JOURNAL OF AIRCRAFT
Vol. 35, No. 2, March–April 1998

Engineering Notes

ENGINEERING NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes cannot exceed 6 manuscript pages and 3 figures; a page of text may be substituted for a figure and vice versa. After informal review by the editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Static Aeroelastic Effects on a Transonic Indicial Response Wing Flutter Calculation

R. M. Kolonay*
U.S. Air Force Research Laboratory,
Wright–Patterson Air Force Base, Ohio 45433
and
Henry T. Y. Yang†
University of California, Santa Barbara,
Santa Barbara, California 93106

Introduction

THE use of the indicial response method (IRM) or other similar methods such as the pulse transfer-function method have been frequently used to approximate nonlinear time-domain unsteady aerodynamics. These methods have been applied to all levels of the nonlinear fluid equations from two-dimensional transonic small disturbance (TSD)[1] to full three-dimensional Navier–Stokes equations.[2] These techniques assume that dynamic deformations are restricted to small perturbations about a given static equilibrium position. With this assumption, it follows that the generalized forces can be expressed as a linear combination of the generalized displacements.

Because the equilibrium position is obtained by solving a nonlinear set of differential equations, the perturbation results depend on the steady-state conditions from which the perturbation takes place. For example, in transonic flow a different set of unsteady aerodynamic forces result for a wing perturbed from a steady-state equilibrium of 1-deg angle of attack compared to a wing that is perturbed from a steady state of 2-deg angle of attack. This is because the pressure distributions and magnitudes differ between these two cases. The same argument can be applied to the difference between using a nonlinear static rigid steady state vs a nonlinear static aeroelastic steady state for the point about which the perturbation is performed. The effect of angle of attack and static aeroelastic deformations on two-dimensional airfoils using the TSD theory was investigated by Bland and Edwards.[3] Another study that used transonic test data to correct subsonic oscillatory aerodynamics including static aeroelastic effects was performed in Ref. 4 on supercritical wings. McGrew et al.[4] concluded that static aeroelastic twist could significantly affect flutter velocity. The effect of static aeroelastic equilibrium on a three-dimensional TSD IRM wing flutter analysis is demonstrated in this research.

Approach

For a given flight condition and set of structural mode shapes, CAP–TSD[5] is used to time integrate the modal equations of motion to a converged static aeroelastic equilibrium. The resultant generalized deformations are used as the aerodynamic surface boundary conditions and the indicial responses initiated from this deformed shape. Once the indicial responses are calculated the procedure developed in Ref. 6 is used to perform the IRM flutter analysis.

To demonstrate the procedure a modified version of the fighter wing sample case considered in Ref. 7 is used. For this study the wing structure in Ref. 7 is terminated at the wing root (no carry-through attachment) and the overall mass of the wing in Ref. 7 is scaled to obtain the desired natural frequencies. In addition, a 4% parabolic airfoil is specified over the entire wing to include thickness effects. Figure 1 shows the finite element model of the wing, the transonic small disturbance mesh, and the wing planform. The TSD mesh is 60 × 23 × 70 with 39 chordwise points and 15 spanwise points on the wing. As can be seen from the finite element model and TSD mesh, the aerodynamic model extends beyond the structural model. The Harder–Desmarais[8] infinite plate spline is used to accommodate the splining requirements between the finite element model and TSD mesh. The flight condition chosen is $M_\infty = 1.1$, $\alpha_0 = 1.0$ deg. Using the time-integration method and the first four fundamental mode shapes, a flutter dynamic pressure of approximately 53.5 psi and a frequency of 20.10 Hz are determined (Table 1). Using a static rigid equilibrium ($\alpha = 1.0$ deg) as the point about which indicial responses are calculated, a flutter analysis is then performed (Table 1). These flutter results compare fairly well with the time-integration results. The flutter dynamic pressure is approximately 7% high with the flutter frequency within 1%. Finally, using a dynamic pressure of 50.0 psi, a static aeroelastic analysis is conducted at $M_\infty = 1.1$, $\alpha_0 = 1.0$ deg. Figure 2 depicts the ΔC_p differences between the rigid and aeroelastic steady-state equilibriums for this case. This figure indicates that the largest differences in the pressure distribution are at the leading-edge outboard portion of the wing surface with the rigid equilibrium giving a greater ΔC_p at this location. This is expected because the aeroelastic deformation of the wing exhibits a nose down rotation or washout characteristic. Taking the generalized deformations from the static aeroelastic analysis and using them as the aerodynamic surface boundary conditions, a set of indicial responses are calculated. Finally, a flutter analysis is performed with the results found in Table 1. This shows that the flutter dynamic pressure and frequency including the static aeroelastic deformations are within 0.1% of the time-integration results. Figure 3 shows the differences between the flutter analyses conducted with and without static aeroelastic effects for U_∞ vs g. This figure shows that the dynamic aeroelastic response of the system differs when static aeroelastic effects are included in the analysis. These results indicate that static aeroelastic effects should be included when using a small perturbation assumption to approximate transonic unsteady aerodynamics. This is because static aeroelastic deformation can effect the

Presented as Paper 96-3983 at the AIAA/USAF/NASA/ISSMO 6th Symposium on Multidisciplinary Analyses and Optimization, Bellevue, WA, Sept. 4–6, 1996; received Dec. 1, 1996; revision received Sept. 20, 1997; accepted for publication Nov. 9, 1997.

