Contents lists available at ScienceDirect

Journal of Fluids and Structures

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

Aeroelastic flutter analysis considering modeling uncertainties

Mikaela Lokatt

KTH Royal Institute of Technology, Aeronautical and Vehicle Engineering, Teknikringen 8, 100 44 Stockholm, Sweden

HIGHLIGHTS

- A perturbation analysis method for aeroelastic flutter analysis is presented.
- The method allows analysis of both structural and aerodynamic uncertainties.
- The method has favorable computational properties.

ARTICLE INFO

Article history:
Received 26 October 2016
Received in revised form 13 June 2017
Accepted 22 June 2017
Available online xxxx

Keywords:
Flutter analysis
Modeling uncertainty
Generalized eigenproblem
Eigenvalue differential
Minkowski sum

ABSTRACT

A method for efficient flutter analysis of aeroelastic systems including modeling uncertainties is presented. The aerodynamic model is approximated by a piece-wise continuous rational polynomial function, allowing the flutter equation to be formulated as a set of piece-wise linear eigenproblems. Feasible sets for eigenvalue variations caused by combinations of modeling uncertainties are computed with an approach based on eigenvalue differentials and Minkowski sums. The method allows a general linear formulation for the nominal system model as well as for the uncertainty description and is thus straightforwardly applicable to linearized aeroelastic models including both structural and aerodynamic uncertainties. It has favorable computational properties and, for a wide range of uncertainty descriptions, feasible sets can be computed in output polynomial time. The method is applied to analyze the flutter characteristics of a delta wing model. It is found that both structural and aerodynamic uncertainties can have a considerable effect on the damping trends of the flutter modes and thus need to be accounted for in order to obtain reliable predictions of the flutter characteristics. This indicates that it can be beneficial to allow a flexible and detailed formulation for both aerodynamic and structural uncertainties, as is possible with the present system formulation.

1. Introduction

Flutter is a dynamic aeroelastic instability in which the interaction of aerodynamic, structural and inertial forces causes the aircraft structure to perform undamped, periodic, oscillations. The structural oscillations can cause problems for the aircraft control system and also damage the aircraft structure. Because of the, sometimes catastrophic, consequences of aircraft flutter, the analysis of flutter instabilities plays an important part in design and flight testing of aircraft (Bisplinghoff and Ashley, 1962; Dowell et al., 2015). During the validation stage, flight testing is used to ensure that the flight envelop is free of flutter instabilities. Both time and money can be saved by using mathematical models, as a complement to experimental testing, to obtain predictions of possible flutter instabilities (Lind and Brenner, 2002; Dowell et al., 2015). This allows flutter

E-mail address: mlokatt@kth.se.

http://dx.doi.org/10.1016/j.jfluidstructs.2017.06.017

instabilities to be discovered already during the design process and can thus provide information of whether an aircraft needs to be redesigned before its aeroelastic stability is evaluated in flight flutter testing.

It is common to base the mathematical models on linearized, frequency domain, structural and aerodynamic models. The resulting system of equations (nominal system model) forms a non-linear eigenproblem and a number of methods have been developed for its solution (Dowell et al., 2015; Borglund and Eller, 2013). Given accurate structural and aerodynamic models, the mathematical analysis can provide relatively accurate flutter speed predictions. In practice, some deviation between the modeled system dynamics and the actual aircraft dynamics is typically present, which can lead to a, more or less significant, difference between the numerically predicted flutter speed and the flutter speed of the real aircraft.

In order to account for this possible variation, so called robust analysis methods have been developed (Pettit, 2004; Danowsky et al., 2010). Robust analysis methods provide information about flutter speed variations caused by modeling uncertainties. They allow a large number of system variations to be accounted for in one analysis, avoiding the need to perform nominal flutter analyzes for all possible combinations of parameter variations which are covered by the uncertainty description. This property is useful in analysis of aeroelastic systems which are subjected to numerous aerodynamic and structural uncertainties, for which a very large number of possible combinations of parameter variations needs to be analyzed.

