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Interval analysis for uncertain aerodynamic loads with uncertain-but-bounded parameters

Jingjing Zhu, Zhiping Qiu *

Institute of Solid Mechanics, Beihang University, Beijing, 100191, PR China

H I G H L I G H T S

- An interval aerodynamic model with uncertain-but-bounded parameters is provided.
- The interval perturbation method is proposed to predict aerodynamic load response.
- The subinterval perturbation method is established for large uncertainty levels.

A R T I C L E I N F O

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A B S T R A C T

In this paper, we make the first effort to apply the interval method to aerodynamic loads analysis considering uncertainty in the case of insufficient sample data, and the effectiveness of this method is validated. The interval perturbation method and subinterval perturbation method are extended to evaluate the uncertain aerodynamic loads region with uncertain-but-bounded parameters. The uncertain parameters with insufficient information are quantified as interval variables. By combining the vortex lattice method and the interval theory, the interval aerodynamic model which is applicable to the subsonic regime is constructed. The first-order Taylor expansion and first-order Neumann series are employed to calculate the response intervals of lift coefficients. Based on the subinterval theory, the subinterval perturbation method for the interval aerodynamic model is developed to solve the aerodynamic problems with large uncertainty level. Two numerical examples for wing models, which consider uncertainty in incoming flow conditions and geometry, are given to validate the feasibility and effectiveness of the proposed methods by comparing the results with Monte Carlo simulations. Moreover, the present methods are extended to evaluate the uncertainty propagation in the pitching moment coefficient and induced drag coefficient.

1. Introduction

Computational aerodynamics is based on fluid mechanical and aerodynamic theory, which is playing a more and more important role in the analysis and design of aerodynamic loads of aircrafts. In traditional aerodynamics, all of the parameters involved in the computation are given deterministic values. Actually, almost all computational models of practical problems are affected by uncertainties, which may arise in the assumptions of the mathematical models, manufacturing errors, and operational parameters and conditions. Particularly, there could be some operational uncertainties in aerodynamics, which is due to unpredictable factors that change the incoming flow condition (Martinelli and Duvigneau, 2010):

* Corresponding author.
E-mail address: zpqiu@buaa.edu.cn (Z. Qiu).

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(a) variations of the angle of attack due to atmospheric conditions during the flight;
(b) uncertainties in Mach and Reynolds numbers originated from atmospheric conditions, or instrumentation tolerances, or variations in flight profile compared to the scenario.

In addition to manufacturing tolerances, the geometric uncertainties also contain geometric variations due to the motion regime (e.g. blades in compressors), degradation (e.g. erosion) and deformation or surface icing under the weight loads.

These uncertainties exert crucial impacts on the accuracy of the results and in some cases significantly lower the aerodynamic performance. If the properties of aircrafts are greatly sensitive to some parameters with uncertainties, it will have serious impact on the performance stability and flight safety of aircrafts and may lead to disastrous consequences even if the uncertain parameters change slightly. To achieve a certain level of robustness or reliability in the final design, it is necessary to take those uncertainties into account during simulation process.

The most widely used uncertain analysis method is Monte Carlo (MC) simulation which is straightforward and easy to carry out in a non-intrusive way (Martinelli and Duvigneau, 2010; Walters and Huyse, 2002). However, it is computationally expensive and infeasible for very high dimensional problems because of its low convergence rate. Therefore, it is usually used as the validation for other approaches. Another straightforward method is the moment method. Moment method approximations are obtained by truncated Taylor series expansion about the nominal values of input parameters (Luc, 2001). The polynomial chaos (PC) method (Ghanem et al., 2005) is a more recent uncertain analysis approach, which projects the variables of the problem onto a stochastic space spanned by a set of orthogonal polynomials. This approach has been successfully applied to a large number of fluid mechanics problems for its merits of high accuracy and low computational cost (Mousaviraad et al., 2013; Sarkar et al., 2009; Bruno et al., 2009). Furthermore, PC method was expanded by Xiu and Karniadakis (2003) to the generalized polynomial chaos (GPC) for different kinds of probabilistic distributions and basis functions (Simon et al., 2010). However, the intrusive method requires considerable modification of the deterministic code and may introduce new numerical errors. The non-intrusive polynomial chaos (NIPC) method was developed to overcome those disadvantages, in which the deterministic solver is used as a black-box for uncertainty propagation (Hosder et al., 2006; Loeven et al., 2007; Kumar et al., 2016).

