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Efficient Aeroelastic Analysis Using Computational Unsteady Aerodynamics

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A methodology for efficient evaluation of generalized aerodynamic forces (GAFs) in transonic flows for use in flutter analysis is presented. GAF matrices are evaluated from a reduced-order model (ROM), which comprises the generalized aerodynamic forces recorded from a time-accurate computational fluid dynamics (CFD) analysis in response to a modal step excitation in each structural mode. With the step response database, that is, the ROM, the comprehensive CFD analysis is replaced by a simple convolution scheme to compute the GAFs. The forces due to excitation of one mode at a given Mach number for all reduced frequencies can be computed from a single step response. Comparison of the GAFs computed from the ROM to those computed by direct sinusoidal excitation of the boundary conditions in a CFD run demonstrate, that for small amplitudes of excitation, the ROM is capable of predicting the unsteady aerodynamic forces very accurately. The use of ROM offers a significant reduction in computational time and makes the calculation of CFD-based unsteady aerodynamic forces for flutter analysis feasible. The CFD-based GAFs are used to conduct a flutter analysis of the AGARD 445.6 wing at several Mach numbers, and the results are compared to wind tunnel test results.

Introduction

IT is widely recognized that computational fluid dynamics (CFD) methods should be more extensively used in aeroelastic analyses and structural design applications. The main argument that supports this notion is that in the transonic flow regime, which is of primary interest in aircraft design, CFD methods have significant advantages over the currently used linear aerodynamic methods. The major obstacles that prohibit extensive use of CFD methods in aircraft design are the large computational resources associated with a single CFD analysis and the fact that traditional frequency-domain flutter analysis methods are based on repeated evaluations of the unsteady aerodynamic forces at different values of reduced frequencies.

Recent studies[1–4] introduced the concepts of reduced-order models (ROMs) and linear model fitting for nonlinear unsteady aerodynamics. These concepts suggest that the input–output relation of the complex CFD system of interest, that is, flow equations and boundary conditions, can be represented by a relatively simple mathematical model, which is the ROM or the linear-fitted model. Feeding an arbitrary input through the ROM is far more efficient than feeding it through the full CFD analysis. Yet, the response captures the physical characteristics of the nonlinear system. For aeroelastic systems, a ROM that relates the aerodynamic forces to modal motion can be defined, offering an efficient method to compute the nonlinear generalized aerodynamic force (GAF) coefficient matrices required for flutter analysis. Cowan et al.[3,4] used a system identification technique to fit a linear model to responses computed by the STARS CFD code. The method was demonstrated on the AGARD 445.6 wing and on a generic hypersonic vehicle. In these cases, the generalized forces computed using the fitted linear model accurately predicted the forces obtained by forced excitation, providing a significant reduction in computational time. The drawback of this method, as noted by the authors, is that the quality of the results depends to a great extent on the correct choice of model and on the input–output data used to fit the model.

Silva[2,5–8] presented a reduced-order aerodynamic model that is founded on the Volterra theory of nonlinear systems. The ROM is made of a set of Volterra kernels that can be identified from a set of aerodynamic impulse responses. Once the Volterra kernels are identified, the nonlinear aerodynamic response to an arbitrary input can be determined using convolution schemes. Retaining all of the kernels in the convolution scheme would theoretically provide the fully nonlinear response, avoiding the linearity assumption discussed earlier, whereas retaining only the first kernel would result in a linearized response over a nonlinear steady state. The method was demonstrated for a plunging rigid wing using the CAP-TSD transonic small disturbance code[7,8] and for a plunging airfoil using the CFL3D Navier–Stokes code.[2,8]

Ballhaus and Goorjian[9] introduced a ROM based on the response of the CFD system to a step (indicial) input. Using a transonic small disturbance code, they computed the lift and moment coefficients of airfoils in response to a harmonically oscillating angle of attack. Comparison of results obtained by using the indicial response to results from direct excitation provided insight on the effects of step amplitude, frequency, and Mach number on the applicability of the method.

