Bayesian inference on structures using differential evolution adaptive Metropolis algorithm considering measurement uncertainty

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Abstract

Recent years witness the fast advancement of system identification which is widely applied in civil engineering such as health monitoring and non-destructive damage detection. Because of its wide applicability, many identification methods have been studied for various purposes and a wide range of analytical methods exist for linear and nonlinear structural system. Many common among these methods are based on an inverse problem using heuristic algorithms such as genetic algorithms (GAs), particle swarm optimization (PSO), and differential evolution (DE) algorithm, etc.. The structural identification is formulated as an inverse problem which is concerned with the derivation of mathematical models from experimental measured data. Given the measured response, a set of candidate models are built up and choosing the optimal one based on a predefined fitness by which the residual error, measuring the fitness between the measure output of the actual system and the response of simulated model, is minimized. However, these heuristic algorithms based identification studies are all treated as a deterministic issue, which inevitably obtain a biased solution if taking uncertainties such as measurement noise or model error into account.

Bayesian posterior density estimation is a classic method to quantify the uncertainty based on a probabilistic model that is defined by stochastic model classes. The model set is a class of parameterized probability models, each of which predicts the behavior of the actual system with a prior probability density. In Bayesian estimation, the identification problem is to infer the plausibility of each candidate model with a posterior density conditioned by the measured data; it is not a quest for the true structural parameters. The posterior density of structural parameters indicates how plausible each model is when considering the uncertainty of predictive errors.

However, it is usually difficult for the Bayesian identification method to obtain the posterior probability density of parameters conditioned by the measured response, because its calculation often requires an evaluation of multidimensional integrals that cannot be easily calculated. The Markov chain Monte Carlo (MCMC) method is a widespread medium for Bayesian inference but its convergence is often slow. It is known that because of the noise corrupted system response, the surface of the residual error lies in a hyper-surface of a multi-dimensional parametric space, which will cause the convergence of the Markov chains difficult to be approached. Moreover, most of these existing MCMC based identification methods use a single Markov Chain, which may be inefficient and unreliable when the surface of posterior probability density function is complicated.

The purpose of this study is to surmount this difficulty that solving the convergence of the Markov chains when the Bayesian inference framework is applied in the structural system. In this thesis, the ability of heuristic algorithms to search for the global optimum will have to be merged with the advantage of the Metropolis-Hasting (MH) algorithm for inferring the posterior probability. We present an improved differential evolution adaptive Metropolis-Hasting algorithm (IDREAM) strategy to estimate the posterior density of structural parameters. The main benefit of IDREAM is its efficient MCMC simulation through its use of the adaptive Metropolis (AM) method with a mutation strategy for ensuring quick convergence and robust solutions. Its effectiveness was demonstrated in simulations on identifying the structural parameters with limited output data and noise polluted measurements.

Moreover, the estimator (maximum a posterior estimator, MAP) of the Bayesian inference is inevitably biased, which may be attributed to the surface of the posterior probability density owning to multiple local optima. Another purpose of this thesis is to improve the accuracy of the MAP estimator. To solve this problem, which is defined as the “equifinality” of Bayesian inference, a two-step Bayesian identification method is proposed. In step 1, the formal likelihood measure is used to obtain the MAP estimator; in step 2, the first-two derivative of the log-likelihood measure is proposed

to formulate a new fitness function to improve the accuracy of the estimator. The benefit of the proposal was demonstrated in simulations on identifying the structural parameters with limited output data and considering noise polluted measurements. Finally, the conclusion is given that the proposal could not only improve the accuracy of the MAP estimator but also reduce the standard deviation (uncertain range) of the posterior samples. The identification using the proposed method is applied into the measured data of a shake-table experiment, called the E-Defense. Comparison with the results that using the existing methods show that our proposed methodology is indeed a powerful tool for the Bayesian identification of building structures.