A common basis for robust analysis is μ-analysis, which employs the structured singular value to evaluate the stability of a nominal system model that is subjected to a set of structured uncertainties (Lind and Brenner, 1999). This analysis method origins from the control community and was introduced for aeroelastic analysis by Lind and Brenner (1997) and Lind (2002). Further development of the μ-framework for aeroelastic applications was made by Borglund, who developed the $\mu - k$ method (Borglund, 2004). The $\mu - k$ method applies μ-analysis directly to pre-computed frequency domain matrices and thereby avoids the need to find an approximate state space representation of the aerodynamic forces, as is needed in the classical framework for μ-analysis (Lind and Brenner, 1999). In subsequent work Borglund presented the $\mu - p$ method which not only enables estimation of a lowest (worst case) flutter speed, but also allows computation of feasible sets within which the eigenvalues may vary when the aeroelastic system is subjected to a given set of uncertainties (Borglund, 2008). Computation of feasible sets has shown to provide useful information for validation of uncertainty models (Heinze et al., 2009) as well as for industrial application in flight flutter testing (Leijonhufvud and Karlsson, 2011).

Computing the value of μ appears to, in general, be a NP hard problem and thus, in practice, upper and lower bounds of μ are computed instead of the exact μ-value (Lind and Brenner, 1999). To avoid unnecessarily conservative estimates of the robust flutter boundaries, it is important to find upper and lower bounds that are close to the actual μ-value. As discussed by Lind and Brenner (1999), the computational cost increases with increasing accuracy of the bounds. In practice, for complex valued structured perturbations, relatively tight bounds can be computed in a reasonable time (Young et al., 1991, 1992). For purely real uncertainties, commonly encountered for structural uncertainties, computing accurate bounds can be difficult (Young et al., 1991, 1992; Gu et al., 2012; Heinze and Borglund, 2008).

Several other methods aimed at analysis of how modeling uncertainties affect aeroelastic stability have been proposed. For example, Gu et al. (2012) and Gu and Yang (2012) suggest that the flutter problem, including modeling uncertainties, can be formulated as an optimization problem and that a worst case flutter condition can be solved for by pattern search or by a genetic algorithm. Bueno et al. (2015) suggest a robust analysis method based on linear matrix inequalities and convex optimization. Schwochov (2009) suggests the use of a continuation method in combination with interval modal analysis to investigate how the flutter speed is affected by structural uncertainties. Wu and Livne (2017) use a Monte Carlo based approach to analyze how the aeroelastic stability is affected by aerodynamic as well as structural uncertainties. Marques et al. (2010) apply Monte Carlo, perturbation and interval analysis based propagation methods to analyze how the aeroelastic stability is affected by structural uncertainties while Dwight et al. (2011) apply probabilistic collocation for the same purpose. An overview of methods for uncertainty quantification in aeroelasticity is found in the review by Pettit (2004) as well as in the review by Beran et al. (2017). The review paper by Livne (2003) includes a large number of references related to the subject of uncertainties in aeroelastic analysis.

Relatively recently, the present author (Lokatt, 2014) suggested that perturbations caused by combinations of modeling uncertainties could be analyzed by a method based on eigenvalue differentials (Magnus, 1985) and Minkowski sums (Weibel, 2007). Eigenvalue differentials provide information of how eigenvalues are affected by modeling uncertainties and have previously been used for sensitivity analysis in a wide range of engineering disciplines, as discussed by Li et al. (2014). Also Minkowski sums have found applications in a wide range of subjects, including areas related to reachability analysis (Hagemann, 2015) as well as motion planning, algebraic statistics and decision processes (Weibel, 2010). Based on the information obtained from the eigenvalue differentials, the Minkowski sums allow computation of feasible sets which estimate eigenvalue variations which can be caused by combinations of modeling uncertainties (Lokatt, 2014). For a wide range of uncertainty descriptions, the approach allows an efficient computational procedure making it an interesting alternative for perturbation analysis of systems which are subjected to a large number of structural and aerodynamic uncertainties.

The work presented in this paper concerns the extension of the previously presented perturbation analysis method (Lokatt, 2014) to allow a more general formulation of the structural and aerodynamic system models. The previously proposed method (Lokatt, 2014) requires that the aerodynamic model can be expressed as a function of the polar radius (i.e. $\boldsymbol{Q}(p) \approx \boldsymbol{Q}(r)$ with $\boldsymbol{Q}$ being the aerodynamic system matrix, $p = re^{i\theta}$ the Laplace variable and r, θ the polar radius and polar angle respectively) and does not provide a straightforward way of accounting for structural damping, limiting