3) robust operation free from clogging or mechanical failure.

## CHAPTER 6. Concluding Remarks

### 6.1 Conclusion ---

In this study, a single-axis Pitot-type waterflow sensor and a multi-inlet two-dimensional waterflow vector sensor, both based on the Pitot-tube principle, were proposed to measure the relative waterflow velocity of marine animals. Experimental evaluations demonstrated that both sensors function effectively as waterflow sensors. Furthermore, by integrating the single-axis sensor into a biologging system, the relative waterflow velocity of wild sea turtles were successfully measured in its natural environment.

The loggerhead turtle (*Caretta caretta*) is selected as the target species. This species inhabits the coastal waters around Japan and allows sensors to be attached relatively easily. The flow sensors were mounted on the turtle's carapace. Based on the swimming characteristics of the loggerhead turtle, the measurement range of the single-axis Pitot-type waterflow sensor is set to 0–2.0 m/s, with a speed resolution of 0.01 m/s (at cruising speed of 0.5 m/s) and a response time of 50 ms. Similarly, the two-axis waterflow vector sensor is designed with the same velocity range of 0–2.0 m/s, a speed accuracy of 0.1 m/s, and an angular accuracy of 10°.

Based on the design requirements, a compact single-axis Pitot-type flow sensor (14 mm × 14 mm × 27 mm) was fabricated. The sensor features a rubber membrane covering the inlet and an oil-filled interior, allowing accurate, high-time-resolution waterflow measurements while preventing interference from suspended particles and biofouling. Its pressure response was linear, and the membrane's mechanical properties did not affect

---

**Concluding remarks**

---

sensitivity. For standalone operation, the sensor was integrated into a biologging device with a dual-sensor configuration that compensates for temperature and acceleration effects. Calibration experiments in a water tunnel confirmed that the sensor output was proportional to the square of the waterflow speed, consistent with Pitot theory. The complete system weighed 159.1 g and had a frontal area of 19 cm<sup>2</sup>, meeting the requirements for attachment to a loggerhead turtle.

The two-axis waterflow vector sensor is also fabricated in accordance with the design requirements. The prototype consists of a spherical housing with a 36 mm diameter and includes three pairs of inlet ports and differential pressure sensors. The pressure distribution on the sensor surface depends on both waterflow speed and direction. To estimate these parameters, the differential pressures among the three inlet pairs are measured and used to train a neural network (NN) model. The trained model achieves root-mean-square errors (RMSEs) of 0.048 m/s for waterflow speed and 4.33° for waterflow angle, corresponding to the sensor's measurement accuracy within the typical swimming velocity range of green turtles (0.6–2.0 m/s). The sensors were integrated into the HTR logger. The complete system weighed 116.8 g and had a frontal area of approximately 11.55 cm<sup>2</sup>. Thus, the proposed two-axis flow sensor successfully satisfies the specified performance requirements.

Finally, a biologging experiment is conducted using the single-axis waterflow sensor integrated into the biologging device. The flow sensor and a propeller logger are attached to the carapace of a subadult loggerhead turtle, which is then released in Otsuchi Bay, Iwate Prefecture. The outputs of the Pitot-type waterflow sensor and the propeller logger show good agreement, confirming that the proposed sensor accurately measures the turtle's relative waterflow velocity. Notably, the Pitot-type sensor provides reliable measurements even at low velocities below 0.2 m/s, where the propeller logger fails to respond. During flapping-type swimming, the sensor records periodic variations absent in the propeller logger's output. These fluctuations correlate with the z-axis acceleration measured by the onboard accelerometer and coincide with the timing of flipper movements captured in underwater drone footage, indicating that the sensor successfully detects velocity fluctuations induced by flipper strokes. No clogging or malfunction caused by suspended particles occurs



during the experiments, demonstrating the high robustness of the sensor system under harsh underwater conditions. Overall, these results demonstrate that the proposed sensor system enables high temporal resolution measurements that are difficult to achieve with conventional methods, while also providing extensibility for multi-axis measurements. Consequently, the system represents a promising and practical tool for accurately measuring the relative waterflow velocity of marine animals.

## 6.2 Impact of the proposed waterflow sensor on biologging methodology

---

The proposed Pitot-type waterflow sensor enables measurement of the relative waterflow velocity of marine animals with both high temporal resolution and multi-axis capability. As demonstrated in Chapter 5, this high temporal resolution enables analysis of swimming dynamics on very short time scales, including speed fluctuations associated with individual flipper strokes in sea turtles. In conventional biologging studies, analyses have largely focused on quasi-steady, time-averaged forward swimming speeds, and few studies have attempted to directly quantify speed variations at the level of individual locomotor actions. The introduction of the proposed sensor enables examination of swimming mechanics at the scale of individual movements. Specifically, it enables direct analysis of how sea turtles actuate their flippers, generate thrust, and subsequently convert that thrust into forward propulsion.

Furthermore, multi-axis measurement enables direct quantification of multidimensional velocity components, such as sideslip angles, which are difficult to evaluate with conventional methods. Previous biologging studies have primarily focused on quasi-steady forward swimming. However, swimming behaviors that involve turning and changes in movement direction are closely associated with survival-related activities, including foraging, predator avoidance, and obstacle negotiation. By introducing the proposed sensor, these unsteady and multidimensional swimming motions can be analyzed in a quantitatively detailed manner. This capability is expected to significantly advance

understanding of multidimensional swimming performance and locomotor control strategies in marine animals.

The swimming performance of marine animals surpasses that of artificial systems such as underwater drones in both energetic efficiency and maneuverability. By utilizing the high temporal resolution and multi-axis relative waterflow velocity data provided by the proposed sensor, these superior swimming characteristics can be quantitatively evaluated. The insights obtained from such analyses can then be translated into design guidelines for biomimetic underwater robots with enhanced maneuverability. In particular, the ability to evaluate time-varying changes in the velocity vector and thrust generation during turning maneuvers enables the development of motion control strategies that extend beyond conventional approaches based on steady-state assumptions.

In addition, the proposed sensor can be miniaturized and optimized by modifying its structure and measurement range, making it adaptable not only to sea turtles but also to a wide variety of animal species, including penguins. This versatility enables comparative analyses of swimming kinematics across species and supports discussions on the evolutionary diversity of swimming strategies at the scale of individual movements. Moreover, the proposed sensor successfully measured swimming speeds below 0.2 m/s, a range that has been difficult to measure with conventional propeller-type sensors. This capability suggests potential applicability to species that swim more slowly than sea turtles, such as the Greenland shark. Although field measurements of the sharks have reported cruising speed on the order of 0.3 m/s [117], this study also indicates that a substantial fraction of records falls the stall speed of the propeller logger. This implied that part of the cruising speed range may be missed by existing approaches. Consequently, for such slow-swimming animals, biologging data remain scarce, and their swimming modes and ecological characteristics are still poorly understood. Therefore, the proposed sensor provides a valuable tool for investigating the locomotion mechanisms of animals adapted to low-speed swimming.

Owing to its structure without moving parts, the proposed sensor is resistant to clogging and mechanical failure, which are persistent problems in propeller-based waterflow sensors. In conventional propeller-based sensors, functional degradation caused by

suspended particles and biofouling poses a constant risk, increasing the likelihood of sensor failure during biologging experiments. In contrast, the robust design of the proposed sensor substantially improves experimental reliability and reduces the operational burden on researchers. Furthermore, the sensor's low power consumption, combined with antifouling technologies such as biofouling-resistant coatings or films, offers the potential to extend waterflow speed measurements from deployments lasting several days to long-term deployments lasting several months. Such extended observation periods may enable analyses of long-timescale behaviors, including gradual changes in swimming speed during migration, which have been difficult to investigate using conventional methods.

High temporal resolution velocity measurements also improve the accuracy of dead-reckoning navigation. Because dead-reckoning estimates 3D swimming paths through time integration of velocity, a sufficiently high sampling rate is essential to reduce integration errors. By combining the proposed sensor with GNSS data, swimming path reconstruction accuracy could be further improved, and the influence of ambient ocean currents may also be estimated. This capability points to a new direction in biologging, in which marine animals serve as mobile platforms for in situ observations of ocean current fields.

In summary, the Pitot-type waterflow sensor proposed in this study overcomes key limitations of conventional biologging methods by enabling robust, high temporal resolution, and multi-axis measurements of relative waterflow velocity. This capability substantially broadens the range of swimming behaviors that can be analyzed quantitatively, spanning scales from individual locomotor actions to long-term and multidimensional movements. As a result, the proposed sensor establishes a strong methodological foundation for future biologging studies, with broad implications for ecology, biomechanics, and bio-inspired engineering.