*Aerospace Engineer, Structures Division, Flight Dynamics Directorate. Member AIAA.

†Professor and Chancellor, Department of Mechanical and Environmental Engineering. Fellow AIAA.

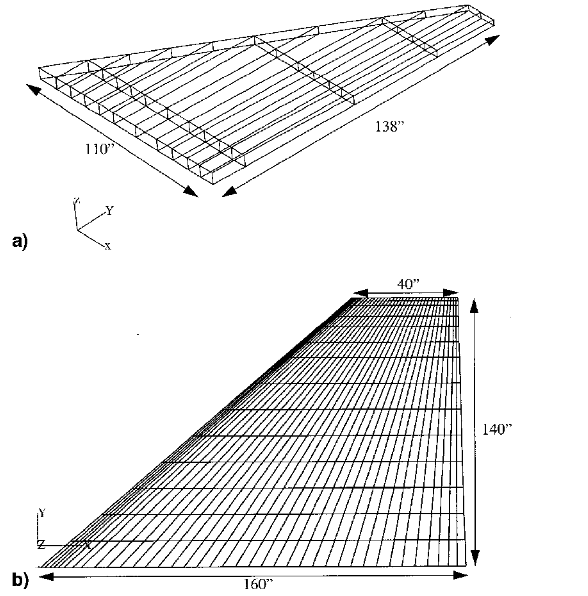

Fig. 1 Fighter wing a) wing box finite element model and b) TSD mesh and planform.

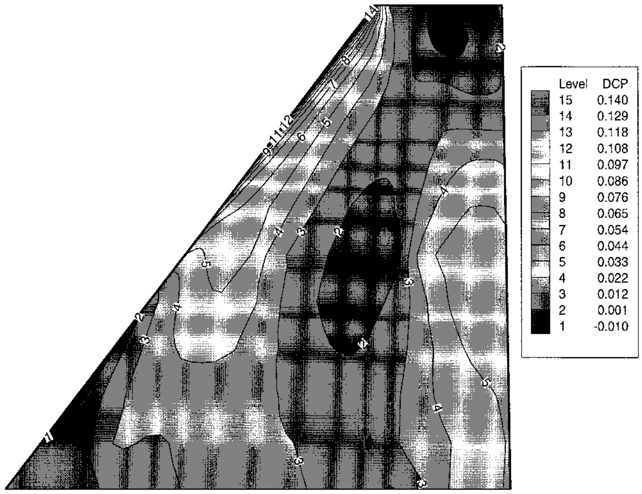

Fig. 2 Fighter wing $\Delta C_{p_{rigid}} - \Delta C_{p_{aeroelastic}}$ (M_∞ = 1.1, α_0 = 1.0 deg, q_∞ = 50.0 psi, U_∞ = 14736.48 in./s).

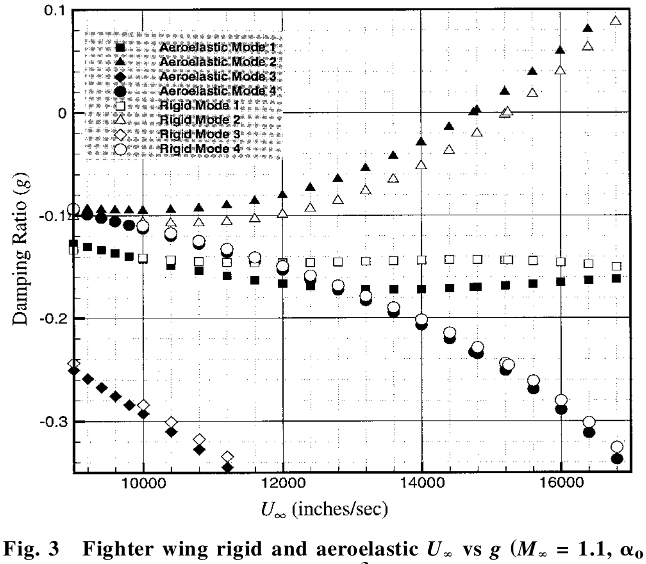

Fig. 3 Fighter wing rigid and aeroelastic U_∞ vs g (M_∞ = 1.1, α_0 = 1.0 deg, ρ_∞ = 3.776E-7 slinches/in.^{3}).