From the overall perspective, current research on uncertain aerodynamic problems is mainly concentrated in the stochastic framework. Generally, a great number of information is necessary to construct the probability distribution functions. However, in practical applications, sufficient information about the uncertainties is usually unavailable or very expensive to collect. Meanwhile, even small variations from real values may result in large errors in probability distributions of the random variables.

In order to overcome the deficiency of probabilistic method, interval analysis has been developed to deal with the problems with uncertain-but-bounded variables whose bounds are well defined rather than their probability distribution functions. The interval method has been an increasing popular research topic for the last years owing to its conceptual simplicity and other merits (Alefeld and Mayer, 2000; Wang et al., 2017; Lv and Liu, 2017, 2018). The interval method can describe the uncertainty that cannot be appropriately modeled by probabilistic method in the case of inadequate data. The theory of the interval method is simple and elegant so that it is easy to implement in engineering applications. The description for uncertain parameters by interval variables conforms to practical tolerance concept. Moreover, the interval method gives conservative results which provide guaranteed enclosures.

Interval analysis approach, as a non-probabilistic approach, was originally built on the basis of the work of Moore (1966) and Alefeld and Herzberger (1983). Up to date, the interval method has been applied to a wide range of structural systems, such as static and dynamic problems of structures (Impollonia and Muscolino, 2011; Liu et al., 2017; Wang et al., 2016) and design optimization (Chen and Wu, 2004). Neumaier investigated the united solution set of the interval equations utilizing the hypercube approximation by the Gaussian elimination scheme (Neumaier, 1990). However, this approximation may be extremely conservative because of a great number of elimination operations (Rao and Berke, 1997). Chen presented the interval finite element approach to solve the uncertainty problems of the beam structures (Chen and Yang, 2000). As an implementation of interval finite element approach, the Hansen–Bliek–Rohn–Ning–Kearfott iterative procedure was discussed in Neumaier (1999). If the structural responses are monotonic with respect to the uncertain input parameters, the exact response intervals can be evaluated by the vertex method (Qiu and Lv, 2017). Combined with interval arithmetic, the first-order Taylor series was used to analyze dynamic response problems of structures (Zhang et al., 2007; Makino and Berz, 1999). Based on the interval theory and perturbation method, the interval perturbation method was proposed by Qiu et al. (1996), Qiu and Wang (2005) and Wang and Qiu (2014) to solve mechanic problems. The subinterval parameter perturbation method by dividing the large interval variables into small subintervals can obtain higher accuracy (Qiu and Elishakoff, 1998). Compared with aforementioned interval approaches, the computational cost of the interval perturbation method is much smaller, and the convergence condition related to the ranges of input interval parameters is more easily guaranteed.

For many fluid problems, the vortex lattice method (VLM) has been found to be a very efficient preliminary aircraft design tool (Paulson, 1976). VLM could realistically represent many properties that are important in engineering applications, while it is a simplification of real flow. As an efficient numerical method compared with CFD methods, VLM has been employed in a large number of applications, such as computation of stability derivatives and flight dynamics analysis (Kay et al., 2012), aerodynamic interference of aircraft (Rossow, 1996), or multidisciplinary optimization (Haghighat et al., 2013), among many others. In the present paper, VLM is utilized to predict aerodynamic characteristics in the uncertain aerodynamic analysis.

This paper focuses on the uncertain aerodynamic loads modeling with poor information and inadequate data. We make the first effort to apply the non-probabilistic interval method to aerodynamic loads analysis and the effects of the