Probabilistic Engineering Mechanics 36 (2014) 45–55

Contents lists available at ScienceDirect

Probabilistic Engineering Mechanics

journal homepage: www.elsevier.com/locate/probengmech

Uncertainties in blade flutter damage prediction under random gust

S. Venkatesh [a], Sunetra Sarkar [a,*], Igor Rychlik [b]

[a] Department of Aerospace Engineering, Indian Institute of Technology Madras, Chennai 600036, India
[b] Department of Mathematical Sciences, Chalmers University of Technology, SE-41296 Gothenburg, Sweden

ARTICLE INFO

Article history:
Received 2 September 2013
Received in revised form
17 January 2014
Accepted 5 March 2014
Available online 19 March 2014

Keywords:
Bending-torsion flutter
Uncertainty quantification
Polynomial chaos expansion
Fatigue damage

ABSTRACT

In the design of highly flexible engineering structures such as rotors of wind turbines, aeroelastic stability is an important issue. A bending-torsion oscillation problem of a model blade section with structural nonlinearity has been considered in the present study. The system is subjected to a horizontal random gust modeled as a stationary process. Uncertainty quantification in highlighting the relative importance of different sources of uncertainty on aeroelastic stability, and consequently the fatigue and failure is an important step of aeroelastic design, which is addressed here. The effect of different sources of uncertainty on the fatigue damage estimate of the structure is highlighted here. Specifically, the effect of the structural parameter, the choice of aeroelastic model (modeling error) and also the stress selection criterion for the damage estimate on the fatigue damage estimate is reported in this work. The structural parameter randomness is modeled through polynomial chaos expansion in analyzing its effect on the damage estimate. The unsteady inviscid flow-field in the aeroelastic model is resolved analytically and also using a higher fidelity vortex lattice algorithm and the relative effect on damage is seen. Finally, the effect of fatigue damage criterion selection is also observed. The damage calculation is done for torsion only, bending only and for multiaxial cases. Multiaxial stresses are converted to an 'equivalent' one using a signed von Mises criterion. A linear damage accumulation rule has been used to estimate the risk for fatigue damage.

1. Introduction

Flutter oscillation is one of the major design considerations in flexible structural systems such as wind turbine rotors when subjected to wind forces. It could be self-induced in nature and leads to structural damage as the resulting oscillation amplitude could be quite high or sustained oscillation could lead to fatigue failure. In the presence of parametric uncertainties, the flutter margin can become sensitive to such parameters. An uncertainty quantification exercise to estimate the propagation of uncertainty is crucial to evaluate the probability of failure or fatigue damage. The paper presents a methodology for studying different sources of uncertainties in fatigue life prediction of blades subjected to gusts. A linear fatigue damage accumulation rule has been used to estimate the risk for fatigue damage. The following typical uncertainties will be considered: modeling error uncertainty in predicting the aerodynamic loads acting on a blade; choice of fatigue criterion and uncertainty in system parameters used to model the blade's motions. Of course there could be many other sources of uncertainty that need to be included in the design process of reliable structures, e.g., uncertainty in material properties and the damage model, distribution of environmental loads and others; for a more complete discussion the readers are referred to Johannesson et al. [1].

The modeling error uncertainty will be studied by comparing fatigue life predictions for two different aeroelastic models of body wake interaction used to evaluate aerodynamic loads acting on the blade. The methods will be presented in Section 4 and 5 for an analytical technique as well as a computational technique called unsteady vortex lattice method (UVLM) model. The analytical formulation is based on the incompressible, inviscid, small perturbation potential flow theory using a time domain impulse response function called the Wagner function [2], where the airfoil body is approximated as a flat plate and the unsteady wake behind the trailing edge is assumed to be fixed behind the body. The computational model considers the actual shape of the airfoil; the airfoil and the wake are discretized into computational elements forming a freely rolling wake structure. The airfoil body is the section of a model blade treated as a cantilever beam fixed at one end with arbitrarily chosen blade parameters. The aeroelastic system is subjected to a horizontal random gust which is a

* Corresponding author.
E-mail addresses: svenky.87@gmail.com (S. Venkatesh), sunetra@iitm.ac.in (S. Sarkar), igor.rychlik@gmail.com (I. Rychlik).

http://dx.doi.org/10.1016/j.probengmech.2014.03.002
0266-8920/

Nomenclature

m	Structural mass per unit span
h	Plunge displacement
I_α	Mass moment of inertia about the elastic axis
S_α	First moment of inertia
c_α, c_h	Viscous damping coefficients in pitch and plunge
K_α, K_h	Linear stiffness coefficients in pitch and plunge
K_{α_1}, K_{h_1}	Cubic stiffness coefficients in pitch and plunge
L_α, M_α	Unsteady aerodynamic lift and moment
U	Wind speed
a_h	Non-dimensional distance from airfoil mid-chord to elastic axis
C_L	Lift coefficient
C_M	Pitching moment coefficient
$u(t)$	Longitudinal turbulence

stationary normal process having a von Karman spectrum. The presence of a gust makes the airfoil oscillate randomly for which the classical bifurcation theory cannot be applied [3]. Various criteria to predict damage rates will be discussed in Section 2. A common engineering approach combining a linear damage accumulation hypothesis with constant amplitude experiments (S–N data) will be employed. More details on this are discussed in the next section. Uncertainties due to the choice of fatigue criterion will be discussed in Section 9. The differences in fatigue life predictions will be investigated while considering stresses due to torsion and bending separately and also by combining the stresses into an equivalent signed von Mises stress. S–N curves established from the torsion and tensile loads on a representative material will be used. For an in-depth reading of fatigue considerations in multi-axial stress situations in structures, the readers are referred to [4,5].

