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Flutter Prediction Methods for Aeroelastic Design Optimization

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The objective of the paper is to demonstrate the validity of flutter predictions obtained using eigenvector orientations (EVO) for realistic wings used in aircraft preliminary design. Comparisons of flutter predictions between the V-g method and the EVO method are presented for an intermediate complexity wing used in optimization studies. The results presented show that the EVO method can predict the onset of flutter for aircraft wings with reasonable accuracy and can be used in design optimization studies of aerospace vehicles/components.

I. Introduction

THE design of modern flight vehicles requires multidisciplinary design optimization (MDO), the integration of structures, aerodynamics, control and propulsion disciplines, to achieve an optimum design based on certain performance criteria and constraints. In the design of flight vehicles, flutter is a critical parameter that must be considered in the early stage of the design cycle. Also, with aging aircraft, certain restrictions need to be imposed in order to avoid flutter instability during the flight regime of the aircraft. A large number of parameter changes must be investigated in the flutter design of military as well as commercial aircraft as a result of the complexity of modern composite/metallic structures. Accurate and efficient methods of flutter prediction for aerospace vehicle components are needed for use in aeroelastic design optimization studies.

There are several aeroelastic design optimization codes being used for aircraft and spacecraft structures, such as the Automated Structural Optimization System (ASTROS)[1] and MSC-NASTRAN.[2] In aeroelastic design optimization the predominant dynamic flutter instability needs to be investigated for most flight vehicles. Several methods are being used to predict the onset of flutter instability in aeroelastic design optimization. Most of these methods are based on complex eigenvalues (p-k method, K-method, or KE method).[2] Recently, Afolabi et al.[3] developed a method based on eigenvector orientations (EVO) to predict the onset of flutter instability. In their work the method of EVO was used for limited examples of panel flutter. To gain a better understanding of the EVO method of flutter prediction, further investigations need to be carried out on realistic aircraft structures. This understanding will help to devise a prediction methodology that may be implemented in MDO codes for the preliminary design of flight vehicles.

The objective of this paper is to further validate the EVO method[3] of flutter prediction for realistic examples used in aircraft preliminary design. A brief review of the EVO method for flutter prediction is described in the next section. An example of an intermediate complexity wing used in design optimization studies is considered, and flutter prediction results are compared to the commonly used V-g method.

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II. EVO Method

The aeroelastic system of equations for an aircraft structural component can be written as

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + ([K] + [K_A])\{x\} = \{0\} \tag{1}$$

where $[M]$ is the mass matrix, $[K]$ is the stiffness matrix, $[C]$ is the damping matrix caused by aerodynamic or structural sources, $[K_A]$ is the unsteady aerodynamic stiffness matrix, and $\{x\}$ is the physical degrees of freedom vector. The preceding system of equations can be solved as a complex eigenvalue problem by assuming the unknowns $\{x\}$ follow a harmonic motion. For a large system the normal modes approach can be used to reduce the aeroelastic system of equations. Usually, a free vibration analysis is performed (neglecting the damping and aerodynamic stiffness) to obtain the natural frequencies and mode shapes. Then, using a sufficient number of lowest modes (usually 6–12 modes), the original aeroelastic system [Eq. (1)] can be reduced as follows:

$$[m]\{\ddot{q}\} + [c]\{\dot{q}\} + ([k] + [k_A])\{q\} = \{0\} \tag{2}$$

where $[m]$, $[c]$, $[k]$, and $[k_A]$ are the modal mass, damping, structural stiffness, and aerodynamic stiffness matrices, respectively. The aeroelastic system of equations in terms of airspeed or the reduced frequency parameter [Eq. (2)] when cast into a complex eigenvalue problem can be solved to get the eigenvalues and eigenvectors.

$$\{[k] - \lambda([m] + [A])\}\{\phi\} = \{0\} \tag{3}$$

where $\lambda = \omega^2/(1 + ig)$ is the complex eigenvalue and $\{\phi\}$ is the complex eigenvector.

