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Material Uncertainty Propagation in Helicopter Nonlinear Aeroelastic Response and Vibration Analysis

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The effect of uncertainty in composite material properties on the nonlinear aeroelastic response and vibratory loads of a four-bladed composite helicopter rotor is studied. The aeroelastic analysis is done using a finite element method in space and time, and the composite cross section is analyzed using a variational asymptotic approach. The effective material properties of composite laminas are first considered as random variables with a coefficient of variation of 5%. The material uncertainty is propagated to cross-sectional stiffness, rotating natural frequencies, aeroelastic response, and vibratory loads of the composite helicopter rotor. The stochastic cross-sectional and aeroelastic analyses are carried out with Monte Carlo simulations. The stochastic stiffness values are scattered up to 15% around the baseline stiffness values and show a Gaussian distribution with a coefficient of variation of about 4%. The uncertainty impact on rotating natural frequencies depends on the level of centrifugal stiffening for different modes. The stochastic rotating natural frequencies indicate a possibility of their coincidence with the integer multiples of rotor speed. The propagation of material uncertainty into aeroelastic response causes large deviations from the baseline predictions and affects the crucial higher harmonics content, which is critical for vibration predictions. The magnitudes of 4/rev vibratory loads show a scattering up to 300% from the baseline value, and their probability density functions show non-Gaussian-type distributions. Further, the uncertainty results for a coefficient of variation of 10% in the material properties are obtained. The uncertainty impact on the aeroelastic response is found to be proportional to the coefficient of variation of the composite material properties.

I. Introduction

THE highly multidisciplinary and complex nature of rotorcraft aeroelasticity has led researchers to focus on improving the fidelity of analytical modeling, developing new solution methods, and validating the aeroelastic results with experimental or flight test data [1–4]. With these advances in computational methods, the predicted aeroelastic performance can still deviate from the actual system response because of the randomness associated with the parameters and operating conditions defined for an aeroelastic analysis. In recent years, much interest has focused on incorporating uncertainties into the aeroelastic analysis [5]. When compared with the research on fixed-wing aircraft [6–10], very few studies have focused on the uncertainty issues involved in rotorcraft aeroelastic analysis and quantification of these uncertainties on its response [11]. However, uncertainty quantification is a key issue in aeroelasticity [5].

Uncertainties can generally be classified as aleatory (random) and epistemic (subjective)[12]. Aleatory uncertainties can be defined as the inherent variations associated with the system parameters or the environment under consideration and are also referred as variabilities, irreducible uncertainties, inherent uncertainties, and stochastic uncertainties. Aleatory uncertainties are generally modeled using a probabilistic description. In structural mechanics, the randomness in mechanical properties such as mass, stiffness, and geometrical imperfections because of fabrication errors or lack of quality controls can be classified as aleatory uncertainties. In the context of aeroelasticity, in addition to structural uncertainty, the randomness in parameters such as wind velocity, lift, and drag coefficients can also be termed as aleatory uncertainties [13,14].

On the other hand, epistemic uncertainty derives from a lack of knowledge or information in any phase of the modeling process and little or no experimental data for a physical parameter. It is also termed as reducible uncertainty, subjective uncertainty, and model-form uncertainty. In structural mechanics, the ignorance of material or geometrical nonlinearity and exclusion of shear deformation in analytical models, definition of failure for a structure, and lack of accurate information about structural damping can be termed as epistemic uncertainties. In aeroelasticity, which is a multiphysics problem, lack of high-fidelity aerodynamic models or unmodeled nonclassical or nonlinear structural effects can be categorized as epistemic. Therefore, a better understanding of the physical process or availability of sufficient data can curtail the epistemic uncertainty of the system. Most current work on rotorcraft aeroelasticity focuses on improved modeling and therefore addresses the reduction of epistemic uncertainty. Corresponding research toward quantifying and reducing the adverse effects of aleatory uncertainty are very limited [11].

Rotorcraft aeroservoelasticity couples the fluid, structure, and control domains. The randomness in the input parameters (aleatory) and the fidelity of mathematical models for analysis (epistemic) in each domain can influence the predicted response. From the structural perspective, composite materials, which are extensively used in today's rotor blades, are a major source of aleatory uncertainty. The macrolevel material properties of a composite lamina depend on the microlevel properties such as fiber and matrix material properties and fabrication variables such as fiber volume ratio, misalignment of fibers leading to fluctuations in ply-angle orientation, variation in ply thickness, fiber waviness or undulation, intralamina voids, incomplete curing of resin, and excess resin between plies. These variables are statistical in nature and influence the macrolevel mechanical properties of composite lamina [15–20]. Therefore, the effect of randomness (aleatory) in composite mechanical properties on rotorcraft aeroelasticity should be evaluated. Such uncertainties can affect the interpretation of results in which aeroelastic analysis results are compared with the experimental or flight test data [3,4].

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