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Stochastic dynamic stability analysis of composite curved panels subjected to non-uniform partial edge loading

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ABSTRACT

The stochastic dynamic stability analysis of laminated composite curved panels under non-uniform partial edge loading is studied using finite element analysis. The system input parameters are randomized to ascertain the stochastic first buckling load and zone of resonance. Considering the effects of transverse shear deformation and rotary inertia, first order shear deformation theory is used to model the composite doubly curved shells. The stochasticity is introduced in Love's and Donnell's theory considering dynamic and shear deformable theory according to the Sander's first approximation by tracers for doubly curved laminated shells. The moving least square method is employed as a surrogate of the actual finite element model to reduce the computational cost. The results are compared with those available in the literature. Statistical results are presented to show the effects of radius of curvatures, material properties, fibre parameters, and non-uniform load parameters on the stability boundaries.

1. Introduction

The use of composite materials have gained immense popularity over the past few decades for the design of structures in aerospace, automotive, civil and other engineering applications. It has improved the performance and reliability of structural system due to its mechanical advantages of specific modulus and specific strength over monolithic materials, improved fatigue, impact resistance, and design flexibility. Such structures subjected to in-plane periodic forces may lead to parametric resonance because of certain random combinations in the values of uncertain parameters. The instability may occur below the stochastic critical load of the structure under compressive loads over wide ranges of resonance frequencies. Specially the aerospace structures such as skin panels in wings, fuselage, submarine hulls and civil application has practical importance of stability analysis of doubly curved panels/open shells subjected to uncertain non-uniform loading condition. Traditionally, structural analysis is formulated with deterministic behaviour of material properties, loads and other system parameters. However, the real-life structures employed in aerospace, naval, civil, and mechanical applications are always subjected to intrusive uncertainties. The inherent sources of such uncertainties in real structural problems can be due to randomness in material properties, loading conditions, geometric properties and other random input parameters. As an inevitable consequence of the uncertainties in these system parameters, the response of structural system will always exhibit some degree of uncertainty. The traditional deterministic analysis based on an exact reliable model would not help in properly accounting the variation in the response and therefore, the analysis based on deterministic material properties may vary significantly from the real behaviour. The incorporation of randomness of input parameters enables the prediction of the performance variation in the presence of uncertainties and more importantly their sensitivity for targeted testing and quality control. In order to provide useful and accurate information about the safe and reliable design of structures, it is essential to incorporate these uncertainties into account for modelling, design and analysis procedure. The steady development of powerful computational technologies in recent years has led to high-resolution numerical models of real-life engineering structural systems. It is also required to quantify uncertainties and robustness associated with a computational model. Hence, the quantification of uncertainties plays a key role in establishing the credibility of a numerical model. Therefore, the development of an

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efficient mathematical model possessing the capability to quantify the uncertainties present in the structures is extremely essential in order to accurately assess the laminated composite structures.

Structural elements under in-plane periodic forces may undergo unstable transverse vibrations, leading to parametric resonance, due to certain combinations of the values of in-plane load parameters and natural frequency of transverse vibration. Several means of combating parametric resonance such as damping and vibration isolation may be inadequate and sometimes dangerous with reverse results (Evan-Iwanowski, 1965). A number of catastrophic incidents can be traced to parametric instability and is often studied in the spectrum of determination of natural frequency and critical load of structures. The stochasticity in the measurement of natural frequencies, critical load and ultimately the excitation frequencies during parametric resonance are of great technical importance in studying the instability behaviour of dynamic systems. Many authors addressed the parametric instability characteristics of laminated composite flat panel subjected to uniform loads (Iwatsubo et al., 1973; Moorthy and Reddy, 1990; Chen and Yang, 1990; Patel et al., 2009; Kochmann and Drugan, 2009; Singha and Daripa, 2009; Kim et al., 2013). In contrast, Bolotin (1964) and Yao (1965) studied the parametric resonance subjected to periodic loads. Stochastic principal parametric resonance of composite laminated beam is numerically investigated by Lan et al. (2014). The influences of transverse shear (Andrzej et al., 2011) and rotary inertia (Ratko et al., 2012) on dynamic instability are studied for cross-ply laminated plates. The parametric dynamic stability analysis is numerically investigated for composite beam (Meng-Kao and Yao, 2004), plates (Dey and Singha, 2006) or shells (Bert and Birman, 1988) and stiffened panel (Sepe et al., 2016). Further studies are also carried out for modelling mesoscopic volume fraction stochastic fluctuations in fiber reinforced composites (Guilleminot et al., 2008) and for parametric instability of graphite-epoxy composite beams under excitation (Yeh and Kuo, 2004). Free vibration and dynamic stability analysis of rotating thin-walled composite beams (Saraviaa et al., 2011) and nonlinear thermal stability of eccentrically stiffened functionally graded truncated conical shells are recently reported (Duc and Cong, 2015). In contrast, many numerical investigations are carried out using response surface methods such as moving least square (MLS) method and other methods for structural analysis (Choi et al., 2004; Wu et al., 2005; Park and Grandhi, 2014; Shu et al., 2007; Kang et al., 2010). Some researchers studied specifically on the moving least squares (MLS) approximation for the regression analysis (Lancaster and Salkauskas, 1981; Breitkpf et al., 2005) instead of the conventional least squares (LS) approximation in conjunction to traditional response surface method (RSM) techniques (Mukhopadhyay et al., 2015; Dey et al., 2015a). Several studies are carried out on uncertainty quantification for dynamic response of structures including different surrogate based analyses of composite beams, plates and shells (Sarrouy et al., 2013; Dey et al., 2015b,c,d, 2016a,b,c,d,e,f, 2018; Mukhopadhyay et al., 2016; Naskar et al., 2017). Few articles have reported the critical comparative assessment of different surrogate models for their performance in dynamic analyses of composite laminates (Dey et al., 2017; Mukhopadhyay et al., 2017).

