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Author	鬼頭, 史城(Kito, Fumiki)
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Report on the Investigations of Vibration of Penstocks of Hydro-Electric Power Plants

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Fumiki KITO*

Abstract

During the past two years, the Author has made investigations on vibration of penstocks of several hydro-electric power plants. In this paper, abridged report on the result of this study is given. Also, comparison between observed values of freq. of vibration and theoretical values of natural freq. of vibration is made.

I. Introduction

During the past two years the Author has made investigations on vibration of penstocks of several hydro-electric power plants. Some of them has been done as a part of work of water-turbine research committee of Society of Mechanical Engineers Japan, of which the Author is a member of the committee. The rest was done by the Author in responce to the request of Electric Power Companies. On the other hand, the Author has made a theoretical study on vibration of penstocks and has obtained a formula giving natural frequency of penstock, in which the effect of hydro-static pressure and the effect of virtual mass of water contained inside the penstock is taken into account, together with the elasticity of the pipe wall. In what follows, comparison between the observed value of frequency of vibration with theoretical natural frequency, together with some considerations about the cause of vibrations, will be given.

II. General Informations about Hydro-electric Power Plants Investigated

Among more than ten hydro-electric power plants, about which the vibration of penstock has been investigated, the five plants are here taken up, because vibration of penstocks of these plants has been considered to be in state of resonance. Some items of these power plants are shown in Table 1.

Table 1. General items of power plants about which the investigation was carried out

No.	Name of power plant	River	Output kw per unit	No. of rev. ∕min.	Head m
1	Ikezirigawa	Ikeziri	Delivery 2.4 m^3/sec.	900/750	85
2	Utsuno	Fuzi	1800	450/375	30

* Dr. Eng., Prof. at Keio University

3	Ohma	Ohi	8600	360/300	78
4	Miho	Tenryu (tributary)	3200	600/500	95
5	Kumanogawa No. 1	Zinzu (tributary)	1940	720	102

Generator cycles / sec.	Type of water turbine	No. of blades of runner	No. of blades of guide vanes	Manufacturer of water turbine
60/50	Horiz. shaft pumping up	9	10	D
60/50	Horiz. Frontal	14	14	B
60/50	Vertical Francis	15	20	D
60/50	Horiz. Francis	15	16	H
60	Horiz. Francis	15	16	H

General items of penstocks of these power plants are as shown in Table 2. The values in this table refer to that part of the penstock where the vibration was most prominent and observation was made. The span length is the length of that part of the penstock measured from one anchor block to the next anchor block. The mean head means the mean value of the hydro-static head of that one span of the penstock.

Table 2. General items of the penstocks investigated

No.	Mean dia. m.	Wall thickness mm.	Mean head m.	Span length m.	General location
1	1.50	6.0	18	38	Uppermost
2	2.27	9.5	9.7	29	Upper part
3	2.42	9.0	27 - 30	30	"
4	1.49	9.5	62	45	Middle lower part
5	0.90	7.0	15	53	Upper part
5a	0.90	12.0	90	23	Lower part

III. Observed Results

Magnitudes of amplitude and frequency of vibration as obtained by our observation are given in Table 3. General arrangements of some penstocks investigated are shown in Figs. 7 to 9. In Figs. 1 to 6, theoretical values of natural freq. of vibration are shown as graphs, the mean hydro-static head of the penstock being taken as abscicca and the ordinates being taken as freq. of vibration per sec. They were obtained by calculation of the following formula: —

$$f=\frac{1}{2\pi r}\sqrt{\frac{Eg}{\gamma}}\cdot\frac{1}{\sqrt{1+\varepsilon}}\cdot\frac{1}{n\sqrt{n^2+1}}\cdot\sqrt{K^4+\frac{n^4(n^2-1)^2}{(1-\sigma^2)}\xi-\frac{(n^2-1)(n^2+K^2)^2}{(1-\sigma^2)}\eta}$$

where

f = frequency per sec. of natural vibration of cylindrical shell

r = radius of " " cm

E = Young's modulus of wall material kg/cm^2

σ = Poisson's ratio of "

g = gravity const. (9.8 m/sec².)