The current study presents a ROM model, based on the first-order Volterra series, for evaluation of the unsteady aerodynamic forces in response to arbitrary modal motion. The ROM is created from responses of the CFD system to modal step inputs introduced to the boundary conditions, and therefore it can be seen as an extension to the ROM methodology presented in Ref. 9. The ROM is used to compute the GAF matrices, at different values of reduced frequencies, for the purpose of flutter analysis. The ROM is dependent on the Mach number, but is independent of the dynamic pressure. Therefore, for a given Mach number, the GAFs at various reduced frequencies can be rapidly evaluated by convolution schemes using a sinusoidal input signal of the required reduced frequency. Responses computed using the ROM are compared to direct responses obtained by harmonically exciting the boundary conditions in a CFD run. This comparison is repeated for various Mach numbers, excitation frequencies, and modes. The method is demonstrated on the AGARD 445.6 wing[10] using the EZNSS Euler/Navier–Stokes code developed

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by Levy. GAF matrices are compared to linear and nonlinear GAFs reported in the literature of the AGARD wing. Finally, these GAFs are used in a flutter analysis of the AGARD wing, comparing flutter characteristics to those reported from wind-tunnel tests.

Methodology

Volterra Theory for Nonlinear Systems

The Volterra theory (see Ref. 11) formulates the input–output relation of a nonlinear system. The response $y[n]$ to an arbitrary input signal $u[n]$ can be evaluated by a multidimensional convolution as

$$y[n] = h_0 + \sum_{k=0}^{N} h_1[n-k]u(k) + \sum_{k1=0}^{N}\sum_{k2=0}^{N} h_2[n-k1, n-k2]u[k1]u[k2] + \cdots + \sum_{k1=0}^{N}\cdots\sum_{kn=0}^{N} h_n[n-k1,\ldots,n-kn]u[k1]\ldots u[kn] \qquad n = 0,1,2,\ldots \tag{1}$$

where n is the discrete-time variable, h_0 is the steady-state response, and the functions $h_n[n-k1,\ldots,n-kn]$ are the Volterra kernels of the system. Silva[8] showed that the nonlinear Navier–Stokes equations can be considered weakly nonlinear, that is, can be accurately represented by a truncated second-order Volterra series, neglecting higher kernels. In the present work, we further assume that the system is a first-order Volterra system, which is a system whose response can be evaluated using only the first term of the Volterra series. Being aware that for nonlinear systems scaling of responses is not valid for a general input amplitude, we limit ourselves to small perturbations about the nonlinear mean flow. The system's response can then be evaluated by convolving the input signal with the system's impulse response $h[n]$ according to

$$y[n] = h[0] + \sum_{k=0}^{N} h[n-k]u[k] \qquad n = 0,1,2,\ldots \tag{2}$$

The impulse response of a system represents the manner in which the system responds to a unit perturbation, which, in a discrete-time, is defined as

$$\delta[n] = \begin{cases} 1.0 & \text{for} \quad n = 0 \\ 0.0 & \text{for} \quad n \neq 0 \end{cases} \qquad n = 0,1,2,\ldots \tag{3}$$

An alternative approach is to relate the CFD system response to a displacement step input, which is equivalent to a velocity impulse input. In this study, the system inputs are modal displacements, and a modal displacement step is introduced to the CFD computation as

$$\xi[n] = \begin{cases} \xi_0 & \text{for} \quad n \geq 0 \\ 0.0 & \text{for} \quad n < 0 \end{cases} \qquad n = 0,1,2,\ldots \tag{4}$$

where ξ_0 is the amplitude of the modal displacement. The recorded response is normalized by ξ_0 to account for the amplitude of the step input not being unity. The response of the CFD system to an arbitrary input is computed by convolution of the normalized step response $s[n]$ with the input signal $u[n]$, according to Duhamel's integral

$$y[n] = u[0]s[n] + \sum_{k=1}^{N} s[n-k](u[k] - u[k-1]) \qquad n = 0,1,2,\ldots \tag{5}$$

An important note should be made regarding the manner in which different CFD schemes handle grid velocities. The more comprehensive approach is to include the time derivatives of the grid by deriving the governing equations in time-dependent general curvilinear coordinates. However, some CFD codes, mainly those that were designed for nonmoving configurations, omit those derivatives, whereas in other codes, such as CFL3D,[12] grid velocities are defined by the analyst, independent of the grid location. The method developed in this study is based on the system response to both the grid displacements and the velocities induced by the input pulse, and therefore it is applicable only to CFD schemes that account for the grid velocity.