### 6.3 Future perspectives

---

The high temporal resolution and multi-axis measurements of relative waterflow velocity achieved in this study have the potential to extend beyond velocity estimation toward

the acquisition of new types of environmental information. Previous studies have shown that the turbulent kinetic energy dissipation rate  $\varepsilon$  [66] can be estimated using Pitot tubes, even at sampling rates lower than those employed in the proposed sensor. Applying similar analytical frameworks to high temporal resolution biologging data may enable estimation of turbulence intensity and ocean mixing conditions directly experienced by marine animals. The turbulent energy dissipation rate is a key physical parameter governing material transport and mixing processes in the ocean. Linking this parameter with animal behavior data could provide new insights into interactions between marine animals and their surrounding physical environment. Accordingly, high-sampling-rate, multi-axis waterflow velocity data contain rich information beyond waterflow velocity alone, and further advances in analysis methods are expected to greatly expand the range of environmental variables that can be investigated through biologging.

In this study, a two-axis waterflow velocity sensor was developed, and its operating principle was demonstrated experimentally. However, the field biologging experiments were conducted using the single-axis sensor, and the multi-axis sensor should therefore be regarded primarily as a proof of principle. In future work, increasing the number of inlets and differential pressure sensor elements could enable extension to full three-axis waterflow velocity measurements. Such an extension would allow more detailed evaluation of complex animal movements and their interactions with three-dimensional waterflow fields in the marine environment.

Furthermore, an important feature of the proposed sensor is its high robustness against interference from suspended particles and biofouling. This robustness is not limited to the performance of a single waterflow sensor but instead indicates a general design concept applicable to sensors operating in marine environments. The structural approach introduced in this study, which combines a membrane with an oil-filled chamber, can be extended to other sensor types beyond waterflow sensors, including pressure, chemical, and force sensors used underwater. Accordingly, this design concept has the potential to support the development of a new class of robust underwater sensing technologies.

In this study, two Pitot-type waterflow sensors were employed to reduce the

influence of environmental disturbances. In future work, hybridization with a vortex-based waterflow sensor represents a promising alternative. When fluid flows past an object, vortices are generated in its wake. The vortex shedding frequency is proportional to the flow speed, and the vortex amplitude scales with the square of the speed. Owing to these characteristics, vortex waterflow sensors are generally less sensitive to environmental disturbances. The signals obtained from the Pitot-type sensor developed in this study already contain components that are likely associated with vortex generation. This observation suggests that, by modifying the sensor geometry, a new flow-sensing configuration combining the Pitot principle with vortex-based measurement could be realized. In such a hybrid sensor, low-frequency velocity components could be measured stably using the vortex-based approach, while high-frequency components could be captured by the Pitot-type sensor. This combination is expected to enable waterflow velocity measurements that achieve both high robustness and high temporal resolution.

The Pitot-type waterflow sensor proposed in this study is a compact, low-power device that operates robustly in underwater environments. Owing to these characteristics, its potential applications extend beyond biologging to a wide range of underwater measurement domains, including motion control sensors for small underwater drones and current monitoring around aquaculture cages. As discussed above, the proposed sensor not only enhances the capabilities of existing biologging techniques but also serves as a foundational technology for broader applications in oceanographic environmental monitoring, ecological behavior analysis, and the development of new design concepts for underwater sensors. Accordingly, the proposed sensor is expected to play an important role in future biologging research and related scientific and engineering fields.

# Acknowledgments

My research activities had been received great cooperation from countless people. At the last of my dissertation, I would like to state appreciation for it.

First and foremost, I would like to express my deepest gratitude to Associate Professor Hidetoshi Takahashi, who has guided me for six years since I joined his laboratory as an undergraduate student. Throughout my bachelor's, master's, and doctoral studies, he has continuously provided invaluable guidance and generous support. He taught me the fundamentals and the joy of research from the very beginning, and I am truly proud to have spent these six years conducting my studies and research in the Takahashi Laboratory.

I would also like to express my sincere appreciation to many others who have offered their guidance and support throughout my research.

I am deeply grateful to Associate Professor Hiroto Tanaka of the Tokyo Institute of Technology, who kindly allowed me to use the water channel and provided valuable advice from the perspective of fluid mechanics. His insightful comments greatly enhanced the quality of my research, and I am also thankful for his generous assistance in proofreading my manuscripts during the paper-writing process.

I am especially indebted to Professor Katsufumi Sato of the University of Tokyo for his tremendous collaboration in this study. He taught me a broad range of ecological knowledge—from animal behavior to fieldwork techniques—and without his guidance, the biologging experiments on sea turtles would not have been possible. He also shared with me the joy of fieldwork, including the memorable experiences of cooking over a charcoal grill after long days in the field. In addition, I am sincerely grateful for the many valuable comments and suggestions he provided from an ecologist's perspective throughout the process of writing this doctoral dissertation. Without his generous support and insightful guidance, I would not have been able to complete this thesis.

I would like to thank Associate Professor Kentaro Sakamoto of the University of

---

## Acknowledgements

---

Tokyo for his generous collaboration and guidance during the field experiments. His practical advice helped me refine the experimental procedures and successfully obtain valuable data from the sea turtle studies. I am also deeply grateful for his kind encouragement and support during our fieldwork in Iwate Prefecture.

My sincere thanks go to Mr. Kenta Kuroda of the University of Tokyo, my research partner in the collaborative experiments. He was the first colleague with whom I shared a common research goal, and working alongside him was both stimulating and inspiring. Through our collaboration, I was able to conduct highly productive and engaging research that significantly enriched my doctoral work.

I am also grateful to all members of Professor Sato's Laboratory at the University of Tokyo, who assisted me with animal handling and provided essential training for biological experiments. Despite my limited experience, they took the lead during field operations and offered their constant support. Thanks to their guidance and camaraderie, my stay in Iwate became an invaluable and deeply fulfilling experience.

I would like to thank Professor Hiroaki Onoe for generously allowing me to use his laboratory facilities and equipment, and for his valuable discussions during academic conferences. I am deeply grateful to him for serving as a member of my doctoral examination committee and for providing insightful comments and constructive advice from a device- and engineering-oriented perspective. His guidance was instrumental in helping me refine the structure and technical clarity of this dissertation. I am also grateful to the members of the Onoe Laboratory for teaching me how to operate their instruments and for many stimulating conversations at conferences. Their enthusiasm and dedication to research were a great source of motivation, especially during the pandemic when opportunities for interaction were limited.

I am deeply grateful to Professor Tetsuo Kan of the University of Electro-Communications for his kind advice and encouragement during academic meetings. I also wish to thank the members of his laboratory for their warm interactions and friendship at conferences, which made my first experiences of inter-lab exchanges both memorable and enjoyable.

---

## Acknowledgements

---

My sincere appreciation goes to Dr. Yu Naruoka at JAXA, who developed the data logger used in my sensor system. Despite his busy schedule, he kindly answered my many questions regarding circuit design. The logger he developed formed the foundation of my research, and without his expertise and support, the completion of my sensor system would not have been possible.

I would like to thank Professor Genya Ishigami for taking the time to examine my doctoral dissertation. He provided valuable comments and constructive advice, particularly from perspectives on statistical analysis and data interpretation that I had not fully considered on my own. His insightful suggestions greatly contributed to improving the rigor and clarity of this dissertation and enabled me to refine and strengthen the thesis from new and broader viewpoints.

I would like to thank Mr. Koichiro Ikeda of Little Leonardo Co., Ltd., for his generous assistance in molding the data logger and for providing extensive technical advice on underwater device design—from cabling to field operation. His expertise and attention to detail were invaluable to the development of the sensor system.

I am deeply thankful to Dr. Shinichi Watanabe, who taught me the fundamentals of biologging, from seabird handling to field techniques. I fondly remember his kindness and the many delicious seafood meals he shared with me in Iwate Prefecture. His guidance not only improved my research skills but also made my fieldwork an enjoyable and memorable experience.

I am also grateful to all the staff of the Enoshima Aquarium, who provided exceptional support during the aquarium experiments. They trained the turtles, coordinated the experimental setup, and offered valuable suggestions that helped improve the sensor design. Their cooperation and professionalism made the aquarium experiments possible.

I would like to express my heartfelt thanks to Ms. Kyoko Nakajima and Ms. Yumiko Sugiyama, the laboratory secretaries, for their dedicated assistance with administrative procedures and documentation related to external experiments. Their continued support ensured that my research activities proceeded smoothly and efficiently.

I would like to express my sincere appreciation to the members of the



---

## Acknowledgements

---

Manufacturing Center, who fabricated various tools and fixtures necessary for my experiments. I am also grateful to Mr. Oiwa, who kindly helped me prototype the sensor housings using a 3D printer.

I would like to extend my heartfelt thanks to everyone at MizLinx Co., Ltd., with whom I had the opportunity to collaborate on a project utilizing my sensor. It was an inspiring and deeply rewarding experience to see my research being implemented in a real-world context. Working alongside such ambitious and dedicated colleagues not only provided strong motivation for my work but also supported me in many aspects of daily life.

I am deeply thankful to my senior colleagues in the laboratory, who guided me in every aspect of research and life — from writing and conducting experiments to providing personal advice. They were the pioneers who built the foundation of our laboratory from scratch, and I have the utmost respect for their dedication. Even after advancing to a higher grade than they were at that time, I continue to admire their achievements.