n = a whole number, $\cos n\theta$ giving the mode of vibration

$K=\frac{\pi}{2}\left(\frac{r}{l}\right)$

l = length of a span of penstock cm

$\eta=\frac{qr}{2Eh}(1-\sigma^2)$ = peripheral contraction

$\xi=h^2/(3r^2)$

h = half the thickness of the wall cm

ε = a factor giving the effect of virtual mass of water contained in the shell

$=\frac{\text{density of water}}{\text{density of wall material}}\cdot\frac{r}{h}\cdot\alpha\cdot\frac{n^2}{n^2+1}$

(α may be taken equal to $1/n$, at least for practical purposes.)

q = mean pressure (in kg/cm^2) of hydro-static head of water.

Table 3. Observed values of vibration amplitude and frequency

	Vibration amplitude mm	Vibration frequency/sec.	Vibrometer used
1	2	6.7	Cambridge vibrograph
2	2.0 0.2	6.2(at 50 cycles) 7.3(at 60 cycles)	Hand vibrograph(Akashi)
3	14.0	4.2	Vibrograph for transmisson line use
4	0.04	140	Hand vibrograph
5		180	Osillograph

IV. Some Remarks on Observed Results

The penstock of No. 1 Power Plant, (Ikezirigawa), the vibration of which we have investigated, belonged to a pumping-up set of the plant. Its observed no. of vibrations per sec. was different either from the value of (no. of rev./sec. of the impeller) or (no. of rev./sec. × no. of blades of impeller). It was considered that a kind of surging phenomena occurring inside the pump (the impeller being of twin type) is the source of vibration of the penstock. When pressure wave of vibration comes up rising through the penstock, one span of it at which the freq. of natural vibration is sufficiently near to that of exciting pressure wave, will make severe vibration of resonance state. But in the present case of this plant, at one span whith lies directly below that span making severe vibration, there was felt no conceivable vibration, in spite of the fact that these two spans had almost the same dimension. On the other hand, making theoretical investigation, it was found out that the natural freq. depend considerably upon the mean static head

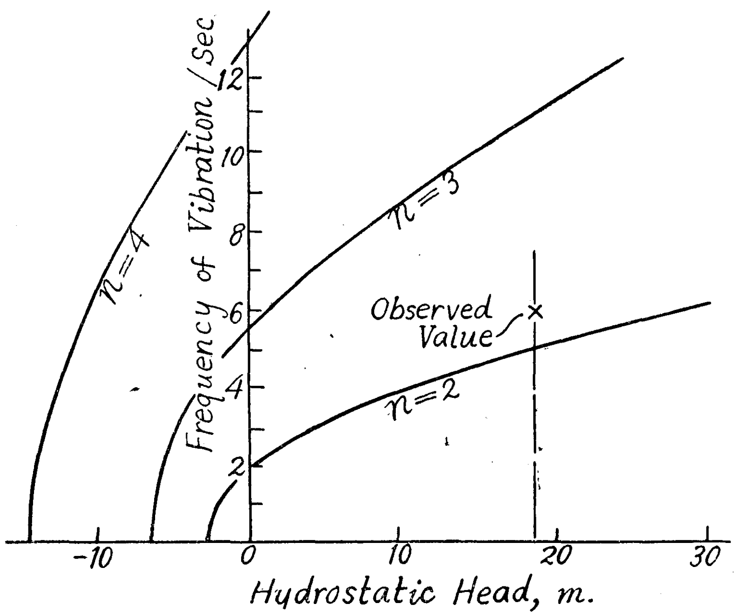

Fig. 1. Vibration freq. for penstock of Ikezirigawa power station (pumping up plant)

of water, together with other quantities. Thus the above mentioned phenomena could be explained, since the two consecutive spans had a difference of altitude of more than 10 m.

In the case of No. 2 Power Plant, freq. of vibration of penstock just coincided with no. of rev. per sec, of turbine runner, at 50 cycle operation. Thus the cause of vibration was to be attributed to action of runner of water turbine.