Table 1 Fighter wing flutter results[a]

Method	q_f, psi	U_f, in./s	ω_f, Hz
Time integration	53.5	14,736	20.10
IRM rigid	57.2	15,243	20.38
IRM aeroelastic	53.6	14,751	20.07

[a]M_∞ = 1.1, α_0 = 1.0°, 4.9272 × 10^{-7} slinches/in.^{3}.

steady-state pressure magnitudes and distribution which, in turn (as a result of the nonlinear flow), affects the perturbation results. This effect is most significant when the structure exhibits a large amount of bend twist coupling.

Concluding Remarks

The static aeroelastic effects on a transonic indicial response wing flutter analysis are presented. The method uses static aeroelastic equilibrium states as aerodynamic surface boundary conditions when performing indicial responses. For the example chosen, the inclusion of static aeroelastic effects reduces the difference between the IRM flutter dynamic pressure and the time integration flutter dynamic pressure from 7 to 0.1%. These results indicate that a more accurate flutter analysis can be obtained if static aeroelastic effects are included when approximating the unsteady aerodynamic forces. Although the magnitude of the static aeroelastic effects will be planform, airfoil, Mach number, initial conditions (angle of attack, dynamic pressure etc.), and structural flexibility dependent, some general guidelines on when to include static aeroelastic deformations in approximate flutter analysis can be postulated. Fundamentally, the static aeroelastic effects must be included if they significantly alter the resulting steady pressure distribution (not magnitude). It is this alteration in the pressure distribution that will affect the perturbation (indicial responses in this study) results and, hence, the approximated unsteady aerodynamic loads.

For the current study it is the transonic flow conditions along with the structural deformations that produce the change in the static pressure distribution. This implies that for Mach numbers ranging from 0.85 to 1.2, the static aeroelastic effects should be included in the approximate flutter analysis. Other conditions that would warrant including the static aeroelastic effects would be highly nonlinear flows (separated flows at high angles of attack, etc.), and/or structures that have a high apparent flexibility at the desired flight condition. The apparent flexibility being determined by a combination of the structural stiffness and the dynamic pressure at a given flight condition. Stiff structures at high dynamic pressures can produce large deformations and, hence, significant changes in the static pressure distribution. Likewise, flexible structures at low dynamic pressures appear rigid and produce no change in the static pressure distribution. In general, the static aeroelastic effects will be most significant when the steady-state flow is highly nonlinear and/or the structural displacements are large.

References

[1]Ballhaus, W. F., and Goorjian, P. M., "Computation of Unsteady Transonic Flows by the Indicial Method," *AIAA Journal*, Vol. 16, No. 2, 1978, pp. 117–124.

[2]Lee-Rausch, E. M., and Batina, J. T., "Calculations of AGARD Wing 445.6 Flutter Using Navier-Stokes Aerodynamics," AIAA Paper 93-3476, Aug. 1993.

[3]Bland, S. R., and Edwards, J. W., "Airfoil Shape and Thickness Effects on Transonic Airloads and Flutter," AIAA Paper 83-0595, 1983.

[4]McGrew, J. A., Giesing, J. P., Pearson, R. M., Zuhuruddin, K., Schmidt, M. E., and Kalman, T. P., "Supercritical Wing Flutter," U.S. Air Force Flight Dynamics Lab., TR-78-37, March 1978.

[5]Batina, J. T., "A Finite-Difference Approximate-Factorization Algorithm for Solution of the Unsteady Transonic Small-Disturbance Equation," NASA TP 3129, Jan. 1992.

[6]Kolonay, R. M., "Transonic Unsteady Aeroelastic Analysis for the Multidisciplinary Design Environment," AIAA Paper 95-1285, Sept. 1995.

[7]Striz, A. G., and Venkayya, V. B., "Influence of Structural and Aerodynamic Modeling on Optimization with Flutter Constraint," *Proceedings of the 3rd USAF/NASA Symposium on Recent Advances in Multidisciplinary Analysis and Optimization*, Anamet Labs., Inc., Haywood, CA, 1990, pp. 431–438.

[8]Harder, R. L., and Desmarais, R. N., "Interpolation Using Surface Splines," *Journal of Aircraft*, Vol. 9, No. 2, 1972, pp. 189–191.