As mentioned before, proper design of the structure is crucial for reliable and safe use of an aeroelastic system. In particular, flutter oscillations are quite undesirable. In the section entitled ‘Governing Equations of Motion’ coupled non-linear oscillators are used to describe the oscillatory motion (plunge and pitch) of the blade. An important parameter ϖ, which is the natural frequency ratio in plunge and pitch, is assumed to be not perfectly known and hence modeled as a random variable. In the realm of uncertainty quantification, the influence of random parameters on the response of interest has traditionally been analyzed with the help of Monte Carlo Simulation (MCS). Of late, however, a spectral uncertainty quantification tool called polynomial chaos expansion (PCE), presented in [6], has been put into use to study such problems. The PCE method will be employed in this work (see Appendix A entitled ‘Polynomial Chaos Expansion’ for an introduction to the method) to study sensitivity of damage rate prediction on uncertain system parameter ϖ.

Some studies which are of interest in the area of influence of uncertainties in flow and aeroelastic systems are discussed briefly here. Poirel and Price [3] have modeled and studied a structurally nonlinear aeroelastic system using the linear aerodynamic theory subjected to gust loading conditions. Monte Carlo Simulations (MCS) were used to investigate the stochastic bifurcation behavior. Pettit et al. [7] have used horizontal and vertical gust models with an unsteady vortex lattice solver on a rigid flat plate. Further, Pettit and Beran [8] have studied the effects of parametric uncertainties on airfoil flutter limit cycle oscillation (LCO) using MCS. Desai and Sarkar [9] have modeled and studied a nonlinear aeroelastic system using a linear aerodynamic theory with structural uncertainties under a uniform wind and have given a comparison between standard MCS and PCE solutions. However, study of the uncertainties of damage rate predictions is in its beginning. In our earlier work [10], we have studied the fatigue damage rate uncertainties for a simpler aeroelastic model of a single degree-of-freedom torsional oscillation. Aerodynamic loads were estimated using a semi-empirical method which is based on fitting load coefficients from experimental data. A stationary random gust was considered on the structure with its mean having a Gaussian variation. It was felt in the previous study that the effect of structural parameter uncertainty should also be taken into consideration. This is now attempted in the present study. Also, the aeroelastic model is improved to take into account pitch-plunge oscillations which could be a more likely scenario in blades. The aerodynamic loads are calculated by both analytical and computational techniques and are modeled more accurately.

2. Fatigue damage criteria

Fatigue damage of a material takes place when the material is subjected to repeated loading and unloading. At the design stage of a structural component, the S–N curves derived using constant amplitude loads are used to estimate the fatigue resistance (strength) of the design. However, the real loads encountered in actual practice are seldom a constant amplitude load. Hence there is a need to follow a cycle counting procedure which reduces the varying stress data into a set of cycles that allows for the application of damage rules in order to assess the fatigue life of the structure. There has been extensive experimental and theoretical work on fatigue processes for irregular loads, see, e.g., the works of Topper and co-workers [11,12]. The S–N curves were also derived for variable amplitude loads where the number of cycles to failure N is regressed on the so-called equivalent amplitudes, see Johannesson et al. [1]. The estimated fatigue strength must also be validated by means of fatigue tests of structural components (or the whole structure) under variable load sequences, representing the loads that the structural component is expected to encounter during its life, see Johannesson and Speckert [13] for a more detailed presentation of this subject. In the present work we are interested in sizes of uncertainties in evaluating stresses from environmental loads and predicted fatigue lives. We will consider an idealized situation at the design stage where wind load variability is described by its mean value and only standard constant amplitude bending and torsion S–N curves will be used. Uncertainties in the S–N curve parameters are neglected. Such uncertainties were analyzed in detail by Johannesson et al. [1].

The rainflow cycle counting was first proposed by Matsuishi and Endo [14]; for a presentation and discussion on the original work the readers can also refer to [15]. The much used “rainflow rule” has been reinterpreted as being equivalent to the work of an idealized hysteretic material – the so-called Massing rule (or analogy), see for example Section 3.1.3 of Johannesson and Speckert [13]. In that section, several algorithms developed to extract rain-flow cycles have been discussed and the often used four point algorithm has been presented in detail. This algorithm is recursive and most efficient to estimate the cycles “on-line”. Here, a local rain-flow cycle counting procedure proposed earlier by one of the authors [16] is used as explained in Fig. 1. The definition is useful for understanding the mathematical and statistical properties of rain-flow cycles. As shown in the figure, from the local maxima, one determines the lowest values in the forward and backward directions between the time point of the local maxima and the