This being in a state of resonance, if no. of freq. per sec. of exciting force arising at the runner was possible to make to change, the state of resonance could be avoided. In order to confirm this inference, 60 cycle operation of this plant was tried. In that case of 60 cycle operation, it was found that no conceivable vibration was felt anywhere at the penstock. (Note: In Japan, there are several power plants which can operate either at 50 or 60 cycles.)

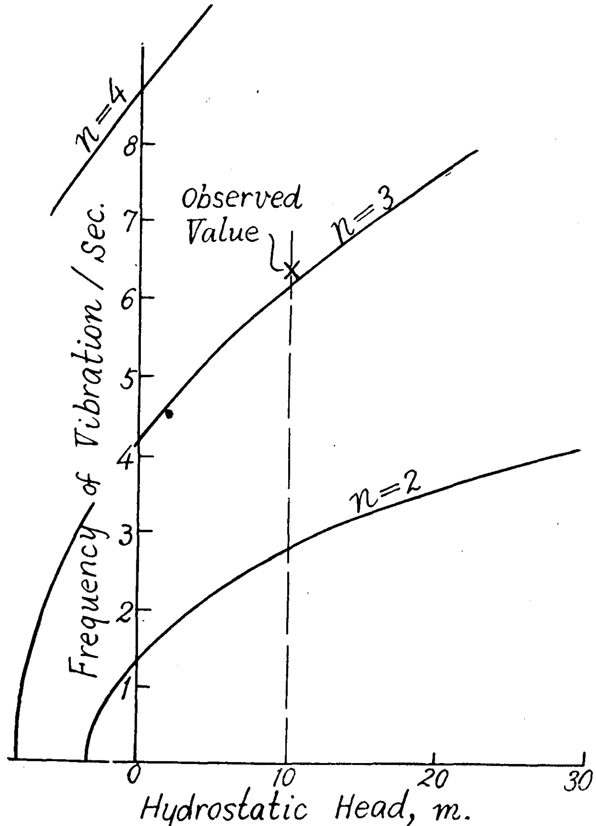

Fig. 2.
Vibration freq. for penstock of Utsuno power station

In the case of No. 3 Power Plant, there appeared tremendous vibration of amplitude amounting to 14 mm. extending to a period of about one month, and after an elapse of that period, the vibration amplitude reduced gradually. The origin of vibration is sought in draft tube of the water tubine, but accurate cause of this phenomenon of tremendous vibration is yet to be investigated.