To the best of authors' knowledge, no literature is reported on uncertainty quantification of parametric instability of doubly curved composite shells. The application of stochastic non-uniform loading on the structural component can significantly alter the global dynamic quantities of interests such as resonance frequency, buckling loads and dynamic stability region (DSR). Thus it is imperative to consider the effect of stochasticity for robust analysis, design and control of the system. The application of moving least square method in this realm as a computationally efficient surrogate of expensive finite element method has not been investigated yet. Even though the perturbation method is an efficient way of stochastic analysis for relatively simpler structures (Kaminski, 2013; Gadade et al., 2016), this intrusive method can be mathematically quite cumbersome for complex problems like stochastic dynamic stability analysis of composite laminates. The main drawback of this method is that it can obtain only the statistical moments (not the entire probability distribution) of the stochastic output quantity of interest. If the nature of the output distribution is known to be Gaussian, the probability distribution can be obtained using the first two moments. However, the nature of distribution of the output parameter may not be known a priori in most engineering problems. Monte Carlo simulation, on the other hand, can obtain the entire probabilistic description of the stochastic output parameter. The main lacuna of traditional Monte Carlo simulation is its computational intensiveness. A surrogate based Monte Carlo simulation approach, as followed in this paper, allows us to quantify the probabilistic descriptions in a computationally efficient manner. In the present study, a moving least square based approach is employed in conjunction with finite element formulation to figure out the random eigenvalue problem and quantify the probabilistic characteristics of the responses related to dynamic stability of composite laminates. The numerical results are shown for first random buckling load and stochastic fundamental resonance frequencies with individual and combined variation of the stochastic input parameters.

2. Importance of stochastic dynamic stability analysis in composite laminates

Engineering structures are often subjected to periodic loads. For examples, aerospace structures are subjected to wind load, rotating machine systems are usually exerted a periodic unbalanced inertia force, bridges are frequently subjected to the cyclic loads from the running vehicles, marine structures are always suffered the periodic wave forces etc. Structural components subjected to in-plane periodic forces undergo an unstable dynamic response known as dynamic instability or parametric instability or parametric resonance. Parametric resonance, may occur for certain combinations of natural frequency of transverse vibration, the frequency of the in-plane forcing functions and the magnitude of the in-plane load. A number of flight accidents can be traced due to parametric instability of structures. In comparison to the principal resonance, the parametric instability can take place not only at a single excitation frequency but even for small excitation amplitudes and combination of frequencies. The difference between good and bad vibration regimes of a structure under in-plane periodic loads can be found from dynamic instability region (DIR) spectra. The computation of these spectra is usually studied in term of natural frequencies and static buckling loads. The parametric instability has a catastrophic effect on structures near critical regions of parametric instability. Hence, the parametric resonance characteristics of structures are of great technical importance for understanding the dynamic characteristics under periodic loads.

As discussed in the preceding paragraph, structures are subjected to dynamic loads more often than static loads. Dynamic load means the load varies with time. Periodic loading is one type of dynamic loading. This type of load occurs in repeated periods or cycles like sine and cosine functions. Structures subjected to in-plane periodic loads can be expressed in the form as suggested by Bolotin (1964): $P(t) = P_s + P_t \cos\Omega t$, where P_s is the static portion of $P(t)$, P_t is the amplitude of the dynamic portion of $P(t)$ and Ω is the frequency of excitation. It can be noted here that the quantities P_s, P_t, Ω possess random values in practical systems. This, in turn, makes the time varying periodic load $P(t)$ random in nature. The