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Bottom up surrogate based approach for stochastic frequency response analysis of laminated composite plates

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ABSTRACT

This paper presents an efficient uncertainty quantification (UQ) scheme for frequency responses of laminated composite plates. A bottom up surrogate based approach is employed to quantify the variability in free vibration responses of composite cantilever plates due to uncertainty in ply orientation angle, elastic modulus and mass density. The finite element method is employed incorporating effects of transverse shear deformation based on Mindlin's theory in conjunction with a random variable approach. Parametric studies are carried out to determine the stochastic frequency response functions (SFRF) along with stochastic natural frequencies and modeshapes. In this study, a surrogate based approach using General High Dimensional Model Representations (GHDMR) is employed for achieving computational efficiency in quantifying uncertainty. Subsequently the effect of noise is investigated in GHDMR based UQ algorithm. This paper also presents an uncertainty quantification scheme using commercial finite element software (ANSYS) and thereby comparative results of stochastic natural frequencies are furnished for UQ using GHDMR approach and ANSYS.

1. Introduction

Managing the risk of uncertainties associated with composite structures has become increasingly important for aircraft and spacecraft industries in recent years with advancement in lightweight designs. The extensive application of such materials not only in aerospace industry, but also in civil, mechanical and marine structures, has prompted many researchers to analyze its performance in depth. The prime reasons of popularity of composites are because of its light-weight, cost-effectiveness, high specific stiffness and application specific tailorable stiffness in different directions. In general, uncertainties are broadly classified into three categories, namely aleatoric (due to variability in the system parameters), epistemic (due to lack of knowledge of the system) and prejudicial (due to absence of variability characterization). The total uncertainty of a system is the combination of these three types of uncertainties. The performance of composite structures is influenced by quality control procedures, as well as operating conditions and environmental effects. It may be observed that there can be uncertainties in input forces, system description, model calibration and computation. Laminated composite plates are typically made from different combinations of polymer prepregs. In the serial production of a composite plate, any small changes in fibre orientation angle and differences in bonding of layers may affect critical responses such as modal vibration characteristics of the composite structure. New aircraft developments (e.g., reusable launch vehicle, high-speed civil transport) are departing dramatically from traditional environments. Application of historical uneconomic uncertainty factors may not be sufficient to provide adequate safety. Conversely, the trend to design for all possible unfavorable events occurring simultaneously could produce an unacceptable dynamic response. Moreover composite materials have more intrinsic variables than metals due to their heterogeneity and are subjected to more manufacturing process sources of variation. For composite materials, the properties of constituent material vary statistically due to lack of precision and accuracy to maintain the exact properties for each layer of the laminate. Hence the uncertainties incurred during manufacturing process are due to the misalignment of ply-orientation, intralaminate voids, incomplete curing of resin, excess resin between plies, excess matrix voids and porosity resulting from machine, human and process inaccuracy. As a result, free vibration responses of such laminated composite shells show volatility from its deterministic

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Nomenclature

L, b, h	length, width and thickness of composite plate, respectively
E_1, E_2	elastic moduli along 1 and 2 axes
G_{12}, G_{13}, G_{23}	shear moduli along 1–2, 1–3 and 2–3 planes, respectively
ν	Poisson's ratio
ρ	mass density
$[M]$	global mass matrix
$[C]$	global Coriolis matrix
$[K]$	elastic stiffness matrix
$[K_\sigma]$	geometric stiffness matrix
$[K_R]$	global rotational stiffness matrix
$\{\delta\}$	global displacement vector
ω_n	natural frequency of composite plate
λ	non-dimensional frequency
u_j, v_j, w_j	nodal displacements
θ_x, θ_y	rotation about x and y axes
$\{Q\}$	transverse shear resultants
$[A]$	extension coefficient
$[B]$	bending-extension coupling coefficient
$[D]$	bending stiffness coefficients
$[B']$	strain-displacement matrix
$[D']$	elasticity matrix
$[\rho]$	inertia matrix
$[N]$	shape function matrix
$\{k\}$	curvature vector
$\{N\}$	in-plane stress-resultants
$\{M\}$	moment resultants
$\{\varepsilon\}$	strain vector
η, ξ	local natural coordinates of the element
x, y, z	local coordinate axes (plate coordinate system)
n	number of layers
ω	non-dimensional frequency parameter