In the case of No. 4 and No. 5 Power Plants, the penstock emitted humming or

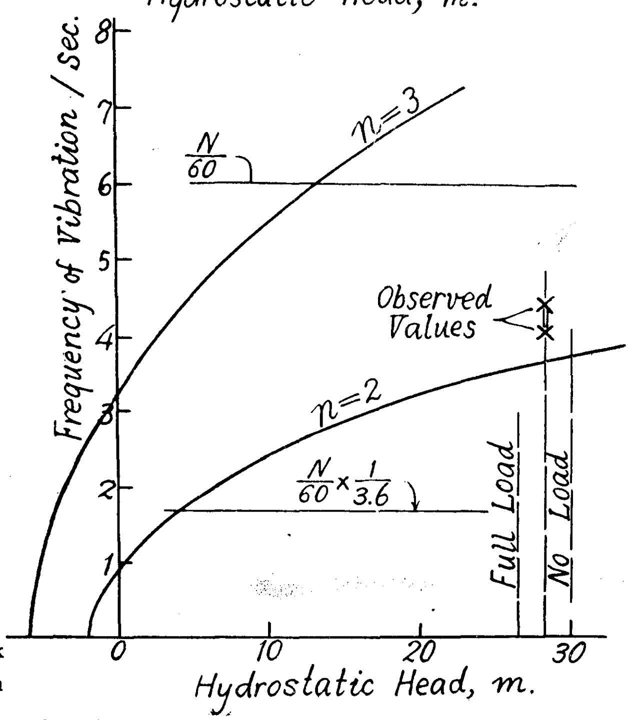

Fig. 3.
Vibration freq. of penstock of Ohma ,power station

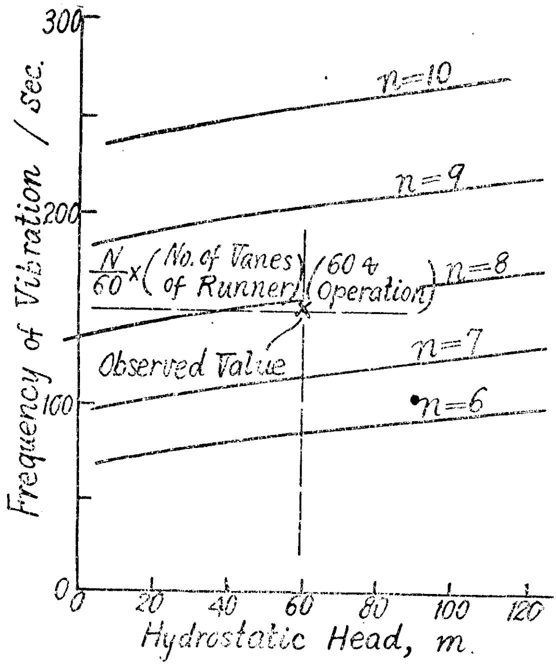

Fig. 4. Vibration freq. of penstock of Miho power station

booming sound, and the freq. of this sound (that is. of vibration of penstock) coincided with (number of rev./sec. of runner × no. of blades of runner). At No. 5 Plant, when operated at normal freq. of 60 cycles per sec., one part of the penstock emitted the sound, while when operated at 57 cycles per sec., the other one span of the penstock began to emit the sound.

In all of the above mentioned five cases, observed freq. of vibration of penstock fairly coincided with the theoretical values of natural freq. of vibration, showing that the state of resonance are nearly occurring.

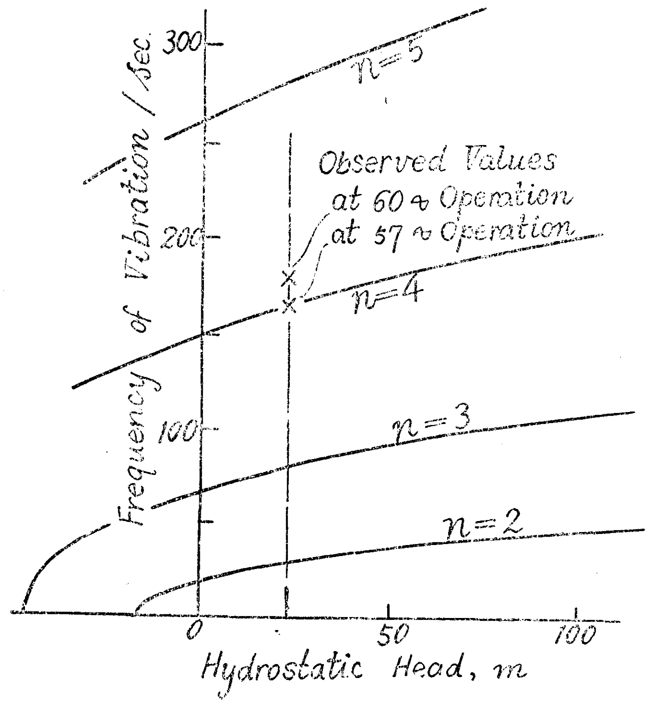

Fig. 5. Vibration freq. of penstock of Kumanogawa No. 1 Power Station (upper part)

This being so, yet such a remarkable amplitude of vibration (or intensity of sound) as observed by us could not have taken place, if the sources of pressure variation were not sufficiently strong enough. So that the most effective remedy for preventing the vibrations of penstocks of these plants would consist in cancelling the source of pressure variation which originate at some part of the water turbine. But, if this could not be done so effectively, the next preventive is to alter the natural freq. of vibration of the part in question, probably by means of stiffener rings etc. But fuller discussion about these matters is omitted here, the present paper being a report on investgations of some power plants at which the vibration of penstock were remarkable.