I would also like to thank my junior colleagues, whose curiosity and enthusiasm brought fresh energy into the lab. I was genuinely happy when some of them chose to join the laboratory because they were interested in my research theme. Their honest feedback, unfiltered by hierarchy, constantly inspired me and strengthened my motivation.

My peers in the laboratory have also been an invaluable source of support and inspiration. We joined when the lab was still small, and together we experienced both challenges and growth. They were not only competitors who drove me to improve but also companions who supported me during difficult times. I am truly grateful to have shared this journey with them, and I wish them continued success in their new endeavors.

Among them, I owe special thanks to Mr. Rihachiro Nakashima, who pursued his doctoral studies alongside me. The doctoral journey was filled with failures and hardships, but his companionship and encouragement helped me persevere through difficult times. Even after advancing to a higher grade than he was at that time, I continue to admire his dedication and achievements. He is the only person who can truly be called a co-founder and comrade of our laboratory, and I take great pride in having become one of the first doctoral graduates together with him.

---

## Acknowledgements

---

Finally, I would like to express my deepest gratitude to my family, who supported me throughout my university life in countless ways. Without their unwavering encouragement and understanding, I would not have been able to complete this research.

There are many other people who have supported and guided me in various ways, though I cannot mention them all here. I would like to extend my heartfelt gratitude to everyone who has contributed to this study in any way.

## References

- [1] M. J. Dickens, K. A. Earle, and L. M. Romero, "Initial transference of wild birds to captivity alters stress physiology," *Gen. Comp. Endocrinol.*, vol. 160, no. 1, pp. 76–83, 2009.
- [2] B. Bárdos, H. K. Török, and I. Nagy, "Comparison of the exploratory behaviour of wild and laboratory mouse species," *Behav. Processes*, vol. 217, art. no. 105031, 2024.
- [3] D. N. Fisher, A. James, R. Rodríguez-Muñoz, and T. Tregenza, "Behaviour in captivity predicts some aspects of natural behaviour, but not others, in a wild cricket population," *Proc. Biol. Sci.*, vol. 282, no. 1809, art. no. 20150708, 2015.
- [4] Y. Naito, "New steps in bio-logging science," *Memoirs of National Institute of Polar Research. Special issue*, vol. 58, pp. 50–57, 2004.
- [5] C. Rutz and G. C. Hays, "New frontiers in biologging science," *Biol. Lett.*, vol. 5, no. 3, pp. 289–292, 2009.
- [6] G. L. Kooyman, "Techniques used in measuring diving capacities of Weddell Seals," *Polar Rec.*, vol. 12, no. 79, pp. 391–394, 1965.
- [7] Y. Naito, T. Asaga, and Y. Ohyama, "Diving behavior of Adelie penguins determined by time-depth recorder," *Condor*, vol. 92, no. 3, pp. 582–586, Aug. 1990.
- [8] G. Kooyman, "Genesis and evolution of bio-logging devices: 1963–2002," *Memoirs of National Institute of Polar Research. Special issue*, vol. 58, pp. 15–22, 2004.
- [9] Y. Naito, "Recent advances in studies of the diving behavior of marine birds and mammals with micro-data loggers," *J. Yamashina Inst. Ornithol.*, vol. 35, no. 2, pp. 88–104, 2004.
- [10] E. S. Bridge *et al.*, "Technology on the move: Recent and forthcoming innovations for tracking migratory birds," *Bioscience*, vol. 61, no. 9, pp. 689–698, 2011.
- [11] Y. Goto, K. Yoda, and K. Sato, "Asymmetry hidden in birds' tracks reveals wind, heading, and orientation ability over the ocean," *Sci. Adv.*, vol. 3, no. 9, art. no. e1700097, 2017.
- [12] R. Kays, M. C. Crofoot, W. Jetz, and M. Wikelski, "ECOLOGY. Terrestrial animal tracking as an eye on life and planet," *Science*, vol. 348, no. 6240, art. no. aaa2478, 2015.
- [13] R. S. Hetem *et al.*, "Body temperature, activity patterns and hunting in free-living cheetah: biologging reveals new insights," *Integr. Zool.*, vol. 14, no. 1, pp. 30–47, 2019.
- [14] K. Kaneda, Y. Ohgi, C. Tanaka, and B. Burkett, "The development of an estimation model for energy expenditure during water walking by acceleration and walking speed," *J. Sci. Med. Sport*, vol. 17, no. 1, pp. 96–101, 2014.
- [15] T. Koizumi, Y. Kameda, and Y. Nakamura, "Retrieval of personal experience records using relevance feedback with a structuring filter," in *2nd European Workshop on the Integration of Knowledge, Semantics and Digital Media Technology (EWIMT 2005)*, London, UK, 2005.

---

References

---

- [16] M. Whitford and A. P. Klimley, “An overview of behavioral, physiological, and environmental sensors used in animal biotelemetry and biologging studies,” *Anim. Biotelemetry*, vol. 7, no. 1, art. no. 26, 2019.
- [17] K. Sato, W. Sakamoto, Y. Matsuzawa, H. Tanaka, and Y. Naito, “Correlation between stomach temperatures and ambient water temperatures in free-ranging loggerhead turtles, *Caretta caretta*,” *Mar. Biol.*, vol. 118, no. 2, pp. 343–351, 1994.
- [18] J.-B. Charrassin, Y.-H. Park, Y. L. Maho, and C.-A. Bost, “Penguins as oceanographers unravel hidden mechanisms of marine productivity,” *Ecol. Lett.*, vol. 5, no. 3, pp. 317–319, 2002.
- [19] K. Yoda *et al.*, “Precise monitoring of porpoising behaviour of Adélie penguins determined using acceleration data loggers,” *J. Exp. Biol.*, vol. 202, no. 22, pp. 3121–3126, 1999.
- [20] K. Sato *et al.*, “Stroke frequency, but not swimming speed, is related to body size in free-ranging seabirds, pinnipeds and cetaceans,” *Proc. Biol. Sci.*, vol. 274, no. 1609, pp. 471–477, 2007.
- [21] S. Lisovski, C. M. Hewson, R. H. G. Klaassen, F. Korner-Nievergelt, M. W. Kristensen, and S. Hahn, “Geolocation by light: accuracy and precision affected by environmental factors,” *Methods in Ecology and Evolution*, vol. 3, no. 3, pp. 603–612, 2012.
- [22] P. Goulet, C. Guinet, C. Campagna, J. Campagna, P. L. Tyack, and M. Johnson, “Flash and grab: deep-diving southern elephant seals trigger anti-predator flashes in bioluminescent prey,” *J. Exp. Biol.*, vol. 223, no. 10, art. no. jeb222810, 2020.
- [23] E. S. Bridge, J. F. Kelly, A. Contina, R. M. Gabrielson, R. B. MacCurdy, and D. W. Winkler, “Advances in tracking small migratory birds: a technical review of light-level geolocation,” *J. Field Ornithol.*, vol. 84, no. 2, pp. 121–137, 2013.
- [24] R. J. Moll, J. J. Millspaugh, J. Beringer, J. Sartwell, and Z. He, “A new ‘view’ of ecology and conservation through animal-borne video systems,” *Trends Ecol. Evol.*, vol. 22, no. 12, pp. 660–668, 2007.
- [25] K. Sato, Y. Mitani, Y. Naito, and H. Kusagaya, “Synchronous shallow dives by Weddell seal mother - pup pairs during lactation,” *Mar. Mamm. Sci.*, vol. 19, no. 2, pp. 384–395, 2003.
- [26] L. Uesaka, C. A. Bost, K. Sato, and K. Q. Sakamoto, “Deep-sea ascending predation by king penguin and its prey reaction observed by animal-borne video camera,” *Ecology*, vol. 106, no. 5, art. no. e70117, 2025.
- [27] S. Greif and Y. Yovel, “Using on-board sound recordings to infer behaviour of free-moving wild animals,” *J. Exp. Biol.*, vol. 222, Suppl 1, art. no. jeb184689, 2019.
- [28] M. P. Johnson and P. L. Tyack, “A digital acoustic recording tag for measuring the response of wild marine mammals to sound,” *IEEE J. Ocean. Eng.*, vol. 28, no. 1, pp. 3–12, 2003.
- [29] T. Noda *et al.*, “Animal-borne soundscape logger as a system for edge classification of sound sources and data transmission for monitoring near-real-time underwater soundscape,” *Sci. Rep.*, vol. 14, no. 1, art. no. 6394, 2024.
- [30] Y. Mitani, K. Sato, S. Ito, M. F. Cameron, D. B. Siniff, and Y. Naito, “A method for reconstructing three-dimensional dive profiles of marine mammals using geomagnetic

