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System identification of a composite plate using hybrid response surface methodology and particle swarm optimization in time domain

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ABSTRACT

Material properties of composites are identified using a novel hybrid RSM–PSO method in this paper. Different response surface methodology (RSM) methods and particle swarm optimization (PSO) methods are studied initially on a 4 degrees-of-freedom (4DOF) dynamic system on their performance in terms of speed and accuracy. The best combination is used as a hybrid RSM–PSO method to evaluate the performance on system identification of an orthotropic plate along with a 4DOF dynamic system and an isotropic plate. The novelty of the present paper is to identify the composite plate material properties using RSM methods based on time domain signals, which is not hitherto reported in the literature. Also, whereas previous papers have used full factorial design for system identification, here CCDI is used. The input factors (design variables) are the system parameters which are to be identified and the response (objective function) is error sum-of-square of acceleration response with respect to new test system. The performance of the proposed method is also evaluated with the addition of 5% Gaussian noise to simulate the experimental errors. The system parameters of the orthotropic plate were identified with 0% and 0.25% average prediction error with zero and 5% addition of noise respectively by the proposed hybrid RSM–PSO method. It is also showed a much better performance and robustness to noise addition when compared to the other RSM methods in the literature.

1. Introduction

Composite materials are used increasingly in aerospace, marine and automotive industry because of their useful mechanical properties such as good strength to weight ratio and corrosion resistance [1,2]. The physical properties of composite materials are not isotropic, they have different properties in different directions; and typically in orthotropic in nature [3]. The manufacturing or curing in the laboratory and/or in the industry affects the mechanical properties of the composites; these mechanical properties of the manufactured composites are different than that of the designed properties because of the stochastic process [4]. Hence, measurement of the material properties of the composites efficiently and accurately is the primary concern in the present scenario of research on composites.

The properties of the composites can be determined by direct methods (viz. tensile test, four point bending test) in the laboratory and by the indirect (inverse) methods using the dynamic (vibration) behavior of the composites in the name of parameter identification or system identification. System identification is the development of a mathematical model for a structural system based on its input

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(structural parameters and/or loading conditions) and corresponding output (structural dynamic response) measurements in nondestructive evaluation (NDE) methods. The system identification methods are classified as parametric and nonparametric methods in relation to the estimation theory, and the other classification is frequency domain and time domain based on the analysis of signal information. The various techniques and fundamentals of system identification methods in structural dynamics are given in the review presented by Imai et al. [5].

The system identification methods using vibration measurements in the literature are grouped hereafter for identifying the mechanical properties of the composite plates, Doebling et al. [6] has presented the different literatures on damage identification and health monitoring of structural and mechanical systems including the system identification of composite structures. Pedersen and Frederiksen [7] identified orthotropic material moduli by a combined numerical and experimental approach based on eigen frequencies for a rectangular plate. The numerical identification problem was formulated as an optimization problem with error minimization; the error was calculated between the modal analysis response and the experimental response. Qian et al. [8] presented a method for determining elastic and damping properties of composite laminates by using measured complex eigen frequencies and mode shapes. These parameters were identified by minimizing the error function containing the deviations of eigen values and responses between experiment and analysis. The reliability of the conventional methods, viz. least square method, maximum likelihood method and extended Kalman filter methods is ineffective and they consume more computational power in system identification.

Response surface methodology (RSM) is one of the powerful system identification tools in comparison with conventional methods and it belongs to the family of design of experiments (DOE). Very few studies are reported in the literature on the application of DOE and RSM techniques for system identification of mechanical dynamic systems and composites, and are presented hereafter, Rutherford et al. [9] used response surface methodology to perform parameter identification of simple five degrees-of-freedom (5DOF) system, where the average percentage error was 10% for identifying the single stiffness value and its location using fractional factorial design (9 design points). Fang and Perera [10] have used 2^k factorial design (21 design points) for identifying the multiple damage situations in a simply supported beam with 9% maximum percentage error. Rikards and Chate [11] used numerical-experimental method for identification of the elastic properties of the laminated polymeric composite plate. The experimental data of measured eigen frequencies was used. The five parameters of a transverse isotropic layer were the two Young's moduli (E_1 and $E_2 = E_3$), the shear moduli (G_{12} and G_{13}) and the Poission's ratio ($\upsilon_{12} = \upsilon_{13}$). The advantage of using RSM based methods for system identification is they consume much less computational power as compared to the conventional methods, where as the limitations are the selection of critical factors, the undefined range of influence, the large variations in the factors can mislead the identification process model and finally it cannot guarantee the accuracy.

Particle swarm optimization (PSO) is also widely applied by many researchers for system identification because of its efficient global solution, which is one of the population based search optimization techniques (genetic algorithms, ant colony optimization etc.). The identification process is through the minimization of fitness value formulated based on the error between given system response and the response obtained from the finite element numerical methods for given set of system parameters. The studies reported on the use of optimization methods in system identification of composites are presented in group hereafter, Araujo et al. [12] has characterized the material properties of composite plate specimens using optimization and experimental vibrational data. Chen et al. [13] proposed a parameter identification algorithm for two-dimensional orthotropic material based on inverse problem formulation. The Levenberg–Marquardt method was employed to solve the nonlinear least squares problem with an objective function representing the differences between the measured displacements and those calculated from the scaled boundary finite element method (SBFEM). Garshasbinia and Jame [14] has identified the system parameters of orthotropic plate with 7.09% average percentage error. The orthotropic composite plate is a carbon fiber reinforced epoxy plate made of unidirectional fiber plies with stacking sequence $(0°)_8$ (i.e. eight layered laminate with fiber orientation angle as zero) which was taken from the study reported by Araujo et al. [12]. The limitations of system identification using population based optimization techniques are they need more computational power and work based on random initial guess.

Identification of orthotropic plate material properties using RSM methods is not hitherto reported in the literature, and the conventional methods are inaccurate and consume more computational power for identifying the mechanical properties of the composites because of their complex behavior. Thus there is need of further investigation on system identification of composite plates using an efficient algorithms and/or numerical techniques to provide reliable accuracy with less computational time. In the present investigation on system identification of composites, a novel technique is developed using the benefits of RSM and PSO algorithms and to overcome the limitations of both algorithms. Initially, the RSM is used for system identification and then the identified system parameters are given as input with statistical initial guess to the PSO optimization technique to find the accurate system parameters. The proposed technique named as hybrid RSM–PSO method and it is applied to identify the system parameters of a 4DOF dynamic system and an isotropic plate; then it is extended to orthotropic plate example. The performance of the proposed hybrid RSM–PSO method in comparison with other conventional methods such as CCDC, CCDI, BBD, DD, NNs and GA is studied in terms of accuracy and computational effort for both non-noisy and noisy inputs. Noise with zero mean and 5% white Gaussian noise is added using MATLAB '*randn*' function to simulate the experimental and modeling errors, it is