A direct method to identify the CFD-system step response is to feed the input signal through the system and record the time history of the GAFs. This is done in two phases. In the first phase, the CFD equations are converged to a steady-state condition. This condition can be defined either by the Mach number and incidences, or it can be defined as a trimmed maneuver (traditionally a transonic cruise). Steady flowfields at trimmed maneuvers can be evaluated by the recently presented methodology of Ref. 13. In the second phase, the step displacement of Eq. (4) is prescribed to each mode separately. This modal displacement is then translated to physical displacements of the CFD surface grid points according to

$$\boldsymbol{u} = \phi_i \xi_i \tag{6}$$

and then applied to the whole grid. The term ϕ_i in Eq. (6) is a vector describing the ith elastic mode shape in the CFD surface grid points. The method that is used to map the modes from the finite element nodes, in which they are computed, to the CFD surface grid points, as well as the method that is used to apply surface displacements to the whole grid, is described in detail in Ref. 14. The generalized aerodynamic forces are recorded during the convergence of the CFD response. At every time step they are calculated by a modal summation of the CFD surface forces $\boldsymbol{F}_A(n)$, according to

$$\boldsymbol{GF}_A[n] = \phi^T \boldsymbol{F}_A[n] \tag{7}$$

A complete database of the CFD-system response is constructed by logging all of the modal step responses. From this database, the generalized aerodynamic forces due to any arbitrary modal motion can be rapidly evaluated using the convolution of Eq. (5).

The results in this paper are all based on step responses, which were found to be more suitable for this application than the impulse responses. A comprehensive study of impulse vs step responses will be presented in another paper. Note that compared to the impulse response, the evaluation of the step response is less efficient. This is because, although the impulse is merely a transient disturbance to the CFD grid, the displacement step defines a new grid shape, and therefore, requires a larger number of CFD iterations to converge to the new steady state. The typical number of iterations for convergence is dependent on the displacement amplitude and on the time step. For example, in the current application, approximately 1000 iterations were required to converge the flowfield after a modal step of amplitude of 0.001 was applied, using a time step of 0.01. Nevertheless, the computational time of the step response is only a small fraction of the time that is required for the full forced-harmonic analysis.

Aeroelastic System

The aeroelastic equation of motion in generalized coordinates is stated as

$$GM\ddot{\boldsymbol{\xi}} + GK\boldsymbol{\xi} - \boldsymbol{GF}_A(t) = 0 \tag{8}$$

where GM and GK are the generalized mass and stiffness matrices, respectively, and $\boldsymbol{GF}_A$ is the GAFs vector that is dependent on the structural deformations, their time derivatives, and time histories. Traditional frequency-domain flutter methods are based on the assumption that the modal motions are simple harmonic motions, so that Eq. (8) can be written as

$$[-\omega^2 GM + GK - q\,\mathrm{GAF}(ik)]\boldsymbol{\xi} = 0 \tag{9}$$

where q is the dynamic pressure and k the reduced frequency defined as

$$k = \omega b/U \tag{10}$$

where ω is the physical frequency and b and U are the reference semichord and velocity, respectively. GAF is the matrix of generalized aerodynamic force coefficients, in which the ith column represents the generalized forces in all modes due to a unit-amplitude harmonic motion of the ith mode. To solve Eq. (9) for the stability boundary, the GAF matrix is first evaluated for different values of reduced frequencies. Numerical search procedures can then be applied to find pairs of frequencies and dynamic pressures at which the system becomes unstable.