## References

- intensity data: results from two lactating Weddell seals,” *Polar Biol.*, vol. 26, no. 5, pp. 311–317, 2003.
- [31] H. J. Williams *et al.*, “Identification of animal movement patterns using tri-axial magnetometry,” *Mov. Ecol.*, vol. 5, art. no. 6, 2017.
- [32] R. W. Davis *et al.*, “Hunting behavior of a marine mammal beneath the antarctic fast Ice,” *Science*, vol. 283, no. 5404, pp. 993–996, 1999.
- [33] K. Q. Sakamoto, M. Miyayama, C. Kinoshita, T. Fukuoka, T. Ishihara, and K. Sato, “A non-invasive system to measure heart rate in hard-shelled sea turtles: potential for field applications,” *Philos. Trans. R. Soc. Lond. B Biol. Sci.*, vol. 376, no. 1830, art. no. 20200222, 2021.
- [34] J. A. Goldbogen *et al.*, “Extreme bradycardia and tachycardia in the world’s largest animal,” *Proc. Natl. Acad. Sci. U. S. A.*, vol. 116, no. 50, pp. 25329–25332, 2019.
- [35] J. M. Kendall-Bar *et al.*, “Brain activity of diving seals reveals short sleep cycles at depth,” *Science*, vol. 380, no. 6642, pp. 260–265, 2023.
- [36] S. M. Tomkiewicz, M. R. Fuller, J. G. Kie, and K. K. Bates, “Global positioning system and associated technologies in animal behaviour and ecological research,” *Philos. Trans. R. Soc. Lond. B Biol. Sci.*, vol. 365, no. 1550, pp. 2163–2176, 2010.
- [37] M. Naruoka *et al.*, “Application of inertial and GNSS integrated navigation to seabird biologging,” *J. Robot. Mechatron.*, vol. 33, no. 3, pp. 526–536, 2021.
- [38] S. K. Hooker and I. L. Boyd, “Salinity sensors on seals: use of marine predators to carry CTD data loggers,” *Deep Sea Res. Part 1 Oceanogr. Res. Pap.*, vol. 50, no. 7, pp. 927–939, 2003.
- [39] Japanese Biologging Research Association (Ed.), *Biologging: Animal Ecology Elucidated by the Latest Science* [in Japanese]. Kyoto, Japan: Kyoto Tsushinsha, 2009.
- [40] K. Sato, K. Aoki, Y. Y. Watanabe, and P. J. O. Miller, “Neutral buoyancy is optimal to minimize the cost of transport in horizontally swimming seals,” *Sci. Rep.*, vol. 3, art. no. 2205, 2013.
- [41] K. Q. Sakamoto, A. Takahashi, T. Iwata, T. Yamamoto, M. Yamamoto, and P. N. Trathan, “Heart rate and estimated energy expenditure of flapping and gliding in black-browed albatrosses,” *J. Exp. Biol.*, vol. 216, no. 16, pp. 3175–3182, 2013.
- [42] H. Chung, J. Lee, and W. Y. Lee, “A review: Marine bio-logging of animal behaviour and ocean environments,” *Ocean Sci. J.*, vol. 56, no. 2, pp. 117–131, 2021.
- [43] T. Narazaki, K. Sato, K. J. Abernathy, G. J. Marshall, and N. Miyazaki, “Loggerhead turtles (*Caretta caretta*) use vision to forage on gelatinous prey in mid-water,” *PLoS One*, vol. 8, no. 6, art. no. e66043, 2013.
- [44] B. W. Bowen, F. A. Abreu-Grobois, G. H. Balazs, N. Kamezaki, C. J. Limpus, and R. J. Ferl, “Trans-Pacific migrations of the loggerhead turtle (*Caretta caretta*) demonstrated with mitochondrial DNA markers,” *Proc. Natl. Acad. Sci. U. S. A.*, vol. 92, no. 9, pp. 3731–3734, 1995.
- [45] W. J. Nichols, A. Resendiz, J. A. Seminoff, and B. Resendiz, “Transpacific migration of a loggerhead turtle monitored by satellite telemetry,” *Bulletin of Marine Science*, vol. 67, no. 3, pp. 937–947, 2000.

---

References

---

- [46] W. Sakamoto, T. Bando, N. Arai, and N. Baba, “Migration paths of the adult female and male loggerhead turtles *Caretta caretta* determined through satellite telemetry,” *Fish. Sci.*, vol. 63, no. 4, pp. 547–552, 1997.
- [47] H. Hatase *et al.*, “Size-related differences in feeding habitat use of adult female loggerhead turtles *Caretta caretta* around Japan determined by stable isotope analyses and satellite telemetry,” *Mar. Ecol. Prog. Ser.*, vol. 233, pp. 273–281, 2002.
- [48] T. Narazaki, K. Sato, and N. Miyazaki, “Summer migration to temperate foraging habitats and active winter diving of juvenile loggerhead turtles *Caretta caretta* in the western North Pacific,” *Mar. Biol.*, vol. 162, no. 6, pp. 1251–1263, 2015.
- [49] J. W. Chapman *et al.*, “Animal orientation strategies for movement in flows,” *Curr. Biol.*, vol. 21, no. 20, pp. R861–870, 2011.
- [50] T. Mattern, M. D. McPherson, U. Ellenberg, Y. van Heezik, and P. J. Seddon, “High definition video loggers provide new insights into behaviour, physiology, and the oceanic habitat of a marine predator, the yellow-eyed penguin,” *PeerJ*, vol. 6, art. no. e5459, 2018.
- [51] P. J. O. Miller, M. P. Johnson, P. L. Tyack, and E. A. Terray, “Swimming gaits, passive drag and buoyancy of diving sperm whales *Physeter macrocephalus*,” *J. Exp. Biol.*, vol. 207, no. 11, pp. 1953–1967, 2004.
- [52] J. A. Goldbogen, J. Calambokidis, R. E. Shadwick, E. M. Oleson, M. A. McDonald, and J. A. Hildebrand, “Kinematics of foraging dives and lunge-feeding in fin whales,” *J. Exp. Biol.*, vol. 209, no. 7, pp. 1231–1244, 2006.
- [53] D. E. Cade, K. R. Barr, J. Calambokidis, A. S. Friedlaender, and J. A. Goldbogen, “Determining forward speed from accelerometer jiggle in aquatic environments,” *J. Exp. Biol.*, vol. 221, no. 2, art. no. jeb170449, 2018.
- [54] K. Sato, Y. Mitani, M. F. Cameron, D. B. Siniff, and Y. Naito, “Factors affecting stroking patterns and body angle in diving Weddell seals under natural conditions,” *J. Exp. Biol.*, vol. 206, no. 9, pp. 1461–1470, 2003.
- [55] T. Narazaki *et al.*, “Similar circling movements observed across marine megafauna taxa,” *iScience*, vol. 24, no. 4, art. no. 102221, 2021.
- [56] N. Harada and H. Tanaka, “Kinematic and hydrodynamic analyses of turning manoeuvres in penguins: body banking and wing upstroke generate centripetal force,” *J. Exp. Biol.*, vol. 225, no. 24, art. no. jeb244124, 2022.
- [57] J. T. W. Kuo, L. Yu, and E. Meng, “Micromachined thermal flow sensors—A review,” *Micromachines (Basel)*, vol. 3, no. 3, pp. 550–573, 2012.
- [58] C. G. Lomas, *Fundamentals of hot wire anemometry*. Cambridge, England: Cambridge University Press, 2011.
- [59] J. Petrie, P. Diplas, M. Gutierrez, and S. Nam, “Data evaluation for acoustic Doppler current profiler measurements obtained at fixed locations in a natural river: Data Evaluation for Adcp Measurements,” *Water Resour. Res.*, vol. 49, no. 2, pp. 1003–1016, 2013.
- [60] RD Instruments, *Acoustic Doppler Current Profiler: Principles of Operation—A Practical Primer*, 2nd ed. San Diego, CA, USA: RD Instruments, 1996.