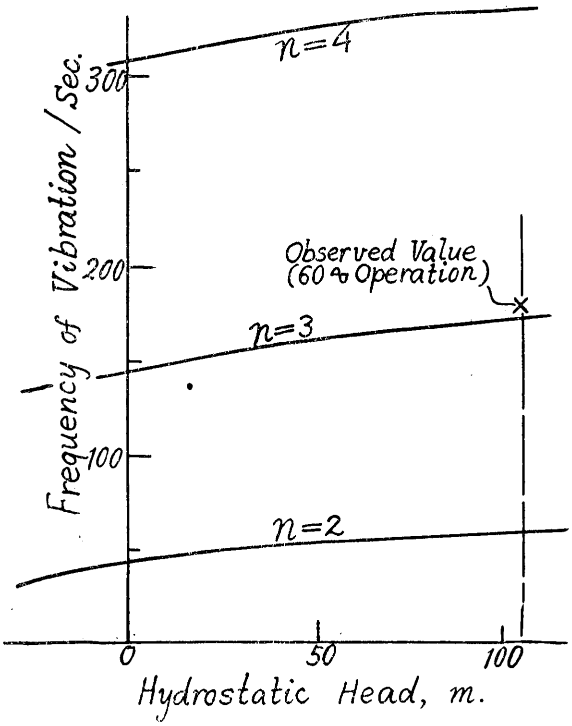

Fig. 6. Vibration freq. of penstock of Kumanogawa No. 1 Power Station (lower part)

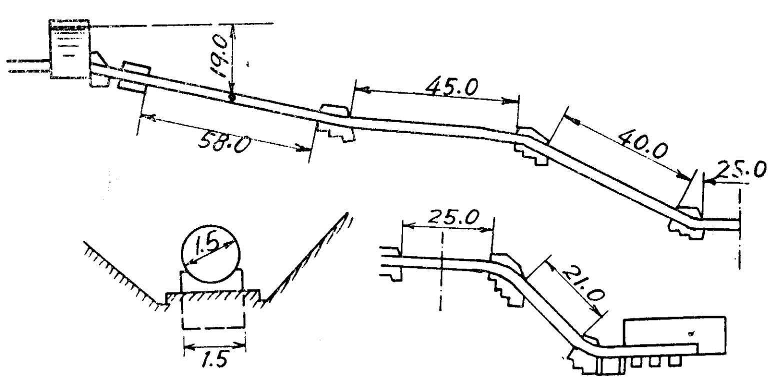

Fig. 7. Arrangement of penstock of Ikezirigawa Power Station (pumping-up plant)

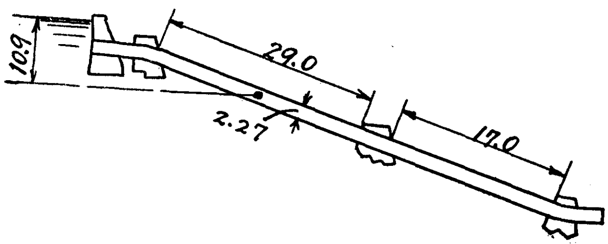

Fig. 8. Arrangement of penstock of Utsuno Power Station

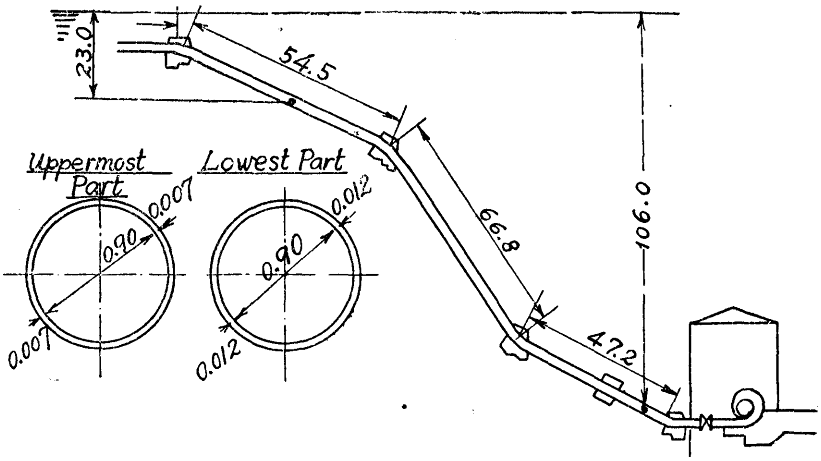

Fig. 9. Arrangement of penstock of Kumanogawa No. 1 Power Station