mean value. Because of its inherent complexity, laminated composite structures can be difficult to manufacture accurately according to its exact design specification which results undesirable uncertainties in responses. The design and analysis of conventional materials is easier than that of composites because for conventional materials both materials and most geometric properties have either little or well-known variation from their nominal value. In contrast, the same does not hold good for design of structures made of laminated composites. Hence, the uncertainty calibration for structural reliability of such composite structures is essential to ensure operational safety by means of safe as well as economic design. The prime sources of random structural uncertainty considered in this study are material properties and fiber orientation of the individual constituent laminae. Because of the randomness in these input parameters, the mass matrices and the stiffness matrices of the composite structure become stochastic in nature. Thus it causes the statistical variation in the eigenvalues and eigenvectors and subsequently the dynamic response as well. Therefore a realistic analysis of composite laminated plates is presented in this article to quantify the uncertainties in dynamic responses arising from the randomness in the variation of parameters like ply-orientation angle, elastic modulus and mass density. A brief literature review on uncertainty quantification (UQ) of laminated composite plates is presented in the next paragraph.

The free vibration characteristics of laminated composites have been extensively considered in the literature. The pioneering work using finite element method (FEM) in conjunction with laminated composite plates is reviewed by Reddy [1]. The deterministic analyses of free vibration for laminated plate structures, incorporating a wide spectrum of approaches are reported in the open literature [2–8]. The vibration analysis of rectangular laminated composite plates is carried out by Wang et al. [9] employing first order shear deformation theory (FSDT) meshless method while the mesh-free method for static and free vibration analysis of for shear deformable laminated composite plates introduced by Dai et al. [10] and successive investigation carried out by Liu et al. [11]. The uncertain frequency responses in composite plates can be developed primarily due to variabilities in material, geometric laminate parameters, environmental and operational factors. The natural frequencies of composite plates with redial basis function (RBF)-pseudo spectral method studied by Ferreira and Fasshauer [12] while free vibrations of uncertain composite plates via stochastic Rayleigh–Ritz approach by Venini and Mariani [13]. The free vibrations of composite cylindrical panels with random material properties are studied [14–16]. The stochastic analysis of vibration of laminated composites with uncertain random material properties is investigated in [17–18]. There have actually been a good number of studies reported involving stochastic modelling of uncertainties considered in composites structures [19–20]. The natural frequencies and vibration modes of laminated composite plates with arbitrary curvilinear fiber shape paths was investigated by Honda and Narita [21]. Sepahvand et al. [22] studied the stochastic free vibration of orthotropic plates using generalized polynomial chaos expansion. Atamturktura et al. [23] studied the uncertainty quantification in model verification and validation applied to large scale historic masonry monuments while António and Hoffbauer [24] studied uncertainty analysis of composite structures followed based on global sensitivity indices. The random failure analysis of fibre composites designs based on deterministic material properties can overestimate the reliability of composite structures significantly. Not surprisingly, there is continued interest in implementing stochastic concepts in material characterization, in structural response assessment, and in developing rational design and effective utilization procedures for laminated composites. Considered as a broad area within stochastic mechanics, such analyses require the identification of uncertainties and the selection of appropriate techniques for uncertainty propagation up to different modelling scales, depending on the response of interest.

Monte Carlo simulation (MCS) technique in conjunction with FEM is found to be widely used for quantifying uncertainties of laminated composite structures, wherein thousands of finite element simulations are needed to be carried out. Thus this approach is of limited practical value due to its computational intensiveness unless some form of model-based extrapolation can be used to make the method more efficient. In view of above, the present investigation attempts to quantify the uncertainty in free vibration responses of laminated composite plates using a bottom up surrogate based approach, where the computationally expensive finite element model can be effectively replaced by an efficient mathematical model. In this approach the effect of uncertainty (such as ply orientation angle, variation in material and geometric properties etc.) is accounted in the elementary level first and then this effect is propagated towards the global responses via surrogates of the actual finite element model. A generalized high dimensional model representation (GHDMR) [25] is employed for surrogate model formation, wherein diffeomorphic modulation under observable response preserving homotopy (D-MORPH) regression is utilized to ensure the hierarchical orthogonality of high