## References

- 
- [61] National Marine Fisheries Service, “2024 update to: technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing (version 3.0): underwater and in-air criteria for onset of auditory injury and temporary threshold shifts,” *NOAA Technical Memorandum NMFS-OPR-71*, National Oceanic and Atmospheric Administration, Silver Spring, MD, USA, 2024.
  - [62] C. Gazioğlu and V. Okutan, “Underwater noise pollution at the Strait of Istanbul (Bosphorus),” *Int. J. Environ. Geoinformatics*, vol. 3, no. 3, pp. 26–39, 2016.
  - [63] M. K. Bevir, “The theory of induced voltage electromagnetic flowmeters,” *J. Fluid Mech.*, vol. 43, no. 3, pp. 577–590, 1970.
  - [64] Z. Watral, J. Jakubowski, and A. Michalski, “Electromagnetic flow meters for open channels: Current state and development prospects,” *Flow Meas. Instrum.*, vol. 42, pp. 16–25, 2015.
  - [65] J. Huiqin, W. Hangchao, D. Ruihong, and Q. Jianyu, “Research on multiphase flow measurement system based on electromagnetic correlation method,” *J. Phys. Conf. Ser.*, vol. 1894, no. 1, art. no. 012048, 2021.
  - [66] J. N. Moum, “Ocean speed and turbulence measurements using pitot-static tubes on moorings,” *J. Atmos. Ocean. Technol.*, vol. 32, no. 7, pp. 1400–1413, 2015.
  - [67] J. Pieniążek, P. Ciecinski, D. Ficek, and M. Szumski, “Dynamic response of the Pitot tube with pressure sensor,” *Sensors (Basel)*, vol. 23, no. 5, art. no. 2843, 2023.
  - [68] M. R. Davis, “Response of small pitot tubes in gas-liquid flows,” *Int. J. Multiphase Flow*, vol. 6, no. 4, pp. 369–373, 1980.
  - [69] R. Allen, L. Traub, E. Johansen, O. Rediniotis, and T. Tsao, “A MEMS-based 5-sensor probe,” in *38th AIAA Aerospace Sciences Meeting and Exhibit*, Reno, NV, USA, 2000.
  - [70] C. Crowley, I. I. Shinder, and M. R. Moldover, “The effect of turbulence on a multi-hole Pitot calibration,” *Flow Meas. Instrum.*, vol. 33, pp. 106–109, 2013.
  - [71] K. M. A. Díaz, J. M. F. Oro, and E. B. Marigorta, “Direct calibration framework of triple-hole pressure probes for incompressible flow,” *Meas. Sci. Technol.*, vol. 19, no. 7, art. no. 075401, 2008.
  - [72] P. Bruschi, M. Dei, and M. Piotta, “A low-power 2-D wind sensor based on integrated flow meters,” *IEEE Sens. J.*, vol. 9, no. 12, pp. 1688–1696, 2009.
  - [73] A. Leoni, V. Stornelli, and L. Pantoli, “A low-cost portable spherical directional anemometer for fixed points measurement,” *Sens. Actuators A Phys.*, vol. 280, pp. 543–551, 2018.
  - [74] S. Matsunaga, H. Ishibashi, and M. Nishi, “Measurement of instantaneous pressure and velocity in nonsteady three-dimensional water flow by means of a combined five-hole probe,” *J. Fluids Eng.*, vol. 102, no. 2, pp. 196–202, 1980.
  - [75] Y. Senoo, Y. Kita, and K. Ookuma, “Measurement of two-dimensional periodic flow with a cobra probe,” *J. Fluids Eng.*, vol. 95, no. 2, pp. 295–299, 1973.
  - [76] K. Haneda *et al.*, “Compact sphere-shaped airflow vector sensor based on MEMS differential pressure sensors,” *Sensors (Basel)*, vol. 22, no. 3, art. no. 1087, 2022.
  - [77] K. Haneda, K. Matsudaira, and H. Takahashi, “Neural network-based airflow vector sensor using multiple MEMS differential pressure sensors,” *IEEE Access*, vol. 11, pp. 40978–40987, 2023.
-

---

References

---

- [78] S. Zhou et al., “Evaluations on supervised learning methods in the calibration of seven-hole pressure probes,” *PLoS One*, vol. 18, no. 1, art. no. e0277672, 2023.
- [79] A. Ghosh, D. M. Birch, and O. Marxen, “Neural-network-based sensor data fusion for multi-hole fluid velocity probes,” *IEEE Sens. J.*, vol. 20, no. 10, pp. 5398–5405, 2020.
- [80] T. Kishimoto, K. Matsudaira, H. Tanaka, and H. Takahashi, “A Sphrical Waterflow Vector Sensor in Deep Sea,” in *2023 IEEE SENSORS*, Vienna, Austria, 2023, pp. 1–4.
- [81] R. Weinzierl, G. Bohrer, B. Kranstauber, W. Fiedler, M. Wikelski, and A. Flack, “Wind estimation based on thermal soaring of birds,” *Ecol. Evol.*, vol. 6, no. 24, pp. 8706–8718, 2016.
- [82] L. Uesaka *et al.*, “Ocean wave observation utilizing motion records of seabirds,” *Prog. Oceanogr.*, vol. 200, art. no. 102713, 2022.
- [83] Y. Yonehara *et al.*, “Flight paths of seabirds soaring over the ocean surface enable measurement of fine-scale wind speed and direction,” *Proc. Natl. Acad. Sci. U. S. A.*, vol. 113, no. 32, pp. 9039–9044, 2016.
- [84] J. Davenport, S. A. Munks, and P. J. Oxford, “A comparison of the swimming of marine and freshwater turtles,” *Proc. Biol. Sci.*, vol. 220, no. 1221, pp. 447–475, 1984.
- [85] N. van der Geest, L. Garcia, R. Nates, and D. A. Godoy, “New insight into the swimming kinematics of wild Green sea turtles (*Chelonia mydas*),” *Sci. Rep.*, vol. 12, art. no. 18151, 2022.
- [86] Y. Ropert-Coudert, N. Knott, A. Chiaradia, and A. Kato, “How do different data logger sizes and attachment positions affect the diving behaviour of little penguins?,” *Deep Sea Res. Part 2 Top. Stud. Oceanogr.*, vol. 54, no. 3–4, pp. 415–423, 2007.
- [87] M. S. Bowlin, P. Henningsson, F. T. Muijres, R. H. E. Vleugels, F. Liechti, and A. Hedenström, “The effects of geolocator drag and weight on the flight ranges of small migrants,” *Methods Ecol. Evol.*, vol. 1, no. 4, pp. 398–402, 2010.
- [88] K. P. Watson and R. A. Granger, “Hydrodynamic effect of a satellite transmitter on a juvenile green turtle (*Chelonia mydas*),” *J. Exp. Biol.*, vol. 201, no. 17, pp. 2497–2505, 1998.
- [89] R. P. Wilson, J. M. Kreye, K. Lucke, and H. Urquhart, “Antennae on transmitters on penguins: balancing energy budgets on the high wire,” *J. Exp. Biol.*, vol. 207, no. 15, pp. 2649–2662, 2004.
- [90] T. Todd Jones *et al.*, “Calculating the ecological impacts of animal - borne instruments on aquatic organisms,” *Methods Ecol. Evol.*, vol. 4, no. 12, pp. 1178–1186, 2013.
- [91] Y. Watanabe, E. A. Baranov, K. Sato, Y. Naito, and N. Miyazaki, “Foraging tactics of Baikal seals differ between day and night,” *Mar. Ecol. Prog. Ser.*, vol. 279, pp. 283–289, 2004.
- [92] T. Narazaki, K. Sato, K. J. Abernathy, G. J. Marshall, and N. Miyazaki, “Sea turtles compensate deflection of heading at the sea surface during directional travel,” *J. Exp. Biol.*, vol. 212, no. 24, pp. 4019–4026, 2009.
- [93] I. Nakamura, Y. Goto, and K. Sato, “Ocean sunfish rewarm at the surface after deep excursions to forage for siphonophores,” *J. Anim. Ecol.*, vol. 84, no. 3, pp. 590–603, 2015.



## References

- 
- [94] T. T. Jones *et al.*, *Determining transmitter drag and best-practice attachment procedures for sea turtle biotelemetry studies*, NOAA Tech. Memo. NOAA-TM-NMFS-SWFSC-480, 2011.
  - [95] C. Kinoshita, T. Fukuoka, T. Narazaki, Y. Niizuma, and K. Sato, “Analysis of why sea turtles swim slowly: a metabolic and mechanical approach,” *J. Exp. Biol.*, vol. 224, no. 4, art. no. jeb236216, 2021.
  - [96] Y. Y. Watanabe *et al.*, “Scaling of swim speed in breath-hold divers: Scaling of swim speed,” *J. Anim. Ecol.*, vol. 80, no. 1, pp. 57–68, 2011.
  - [97] K. Sato *et al.*, “Buoyancy and maximal diving depth in penguins: do they control inhaling air volume?,” *J. Exp. Biol.*, vol. 205, no. 9, pp. 1189–1197, 2002.
  - [98] Y. Y. Watanabe, N. L. Payne, J. M. Semmens, A. Fox, and C. Huveneers, “Swimming strategies and energetics of endothermic white sharks during foraging,” *J. Exp. Biol.*, vol. 222, no. 4, art. no. jeb185603, 2019.
  - [99] P. A. Blackmore, “A static pressure probe for use in turbulent three-dimensional flows,” *J. Wind Eng. Ind. Aerodyn.*, vol. 25, no. 2, pp. 207–218, 1987.
  - [100] F. M. White, *Fluid Mechanics*. New York, NY, USA: McGraw-Hill, 1979.
  - [101] S. P. Timoshenko and S. Woinowsky-Krieger, *Theory of Plates and Shells*, 2nd ed. New York, NY, USA: McGraw-Hill, 1959.
  - [102] Shin-Etsu Silicone Co., Ltd., “Oil: Properties of silicone oil,” Shin-Etsu Silicone, [Online]. Available: <https://www.silicone.jp/products/type/oil/detail/about/index2-shtml>. [Accessed: Jan. 20, 2026]. [in Japanese].
  - [103] N. Binh-Khiem, K. Matsumoto, and I. Shimoyama, “Polymer thin film deposited on liquid for varifocal encapsulated liquid lenses,” *Appl. Phys. Lett.*, vol. 93, no. 12, art. no. 124101, 2008.
  - [104] B.-K. Nguyen, K. Matsumoto, and I. Shimoyama, “Tensile film stress of parylene deposited on liquid,” *Langmuir*, vol. 26, no. 24, pp. 18771–18775, 2010.
  - [105] J. Yu *et al.*, “A resonant high-pressure microsensor based on the vertical dual resonators with oil-filled isolated structure,” *IEEE Electron Device Lett.*, vol. 44, no. 3, pp. 508–511, 2023.
  - [106] T. Li, H. Shang, B. Wang, C. Mao, and W. Wang, “High-pressure sensor with high sensitivity and high accuracy for full ocean depth measurements,” *IEEE Sens. J.*, vol. 22, no. 5, pp. 3994–4003, 2022.
  - [107] A. M. Shapero, Y. Liu, and Y.-C. Tai, “Parylene-on-oil packaging for long-term implantable pressure sensors,” *Biomed. Microdevices*, vol. 18, no. 4, p. 66, 2016.
  - [108] T. Hyakudome, H. Yoshida, S. Ishibashi, T. Sawa, and M. Nakamura, “Development of advanced Lithium-ion battery for underwater vehicle,” in *2011 IEEE Symposium on Underwater Technology and Workshop on Scientific Use of Submarine Cables and Related Technologies*, Tokyo, Japan, 2011, pp. 1–4.
  - [109] T. Kishimoto, R. Saito, H. Tanaka, and H. Takahashi, “Pitot-static-tube-based waterflow sensor for marine biologging via inside sealing of an incompressible liquid,” *IEEE Sens. J.*, vol. 21, no. 18, pp. 19806–19814, 2021.
  - [110] H. Lamb, *Hydrodynamics*, 5th ed. Cambridge, U.K.: Cambridge University Press, 1924.
-