Sensitivity of Open-Loop Typical Section Gust Response to Structural Parameters

Jeffrey B. Layton*
Clarkson University, Potsdam, New York 13699

Introduction

THE alleviation of the gust response of aircraft has been a topic of research for a number of years.[1] The goals of this research have been 1) to reduce the rms values of the loads that the aircraft experiences from a gust, 2) to increase fatigue life, 3) to better design the structure, 4) to provide increased comfort for the passengers and crew, and 5) to decrease the effect of the gust on the cargo.[1] One approach to gust alleviation is a passive approach, where an existing structure is resized to alleviate gust loads or to minimize the structural mass when subjected to a given gust.[2,3] The most common approach has been to include active control systems in the design.[4]

However, to the best of the author's knowledge, except for the very preliminary results of Ref. 3, there has not been an effort toward understanding the effects of structural modifications on the gust response of the wing with or without a control system. More significantly, there has been no research into understanding or quantifying the magnitude of the change in the open-loop gust response of a wing caused solely by structural modifications, nor into quantifying the sensitivity of the gust response caused by structural modifications. In particular, could a pure structural redesign significantly reduce the gust response? This Note seeks to begin to examine these issues by using a typical section model.

This Note uses the rms response as a measure of the gust response. This was done because it is a convenient and physically meaningful measure of the system response to a random input (the gust). For past aeroelastic research efforts, the rms has been used only for examining closed-loop aeroservoelastic systems. The rms approach has not been used to determine the influence of solely the structure on the gust response (open-loop), nor to quantify to what extent structural modifications can change the open-loop gust response of the aeroelastic system. Moreover, past researchers have typically examined the sensitivity of the weighted control cost, not the output response for pitch and plunge.

In this Note, the rms response of a typical section model subjected to a gust is examined using the state covariance matrix. In addition to determining the rms, this Note will use it as a guide for understanding (characterizing) the gust behavior of aeroelastic systems. The sensitivity of the rms behavior with respect to several aeroelastic parameters will be examined to gain some insight into passive aeroelastic stability augmentation design for gust alleviation. As a result of the characterization of the gust response sensitivity, the usefulness of the state covariance matrix for passive aeroelastic tailoring for gust response will be demonstrated.

It is hoped that from the characterization a range of questions can begin to be addressed. Is there one characteristic parameter or a small group of parameters that may be used to assess the full range of design possibilities over a range of airspeeds? In addition, if a parameter or combination of parameters identifies a design with a desired gust response, can it be extended to similar planforms? What, if any, are the limitations to reducing the gust response by inertial and structural redesign? This Note will begin to examine these questions by approaching the gust response as a mechanical dynamic response whose underlying cause is the aeroelastic interaction between characteristic deformations of the typical section.

Received July 24, 1995; revision received July 20, 1997; accepted for publication Oct. 8, 1997.

*Assistant Professor, Department of Mechanical and Aeronautical Engineering. Senior Member AIAA.

Model

This Note uses a typical section model that is quite well documented in the literature.[4] Although it is a simple model, and in some sense an educational model, it retains the major elements of aeroelastic behavior and does allow for insight into the fundamental behavior of aeroelastic models. Its simplicity allows for some characterization of general behavior that would not be practical for a more complex model.

Determination of the System RMS

The rms provides a convenient, scalar measure of the energy that the disturbance injects into the different modes of motion of the system. Moreover, it is a useful, physically meaningful measure of the response of a system to a random disturbance. Furthermore, it is a relatively easy quantity to compute for linear time-invariant systems.

Consider a linear time-invariant state–space model of an aeroelastic system

$$\dot{\boldsymbol{x}} = A\boldsymbol{x} + G\boldsymbol{w}, \qquad \boldsymbol{y} = C\boldsymbol{x} \tag{1}$$

where $\boldsymbol{x}$ is the state vector, $\boldsymbol{u}$ is the control input vector, $\boldsymbol{w}$ is the vector of disturbances, and $\boldsymbol{y}$ is the vector of system outputs. In general, provided that the plant is observable and controllable, stability is proven by finding a Lyapunov function for the system. For linear time-invariant systems, such as those described by Eq. (1), stability is then conditioned on the existence of a positive definite solution X to the following Lyapunov equation:

$$AX + XA^T + GWG^T = 0 \tag{2}$$

where A is the plant matrix, W is the intensity matrix of the disturbance (in this case the gust), and G describes how the disturbance affects the plant. X is the system covariance matrix. The system covariance matrix is related to the output covariance matrix Y by the following:

$$Y = CXC^T \tag{3}$$

where the matrix C is termed the output matrix in a first-order state–space model, and Y is n_y by n_y. The diagonal elements of Y are the mean square outputs of the system

$$\sigma_i^2 = [CXC^T]_{ii}, \qquad i = 1, \ldots, n_y \tag{4}$$

where σ_i^2 are the mean square outputs and σ_i is the rms measure of the system outputs. Because this is an open-loop model, by judiciously choosing the output matrix, the rms of any desired state can be easily computed. In the case of a modal model, the same situation is true, but involves the eigenvector matrix of the structural system in the C matrix.