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A bi-level approximation tool for the computation of FRFs in stochastic dynamic systems

Tanmoy Chatterjee, Souvik Chakraborty *, Rajib Chowdhury

Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee 247667, India

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ABSTRACT

Frequency response functions (FRFs) are considered to be a significant aspect in the evaluation of structural response subjected to dynamic loading. A new approach, referred to as the hybrid polynomial correlated function expansion (H-PCFE) has been developed for predicting the natural frequencies and the FRF of stochastic dynamical systems. H-PCFE has been developed by incorporating the advantages of two available techniques namely, PCFE and Gaussian process (GP) modeling. These two methods are coupled in such a way that PCFE handles the global behavior of the model using a set of component functions and GP interpolates local variations as a function of the sample points, performing as a two level approximation. Implementation of the proposed approach for stochastic dynamic problems has been demonstrated with four problems. The main focus of this study lies in the prediction of FRFs. The efficiency and accuracy of H-PCFE to compute FRFs of stochastic dynamic systems is assessed by a comparison with direct Monte Carlo simulation (MCS). Excellent results in terms of accuracy and computational effort obtained makes the proposed methodology potential for application in large scale structural applications.

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1. Introduction

Frequency response function (FRF) matrix is a fundamental quantity of interest in evaluating the structural response over a frequency band. FRF matrix has been employed in many areas of research such as model updating [1], vibration control [2,3], system identification [4] and optimization [5] in the past. It includes not only the resonant frequencies but also the amplitudes of dynamic responses under unit excitations. Generally, it has been observed that the first few natural frequencies of various structural systems are well separated. Their contribution seems to be very prominent in the response and hence, are essential for the structural analysis under dynamic excitation.

The consideration of uncertainties is indispensable in carrying out the dynamic analysis of a structure. Increased parametric sensitivity of the structural dynamic response can be observed due to variations, such as parametric variation in density, Young's modulus or error in the model of damping etc. [6]. A state-of-the-art report accounting uncertainties in structural dynamics can be found in [7]. The source of variation in the FRFs lies in the uncertainty in input parameter space and unknown mechanisms of the structure.

* Corresponding author. Mobile: +91 9720450402.
E-mail addresses: tanmoydce88@gmail.com (T. Chatterjee), csouvik41@gmail.com (S. Chakraborty), rajibfce@iitr.ac.in (R. Chowdhury).

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The most popular method for uncertainty quantification is the direct Monte Carlo simulation (MCS) [8–11]. This is a straightforward approach, involving deterministic response evaluation at random input samples. It serves as a benchmark solution of systems involving uncertain parameters and is used for validation of new methods. However, MCS can prove to be computationally intensive. In order to overcome the problem of computational effort required, the concept of different approximation/surrogate schemes have been developed.

Surrogate approach decreases simulation time by approximating the underlying computational model in a sample space [12–15]. The widely used surrogate procedures are least squares approximation [16], moving least square [17,18], polynomial chaos expansion [19], high dimensional model representation [20], Kriging [21] and radial basis functions [22]. A review of various procedures of this kind can be found in [23–25].

In this paper, an attempt has been made to predict the FRFs of stochastic dynamic systems using a novel technique, referred to as hybrid polynomial correlated function approximation (H-PCFE). The proposed approach has been applied in four examples related to stochastic dynamic systems. The results obtained using H-PCFE have been validated by comparison with that of direct MCS. A comparison of FRF envelope based on extreme values of realizations and the mean frequencies or, eigenvalues using H-PCFE and MCS have also been presented.

The paper has been organized in the following sequence. The computational procedure for the evaluation of FRF of dynamic systems have been explained in Section 2. In Section 3, brief concepts of PCFE and Gaussian process (GP) modeling has been presented, which essentially serves as the theory behind the implementation of bi-level approximation tool. Section 4 presents the formulation of the proposed methodology. In Section 5, four examples relating to structural stochastic dynamics has been studied in order to determine the applicability and efficiency of H-PCFE. Finally, conclusion has been drawn by highlighting advantageous features of the proposed methodology.

2. Problem setup

Considering a dynamic system of N degrees of freedom (DOF) subjected to harmonic loading as shown in Fig. 1. The governing differential equation of this system is given as:

$$M\ddot{\mathbf{x}}(t) + C\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{F}(t) \tag{1}$$

Where, mass matrix, damping matrix, stiffness matrix and force vector are represented as:

$$\mathbf{M} = \begin{pmatrix} m_1 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & m_n \end{pmatrix}, \tag{2}$$

$$\mathbf{C} = \begin{pmatrix} C_1 + C_2 & -C_2 & 0 & \cdots & 0 & 0 \\ -C_2 & C_2 + C_3 & -C_3 & \cdots & 0 & 0 \\ 0 & -C_3 & C_3 + C_4 & \ddots & 0 & 0 \\ \vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & 0 & 0 & \ddots & C_{n-1} + C_n & -C_n \\ 0 & 0 & 0 & \cdots & -C_n & C_n \end{pmatrix}, \tag{3}$$

$$\mathbf{K} = \begin{pmatrix} K_1 + K_2 & -K_2 & 0 & \cdots & 0 & 0 \\ -K_2 & K_2 + K_3 & -K_3 & \cdots & 0 & 0 \\ 0 & -K_3 & K_3 + K_4 & \ddots & 0 & 0 \\ \vdots & \vdots & \ddots & \ddots & \ddots & \vdots \\ 0 & 0 & 0 & \ddots & K_{n-1} + K_n & -K_n \\ 0 & 0 & 0 & \cdots & -K_n & K_n \end{pmatrix}, \tag{4}$$

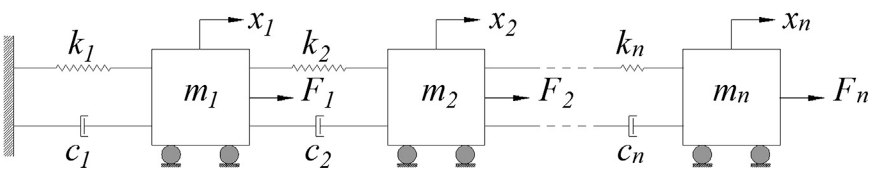

Fig. 1. Mathematical model of dynamic system of N DOFs.

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