---

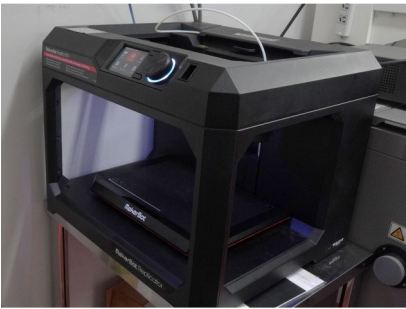
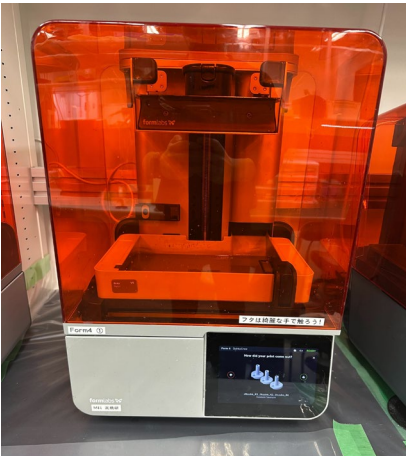
References

---

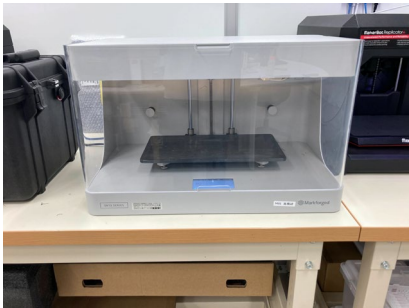
- [111] B. K. Shivamoggi, *Theoretical Fluid Dynamics*, 2nd ed. New York, NY, USA: John Wiley & Sons, 1998.
- [112] Y. Q. Wang, P. Jackson, and J. Ackerman, “Numerical investigation of flow over a sphere using LES and the spalart-allmaras turbulence model,” *Computational Fluid Dynamics Journal*, vol. 15, no. 1, pp. 198–205, 2006.
- [113] S. F. Hoerner, *Fluid Dynamic Drag*. bakersfield, CA, USA, 1965, pp. 48–50.
- [114] A. Ria, P. Bruschi, and M. Piotta, “A Compact Fault Tolerant 2-D Anemometer,” *IEEE Sens. J.*, vol. 24, no. 6, pp. 8642–8650, 2024.
- [115] T. Photopoulou, M. A. Fedak, J. Matthiopoulos, B. McConnell, and P. Lovell, “The generalized data management and collection protocol for Conductivity-Temperature-Depth Satellite Relay Data Loggers,” *Anim. Biotelemetry*, vol. 3, art. no. 21, 2015.
- [116] Y. Watanuki, Y. Niizuma, G. W. Gabrielsen, K. Sato, and Y. Naito, “Stroke and glide of wing-propelled divers: deep diving seabirds adjust surge frequency to buoyancy change with depth,” *Proc. Biol. Sci.*, vol. 270, no. 1514, pp. 483–488, 2003.
- [117] Y. Y. Watanabe, C. Lydersen, A. T. Fisk, and K. M. Kovacs, “The slowest fish: Swim speed and tail-beat frequency of Greenland sharks,” *J. Exp. Mar. Bio. Ecol.*, vol. 426–427, pp. 5–11, 2012.

## Appendix A Equipment

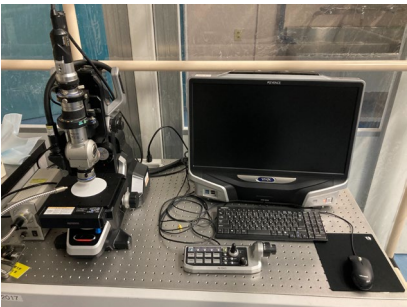
The equipment used in this study is listed below.

| Photo                                                                               | Equipment name | Model                | Manufacture              |
|-------------------------------------------------------------------------------------|----------------|----------------------|--------------------------|
|   | 3D printer     | Makerbot replicater+ | MakerBot Industries, LLC |
|  | 3D printer     | Form3                | Formlabs Inc.            |
|  | 3D printer     | Form4                | Formlabs Inc.            |

## Appendix

|                                                                                     |                     |                          |                                         |
|-------------------------------------------------------------------------------------|---------------------|--------------------------|-----------------------------------------|
|    | Post-curing machine | Form Cure                | Formlabs Inc.                           |
|   | 3D printer          | Onyx one                 | Markforged, Inc.                        |
|  | 3D printer          | Bambu Lab X1-Carbon      | Shenzhen TuoZhu Technology Co., Ltd.    |
|  | ScopeCorder         | DL850 ScopeCorder Series | Yokogawa Test & Measurement Corporation |

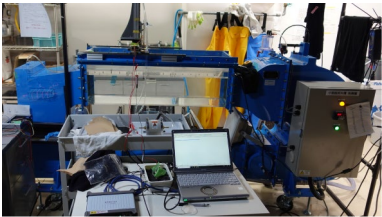
## Appendix

|                                                                                     |                             |                          |                      |
|-------------------------------------------------------------------------------------|-----------------------------|--------------------------|----------------------|
|    | Digital microscope          | VHX-6000                 | KEYENCE CORPORATION  |
|   | Pressure application system |                          |                      |
|  | Pressure application system | PV-5-90-120-750-AC-AG/DG | Syn Corporation Ltd. |

---

Appendix

---

|                                                                                     |                                 |                                   |                                                    |
|-------------------------------------------------------------------------------------|---------------------------------|-----------------------------------|----------------------------------------------------|
|    | Constant-temperature water bath | SH-222                            | ESPEC CORP.                                        |
|   | Pressure calibrator             | KAL200                            | halstrup-walcher GmbH                              |
|  | Water tunnel                    | Personal Tank PB-70SP             | Nishinippon Fluid Engineering Laboratory Co., Ltd. |
|  | Wire Bonder                     | Series 53XXBDA (Ball Deep Access) | F&S BONDTEC Semiconductor GmbH                     |

## Appendix

|                                                                                   |                                  |                               |                                      |
|-----------------------------------------------------------------------------------|----------------------------------|-------------------------------|--------------------------------------|
|  | Parylene<br>Deposition<br>System | SCS Labcoter®<br>2 (PDS 2010) | Specialty<br>Coating<br>Systems Inc. |
|-----------------------------------------------------------------------------------|----------------------------------|-------------------------------|--------------------------------------|



## Appendix B Water Tunnel Experiment of Sensor P-S

As shown in Fig. B. 1, Sensor P-S was fixed in the water tunnel for waterflow-speed calibration. The tunnel generated controlled waterflow speeds from 0 to 1.6 m/s in 0.2 m/s increments, and the sensor output was recorded at each speed. Data were acquired with a Ninja data logger at a sampling rate of 6.25 Hz. This calibration was performed using a single Sensor P-S.

