Available online at www.sciencedirect.com
ScienceDirect
Chinese Journal of Aeronautics 22(2009) 513-519
Chinese Journal of Aeronautics
www.elsevier.com/locate/cja

Reliability and Sensitivity Analysis of Transonic Flutter Using Improved Line Sampling Technique

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Received 15 August 2008; accepted 29 December 2008

Abstract

The improved line sampling (LS) technique, an effective numerical simulation method, is employed to analyze the probabilistic characteristics and reliability sensitivity of flutter with random structural parameter in transonic flow. The improved LS technique is a novel methodology for reliability and sensitivity analysis of high dimensionality and low probability problem with implicit limit state function, and it does not require any approximating surrogate of the implicit limit state equation. The improved LS is used to estimate the flutter reliability and the sensitivity of a two-dimensional wing, in which some structural properties, such as frequency, parameters of gravity center and mass ratio, are considered as random variables. Computational fluid dynamics (CFD) based unsteady aerodynamic reduced order model (ROM) method is used to construct the aerodynamic state equations. Coupling structural state equations with aerodynamic state equations, the safety margin of flutter is founded by using the critical velocity of flutter. The results show that the improved LS technique can effectively decrease the computational cost in the random uncertainty analysis of flutter. The reliability sensitivity, defined by the partial derivative of the failure probability with respect to the distribution parameter of random variable, can help to identify the important parameters and guide the structural optimization design.

Keywords: flutter; aeroelastic; line sampling technique; Monte Carlo simulation; uncertainty; reduced order model

1. Introduction

Aeroelastic analysis is very important in the aircraft design[1-2], and it is an interdisciplinary subject of aerodynamic load, elastic force and inertia force. Flutter, a typical aeroelastic problem in aircraft design, can lead to aviation tragedy due to structural vibration divergence in a short time. Conventional studies about the flutter issue are based on the assumption of complete determinacy of structural parameters. This is usually referred to as deterministic analysis. However, there are uncertainties of geometric properties, material properties, loads distributions and working environment, etc. existing in the engineering practice, so the deterministic analysis cannot provide complete information about the flutter responses. In order to study the issue of wing flutter more rationally under the random uncertainties, the probabilistic analysis, an appropriate tool for the analysis of structural system with the random uncertainties[3-4], must be introduced.

The reliability analysis of flutter is a relatively new subject. The reference on probabilistic wing flutter analysis is infrequent up to now. Y. W. Liu, et al.[5] presented the sequence response surface method for the reliability analysis of wing flutter with the random natural frequency, and in several references, research on the issue of suspension bridge flutter is conducted by using the reliability analysis of flutter response by considering various uncertainties with different methods[6-8]. In general, these methods may be divided into four categories: ① first-order reliability method, ② stochastic finite element method (SFEM), ③ response surface method (RSM), and ④ Monte Carlo simulation (MCS).

In previous studies[9-10], the limit state function is explicitly expressed in terms of the random variables. However, the flutter response in practical applications is an implicit function of these random variables. In other words, a closed form solution of flutter response is not available due to its complexity. Under such conditions, the first-order reliability method and its corre-

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Foundation items: National Natural Science Foundation of China (NSFC 10572117, 10802063, 50875213); National High-tech Research and Development Program (2007AA04Z401); Aeronautical Science Foundation of China (2007ZA53012); New Century Program For Excellent Talents of Ministry of Education of China (NCET-05-0868); Ph.D. Program Foundation of Northwestern Polytechnical University (CX200801).

doi: 10.1016/S1000-9361(08)60134-X

sponding improved methods for the explicit limit state function will be impracticable due to the inaccuracy or the insufferable computational cost[3].

The SFEM[11-14] has been developed to predict the frequency response of the random structures. In addition, the SFEM being used in practical works has some drawbacks. First, it needs to derive the statistical properties of the system response from those of the input variables. The evaluation of statistical properties may face severe mathematical and numerical difficulties for complex structures. Second, the derived information of the system response cannot be provided by the existing deterministic finite element model. Hence, using SFEM will result in trouble concerning some modification of the existing deterministic finite element model. Third, the method is not applicable to the random variables with high dimensions.