The flutter boundary is obtained when the lowest two eigenvalues coalesce at a critical value of k or q (assuming no aerodynamic damping), or the damping (g) of one of the modes is zero when crossing from negative (stable) to positive (unstable) values. Both the K method and the p-k method of flutter solution are based on the complex eigenvalues (tracking the zero values of modal damping) to predict the onset of flutter instability.[2] In other words, when the damping is ignored, the flutter instability is found when the lowest two eigenvalues coalesce and become complex conjugate pairs. Previous studies in the literature focussed mostly on the complex eigenvalues but not on the complex eigenvectors. Recently, Afolabi et al.[3] used the idea of EVO based on complex eigenvectors to predict the onset of the flutter instability. The eigenvectors, initially real and orthogonal to each other, lose their orthogonality at the flutter instability. So, when the angle between any two eigenvectors deviates from 90 deg that indicates the extent to which the aeroelastic system is close to the flutter boundary. Therefore, in the EVO method the angle between any two complex eigenvectors (any modes), or its deviation from 90 deg or when the rate of change of the EVO angle is zero, can be used to track the flutter condition. For a real-time flutter control process one can use the EVO method because it can be easily monitored, where the EVO angle close to zero indicates the flutter condition. The EVO method serves as a complement to the existing methods based on eigenvalues.

The angle between two complex vectors is calculated by mapping a complex vector into a real vector by grouping the imaginary components after the real components.[3] Then the angle between two real eigenvectors (ϕ_1 and ϕ_2) can be found as

$$\theta_{12} = \cos^{-1}\left(\frac{\phi_1 \cdot \phi_2}{||\phi_1||||\phi_2||}\right) \tag{4}$$

The angle between any two eigenvectors is 90 deg initially (orthogonal modes) and approaches zero at the flutter instability (modes are no longer orthogonal) when the airspeed V or reduced frequency k is varied. This method of tracking the flutter condition is completely different from the V-g plot using the K and p-k methods used previously in the literature.

III. Application

The example of an intermediate complexity wing is considered to demonstrate the flutter prediction based on an EVO analysis as discussed in the preceding section. The software MSC/NASTRAN was used to calculate the flutter condition based on the V-g plot using the PK method. A postprocessing program was written to extract the complex eigenvectors and determine the angle between them by the EVO method. Several other examples of aircraft wings were studied and presented in Ref. 4. The results of the flutter boundaries for the intermediate complexity wing are presented to illustrate the relative merits of the EVO method compared to the V-g method for tracking the onset of the flutter condition.

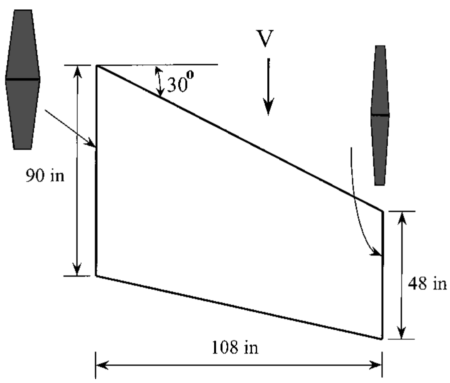

Fig. 1 Example of an ICW studied for flutter prediction.

The intermediate complexity wing (ICW) example is taken from ASTROS and has been used in many applications in MDO. The wing geometry is given in Fig. 1. The ICW is a 30-deg sweptback wing with upper and lower skin surfaces consisting of a balanced composite layup of (0 deg/$\pm$45 deg/90 deg) with the 0-deg fibers aligned along the midspar of the wing. The finite element model of the wing (total 88 nodes) consists of 62 quadrilateral and 2 triangular membrane elements (skins), 55 shear panels (ribs and spars), and 39 rod elements (posts). The wing is cantilevered at the root. The finite element model and the aerodynamic model can be found in Ref. 5. For aerodynamics the wing is modeled as a flat plate lifting surface with 72 boxes (9 spanwise and 8 chordwise with unequal spacing). The aerostructural interconnection is defined by two surface splines. A flutter analysis was carried out at $M = 0.7$ using the PK method. Figures 2 and 3 show the results of the flutter analysis using the V-g and EVO methods. The EVO method predicts the flutter speed around 800 ft/s (243.84 m/s), whereas the V-g method predicts the flutter speed to be 939 and 926 ft/s (286.21 and 282.2 m/s) using NASTRAN and ASTROS, respectively. The difference in flutter speed between the EVO and V-g method may be attributed to the fact that the present finite element model is not accurate enough to give good mode shapes based on observation of the flutter mode shape. This could be a limitation of the EVO approach to predicting the onset of flutter, which needs further investigation.

The ICW example studied in this investigation along with the other examples studied in Ref. 4 illustrate that the EVO method of flutter prediction indeed predicts results comparable to the V-g method and experiments. The question now is to address the possible benefits of the EVO method as compared to the V-g method. In the EVO method the angle reduces from 90 deg monotonically, definitely reaches a minimum, and increases again. If one is to use real-time automatic tracking of the flutter instability, then tracking the EVO angle from 90 deg seems an easy task compared to tracking the damping (which could be multiple valued). The EVO method can also be used to monitor the flutter instability in the wind-tunnel experiments by tracking the EVO angle close to zero.