Figure B. 2 shows the time series of the sensor system output during the full experiment, together with an example output recorded at a waterflow speed of 0.8 m/s. The

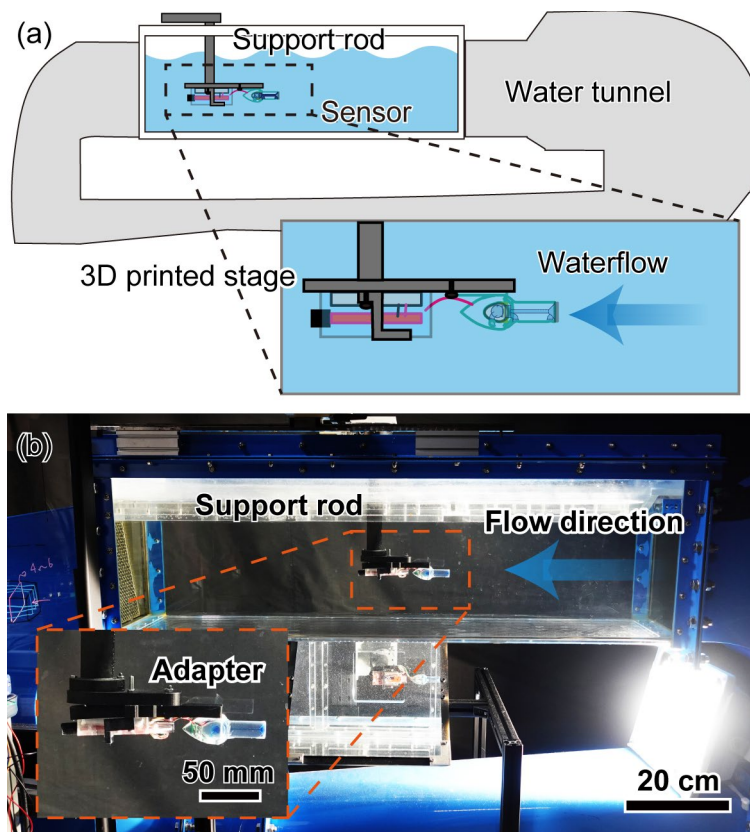


Fig. B. 1 (a) Schematic diagram and (b) photograph of the water tunnel experiment for Sensor P-S



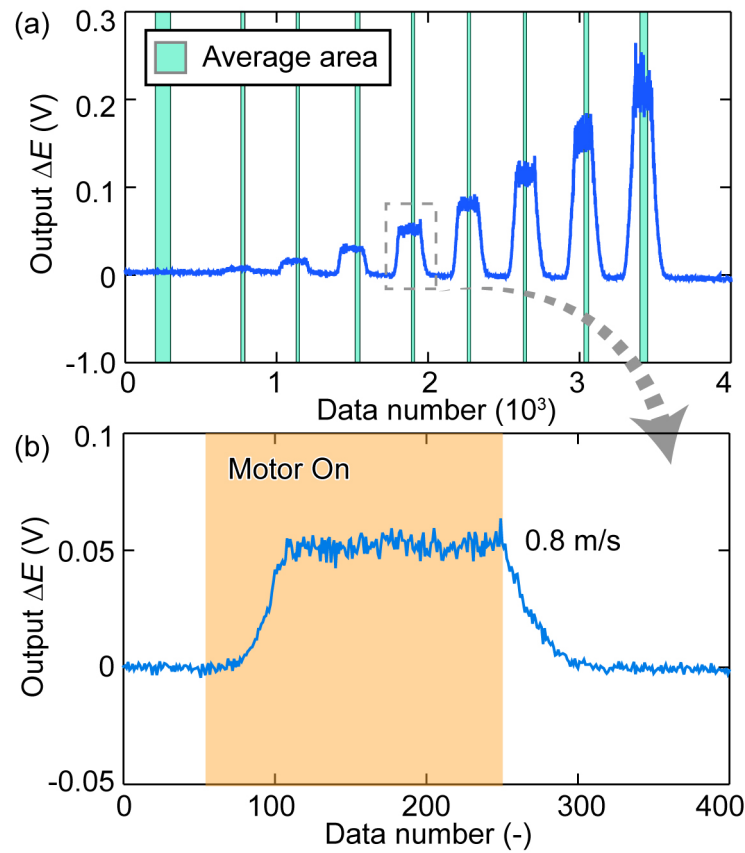


Fig. B. 2 (a) Sensor response during the waterflow tunnel experiment. (b) Sensor response at an imposed waterflow speed of 0.8 m/s.

output increased immediately when the waterflow was applied and returned to the pre-waterflow voltage when the water tunnel was stopped. The output also increased as the imposed waterflow speed increased, indicating a clear response to waterflow speed. Figure B. 3 summarizes the relationship between the differential pressure measured by the sensor system and the waterflow speed. The differential pressure was obtained by averaging the data within the blue region shown in Figure B. 2 (a). The sensor system responded to the square of the waterflow speed, as expected for Bernoulli theorem. The calibration equation yielded the following relationship:

$$\Delta P = 0.49 \rho v^2. \quad (\text{B.1})$$

In the aquarium experiment, flow speed was estimated using the calibration equation derived

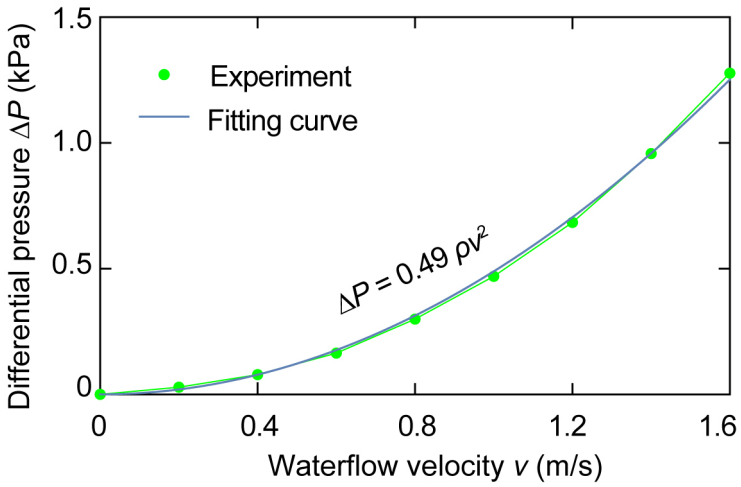


Fig. B. 3 Relationship between the differential pressure measured by the Sensor P-S and the imposed waterflow speed.

from this experiment.

## Appendix C Supplementary Raw Sensor Data from the Biologging Experiments

This appendix presents the raw sensor data recorded during the biologging experiments conducted in this study, which were not included in the main text. For trials of

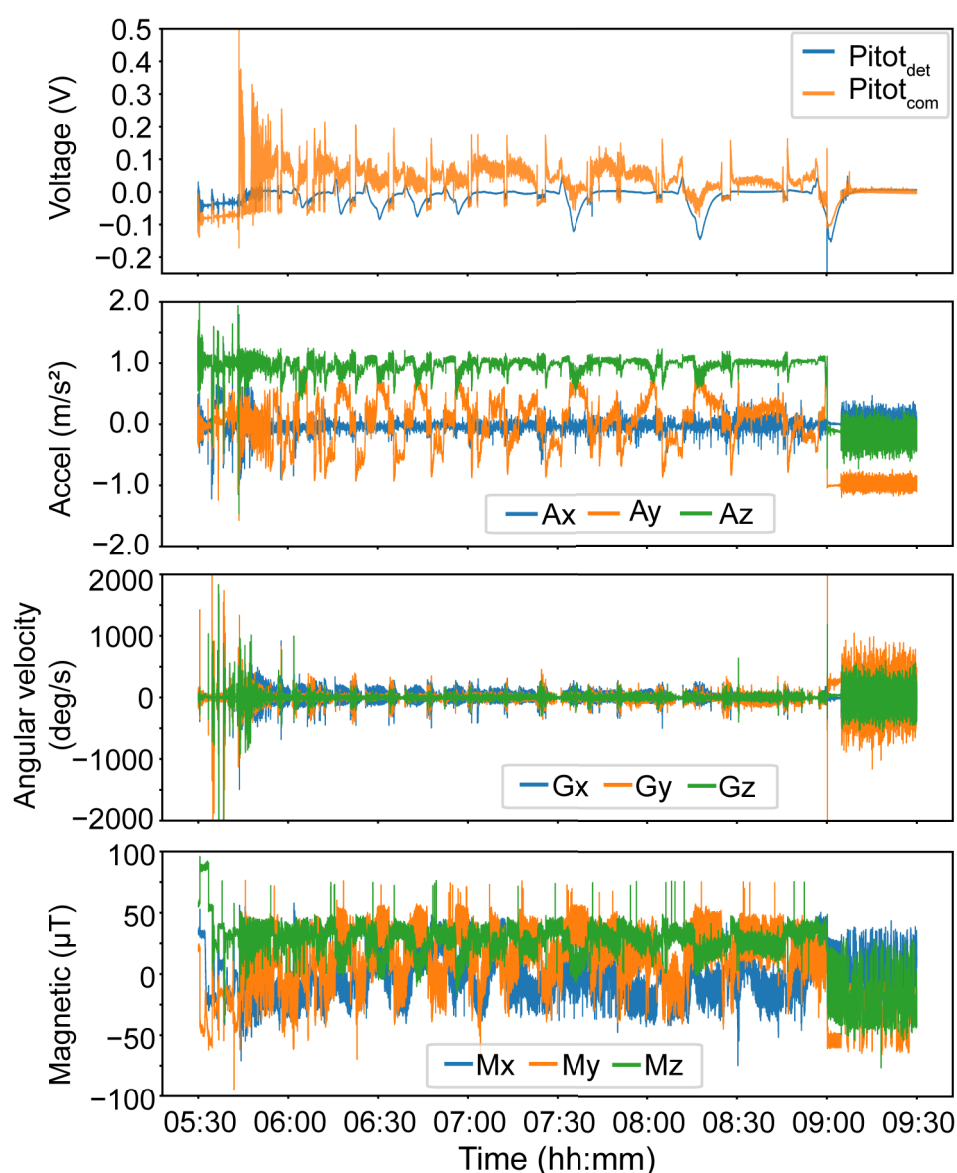


Fig. C. 1 Raw sensor data from the L2536 trial.