RSM[15-19] is suitable for the reliability analysis of structures with implicit limit state functions. The basic idea of this method is to approximate the original implicit limit state function by a simple response surface function. A major advantage of this method is that the implicit limit state function is represented by the explicit form, and the existing reliability analysis methods can be readily implemented. So the RSM has been widely applied to the reliability analysis of structures. However, the selection of experimental points and the form of response surface function are two unsolved problems for the reliability analysis of complex structure with highly nonlinear limit state function, and sometimes the RSM may be not converged.

MCS[20-22] is a traditional method for the probabilistic analysis. Its wide applicability is well known. The main advantages of this method are as follows: ① engineers with only a basic knowledge of probability and statistics will be able to use it; ② it always provides correct results when very large times of simulations are performed. However, its computational cost is seldom affordable for engineering application with small failure probability.

To reduce the computational cost, different variance reduction techniques such as importance sampling[23] are developed. Refs.[24]-[27] presented the line sampling (LS) technique to estimate the failure probability effectively. LS does not require any approximating surrogate of the limit state equation and combines the robustness with the accuracy. The LS technique can be widely applied to high dimensions, multiple failure domains and implicit performance function. On the basis of the LS method, Refs.[28]-[30] proposed the improved LS method and LS-based reliability sensitivity analysis method, which propagated the advantages of the LS method. In this article, the reliability and sensitivity analysis based on the improved LS is employed for the reliability analysis of transonic flutter.

The reliability and sensitivity of transonic wing flutter model for the two-dimensional wing are analyzed using the improved LS technique. For flutter analysis, coupling structural equations with Euler/Navier-Stokes (N-S) equations-based unsteady computational fluid dynamics (CFD) algorithm, the structural response can be predicted in time domain with the fewest assumptions about the characteristics of the flow field. However, the challenges offered by this kind of aeroelastic analysis are those of computational time and their low effectiveness in the flutter elimination and parametrical design environments. In order to solve the contradiction between computational efficiency and computational quality, many researchers turned to use CFD-based unsteady aerodynamic reduced order modeling (ROM) method to improve the aeroelastic computational efficiency in the last decade. Refs.[31]-[33] presented ROM and its applications on non-linear aeroelastic analysis. Ref.[33] compared the efficiency of ROM-based method and CFD direct simulation method. The efficiency of ROM-based method can be improved by 1-2 orders of magnitude with accuracy still being retained. Refs.[34]-[35] used CFD-based ROM to perform aeroservoelastic analysis, active flutter suppression and flutter analysis at high angle of attack. Based on the available methods of the flutter analysis, the safety margin of flutter reliability analysis is founded by use of the critical velocity of flutter.

This article devotes to analyzing the reliability and sensitivity for the transonic flutter by use of the improved LS method and uses the results of the reliability and reliability sensitivity analysis to investigate the effects of various parameters on the statistical properties of flutter responses.

2. Improved LS-based Reliability and Sensitivity Analysis

2.1. Improved LS-based reliability analysis

LS evolved from the need for treating high dimensional reliability problems with an implicit performance function. The procedure is performed in standard normal space, which is denoted by $\boldsymbol{y}$ usually. Conceptually, in the LS procedure, conditional MCS is applied.

Before drawing samples, the important direction, usually denoted by $\boldsymbol{\alpha}$, should be determined. In the standard normal space, the direction being from the origin of coordinate to the most probable point (MPP) in the failure domain is the optimal important direction. The vector $\boldsymbol{\alpha}$ points to the direction of having greatest impact on the limit state function in the standard normal space. The key steps of LS are concerned with the searching of the optimal important direction and the drawing of the samples for the estimation of failure probability. In this article, these two key steps are implemented with the aid of the samples distributed in the failure domain (denoted by F usually) and the samples distributed in F are simulated by Markov chain simulation.

In order to determine the optimal $\boldsymbol{\alpha}$, we simulate the samples distributed in F by Markov chain simulation. Using $f(\boldsymbol{y})$ to denote the probability density function (PDF) of random input variables and P_f to denote the failure probability, the conditional PDF $q(\boldsymbol{y}|F)$ of $\boldsymbol{y}$