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Stochastic finite element method for random harmonic analysis of composite plates with uncertain modal damping parameters

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ABSTRACT

Damping parameters of fiber-reinforced composite possess significant uncertainty due to the structural complexity of such materials. Considering the parameters as random variables, this paper uses the generalized polynomial chaos (gPC) expansion to capture the uncertainty in the damping and frequency response function of composite plate structures. A spectral stochastic finite element formulation for damped vibration analysis of laminate plates is employed. Experimental modal data for samples of plates is used to identify and realize the range and probability distributions of uncertain damping parameters. The constructed gPC expansions for the uncertain parameters are used as inputs to a deterministic finite element model to realize random frequency responses on a few numbers of collocation points generated in random space. The realizations then are employed to estimate the unknown deterministic functions of the gPC expansion approximating the responses. Employing modal superposition method to solve harmonic analysis problem yields an efficient sparse gPC expansion representing the responses. The results show while the responses are influenced by the damping uncertainties at the mid and high frequency ranges, the impact in low frequency modes can be safely ignored. Utilizing a few random collocation points, the method indicates also a very good agreement compared to the sampling-based Monte Carlo simulations with large number of realizations. As the deterministic finite element model serves as black-box solver, the procedure can be efficiently adopted to complex structural systems with uncertain parameters in terms of computational time.

1. Introduction

The high strength to weight of fiber-reinforced composite (FRC) makes them ideal for weight reduction and consequently energy saving in many industries. This is, in the most cases, in contrast to the optimal vibrational behavior of the structures made from such materials owing to the fact that achieving high damping is mostly coupled with low stiffness and vice versa. Damping is mainly effective in the range of vibrational resonances where the structural vibrations and structural borne sound power transmission become critical. Therefore, accurate prediction of the modal damping is a critical issue in proper designing of FRC structures.

Unlike dynamical properties such as mass and stiffness, the structural damping prediction is often the most difficult

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process due to the complicated damping mechanism and related inherent uncertainties [1]. Due to the viscoelastic properties of the polymeric matrix, the damping of the FRC can be several orders higher than the conventional materials. However, increasing the matrix volume has contrast impact on the structure stiffness and strength. It is also shown that the damping properties of the FRC increase as the matrix volume increased, reaching an almost constant volume of 60%, cf. [2–4]. Thermoplastic polymers exhibit high damping levels compared to thermosets though the former show high viscosity even at high processing temperatures. The ply orientations and stacking sequences exhibit important impact on the damping of FRC. It is shown that damping parameters of the FRC structures depend on fiber volume content, fiber orientation as well as stacking sequence resulting in non-linear dependencies [5]. As a general rule, any orientations and stacking combinations which maximize the shear stress components lead to higher order level of damping [6,7].

Damping modeling in structural dynamics is still a challenging issue. Various damping models have been introduced in this regards, cf. [8] for instance. Accordingly, in recent decades, a variety of mathematical, numerical, experimental and mixed models have been developed to identify the FRC damping parameters. A comprehensive review on the available literature on damping in composite materials using analytical, numerical and experimental methods is given in [9]. A straightforward way to represent the FRC damping is to use linear parametric viscoelastic models such as Kelvin-Voigt and Maxwell [10]. Though, such models require a few parameters to represent the damping, they fail to fully capture the real mechanism of the energy dissipation. The Prony series is an improved method to overcome some drawbacks of the simple viscoelastic models, nonetheless, identification of the time constants enforced large numbers of experimental tests. The numerical models based on the complex modulus are the most common method for damping prediction of the FRC structures. Here, the constitutive complex material model is employed in which the real part (restoring modulus) denotes the elastic properties and the imaginary part (loss modulus) referring as the descriptive behavior. The loss factor is then defined as the ratio of the real and imaginary parts [11–15]. The method is limited to the finite bandwidth, and consequently, the frequency-dependent loss factors are improved alternatively [16].

Various analytical and numerical techniques have been developed based on the strain energy to estimate damping characteristics of the FRC using global or local constitutive equations [17–22] and the laminate theory [2,19,23–25] and combined with the finite element method (FEM) as addressed in [26]. Consequently, the so-called specific damping capacity (SDC) is defined as the ratio of the unit energy absorbed per unit volume per cycle to the maximum strain energy per unit volume in the elastic deformation mode along each principal directions. While SDC gives accurate values for the damping capacity for the principle directions, it yields inaccurate damping for the uncoupled vibration modes [10]. The major advantage is that the interlaminar stresses are included in the prediction process. This advantage, however, can be ignored for thin structures. Furthermore, the accuracy of the energy based methods depends on the underlying laminate theory used for description of the mechanics of laminate, e.g. classical laminate theory. A better understanding of the physics underlying the dissipation mechanism of FRC can be addressed by experimental based methods [27,28]. Due to the low relative weight of the FRC test specimens, the classical experimental modal analysis using contact transducers and excitation by shaker yields discrepancies predicted and measured damping values. Non-contact based testing method using laser Vibrometer and impulse hammer is more suitable for in situ testing [29]. In all these analytical, numerical and experimental works damping parameters have been assumed to be deterministic and the associated uncertainties have been ignored.

In spite of the method employing to characterize the damping parameters of FRC structures, it is not easily possible to assign deterministic values for the damping properties of the FRC owing to the fact that they exhibit high structural complexity and possess considerable degrees of uncertainties. These uncertainties result from the varying properties of the individual layers and the way they are connected together [30–34]. Therefore, it is particularly desirable to develop a clear, fast and yet flexible method for the estimation of damping parameters taking into account the associated uncertainty. The uncertain damping parameters may be represented as random variables having an expected mean value and a variation range denoted by the standard deviation [35]. This is, however, true if one makes sure that damping parameters can be estimated as Gaussian random variables. For non-Gaussian uncertain parameters, the whole range of uncertainty cannot be captured only by means of the mean value and the standard deviation. For that reason, in this paper the spectral based method [36] for uncertainty quantification is employed in which the generalized polynomial chaos (gPC) expansion [37–40] plays the major role.

This work uses the gPC expansion for representation of the modal damping parameters of the FRC structures. The optimal higher order expansions are employed to capture the range of damping uncertainty. As the major contribution of the paper, information on the uncertainty range and the probability distributions are obtained from experimental modal tests on 100 samples of FRC plates having identical nominal topology. Moreover, the random frequency response function (rFRF) is represented in implicit form in which a FEM model of the structure is served as deterministic black-box solver. The experimental data is used to construct the gPC expansion for the modal damping of each vibration mode. In such a way, the random damping parameters are realized and the gPC representations are directly combined with the stochastic FEM (SFEM) of the FRC vibration to estimate the rFRF. The rFRF at a typical FEM nodal point is considered as a random process and approximated by means of the gPC expansion with unknown frequency-dependent deterministic functions. A nominal deterministic FEM model of the problem operates as black-box to realize samples of the responses, here the FRF, on a set of collocation points generated in the random space. The modal superposition method is employed to solve harmonic analysis. This yields in an efficient sparse gPC expansion with a few unknown functions representing rFRF. The realizations then are served to estimate the unknown functions. This provides the major advantage to use limited number of realizations to estimate the system responses which normally requires large number of realizations when using the Monte Carlo (MC)