L2536, L2545, and L2568, the measurements from the Pitot-type waterflow sensor system are shown, including motion data (three-axis acceleration and three-axis angular velocity), the three-axis geomagnetic field, and the Pitot-type waterflow sensor output.

Figure C. 1 shows the outputs from each sensor during the L2536 trial. Figure C. 2 shows the outputs from the L2545 trial. Figure C. 3 shows the outputs from the L2568 trial.

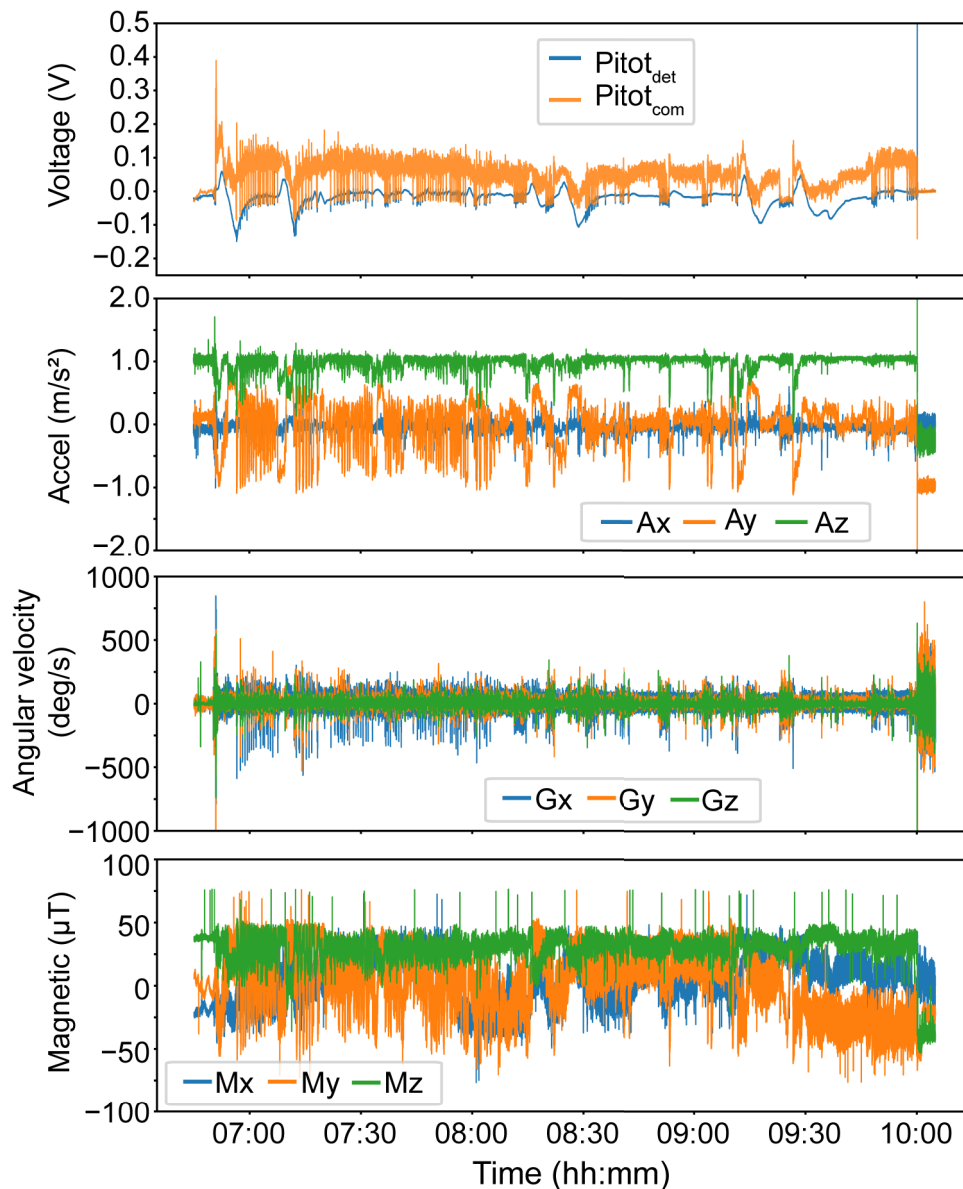


Fig. C. 2 Raw sensor data from the L2545 trial.

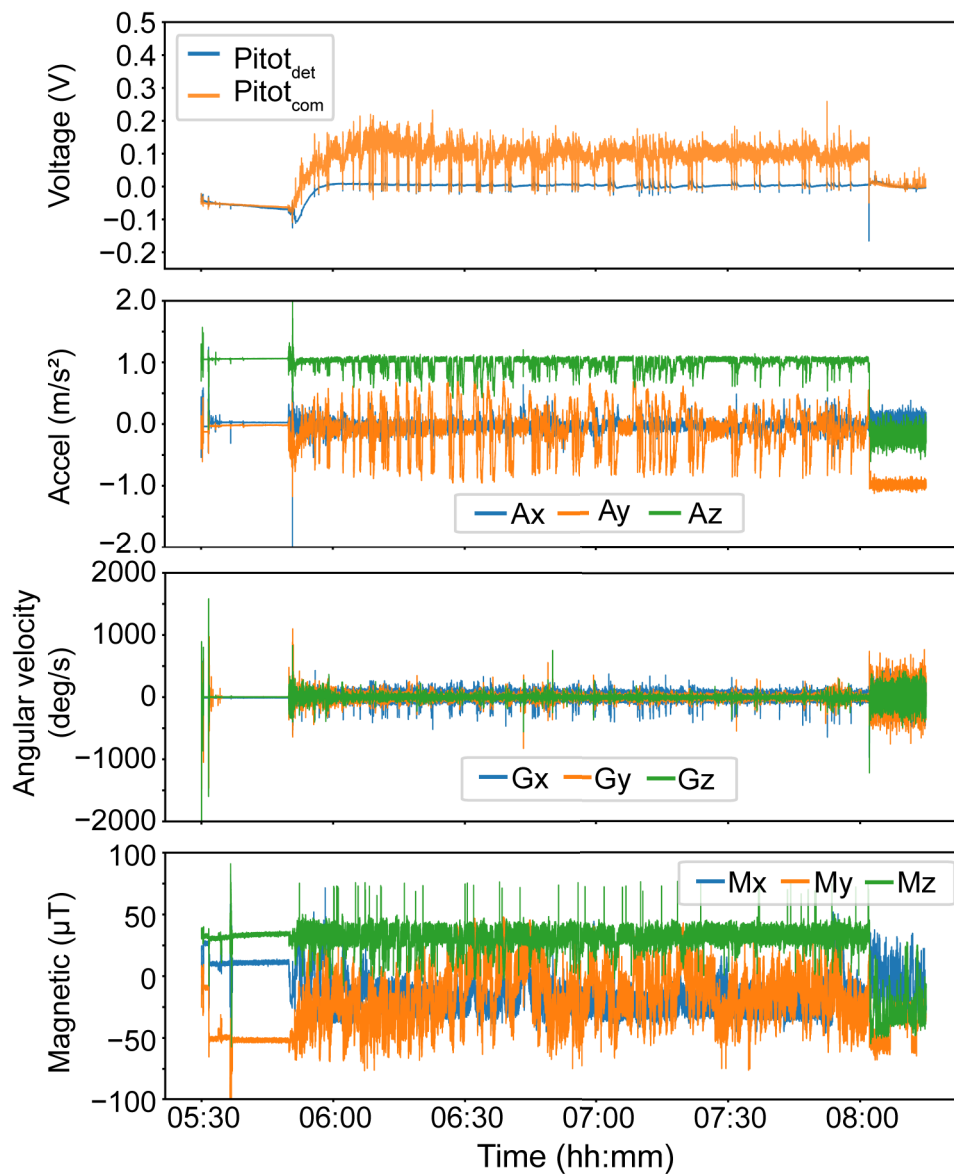


Fig. C. 3 Raw sensor data from the L2568 trial.