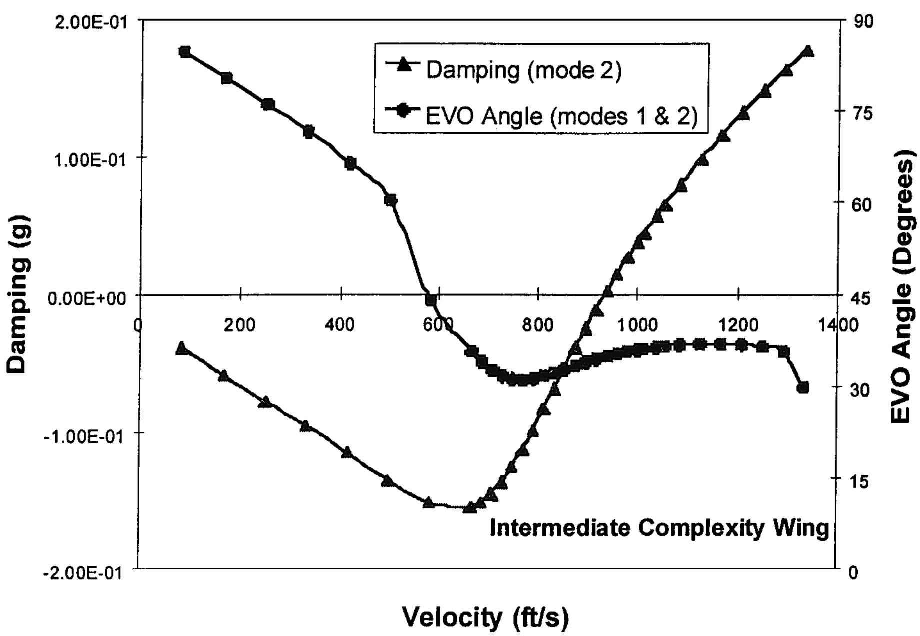

Fig. 2 Comparision of V-g vs V-EVO angle plots for the ICW.

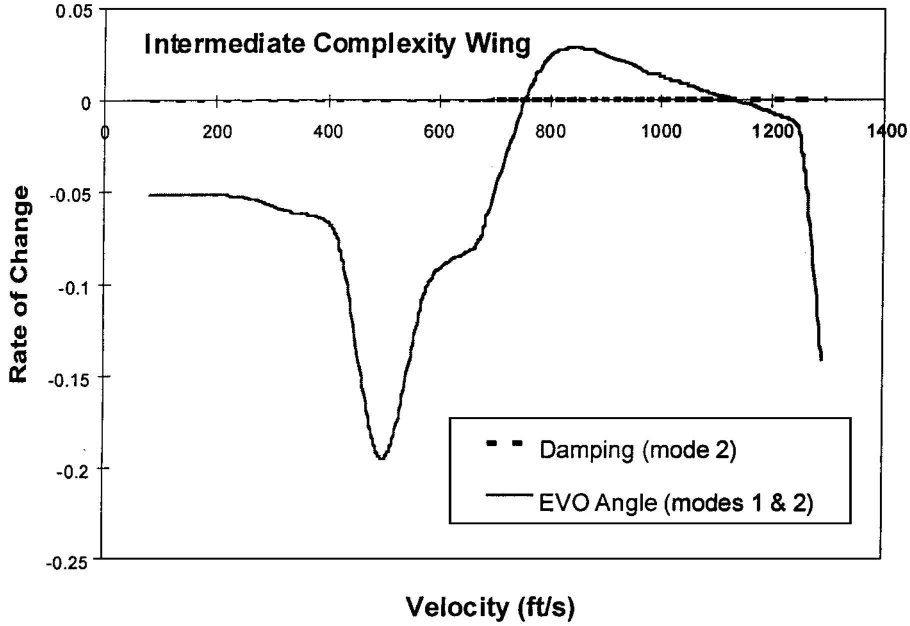

Fig. 3 Rate of change of damping and EVO angle plots for the ICW.

IV. Concluding Remarks

A flutter prediction method based on complex eigenvectors was reviewed. Comparison of flutter prediction between the popular V-g method and the new EVO method was made for an intermediate complexity wing used in design optimization studies. A reasonably good comparison of the flutter speed between the EVO method and the V-g method was obtained. One limitation of the EVO method of flutter prediction may be the dependency between the size of the finite element mesh and accuracy mode shapes in determining the angle between various modes.

Acknowledgment

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