In this study, nonlinear GAF matrices are introduced into Eq. (9). The term nonlinear GAFs may sound inappropriate inasmuch as the formulation of the aeroelastic equations for linear stability analysis [Eq. (9)] is based on the assumption that the aerodynamic forces linearly depend on the structural deformation amplitudes. However, in this context, the term nonlinear GAFs refers to GAFs evaluated from a nonlinear flow analysis that are used to compute the response to small-amplitude modal excitation about the steady-state nonlinear flow conditions. This implies that the nonlinear GAFs retain the nonlinear properties of the mean flow (unlike the linear GAFs that are independent of the mean flow) and also that the superposition is limited to small perturbations about the steady-state condition.

The nonlinear GAF matrix can be rapidly evaluated by the convolution of Eq. (5), in which the step response $s[n]$ for every mode is available from the step-response database, and the input $u[n]$ is a simple harmonic motion in a reduced frequency k. For $k = 0$, the real part of the ith GAF column is simply the converged value of the ith mode step response, normalized by the step amplitude and the dynamic pressure. The imaginary part at $k = 0$ equals zero.

There are different numerical methods to solve Eq. (9). Flutter analysis in this study is performed by introducing the nonlinear GAFs into a g-method[15] flutter analysis, performed by ZAERO.[16] The nonlinear GAFs are used instead of the linear GAFs that are normally computed in ZAERO by its linear panel methods ZONA6[16] (for subsonic flows) and ZONA7[16] (for supersonic flows). ZAERO also has a transonic aerodynamic method, ZTAIC,[16] that relies on steady pressure distribution from CFD analysis to account for nonlinear effects. The results section of this paper presents comparison of the CFD-based GAFs and the ZAERO GAFs (linear and nonlinear where available) and the corresponding flutter characteristics.

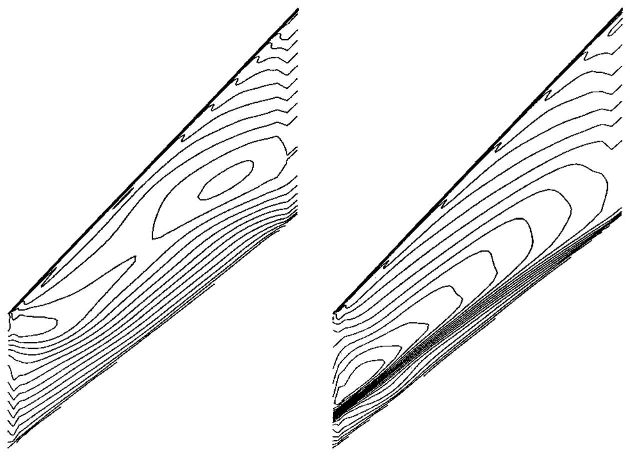
Results

The proposed ROM methodology of this study is demonstrated with the AGARD 445.6 wing.[10] The AGARD 445.6 wing was tested for flutter characteristics in the transonic dynamic tunnel at NASA Langley Research Center and was used as a test case in many studies on the subject of transonic unsteady aerodynamics, for example, Refs. 3 and 17–19.

For the CFD computations, the flowfield around the AGARD 445.6 wing was evaluated using a C–H type grid, with 193 grid points in the chordwise direction along the wing and its wake, 65 grid points in the spanwise direction, and 41 grid points along a direction normal to the wing surface. The grid dimensions are similar to the dimensions used in Ref. 19, where a grid-density study indicated that these grid dimensions are adequate for the investigated flow conditions.

The flow is analyzed by the EZNSS[20] Euler/Navier–Stokes code. Initial analyses provided the steady-state inviscid flowfield at several freestream Mach numbers, at a zero angle of attack. Steady-state pressure coefficient contours at Mach numbers 0.96 and 1.141 are shown in Fig. 1. The pressure contours of Fig. 1 are similar to those presented in Ref. 18 for an analysis performed using the CFL3D code. With the lack of wind-tunnel pressure measurements for the AGARD 445.6 wing, comparison to results obtained with other CFD codes served as a verification of the EZNSS results.

Before proceeding to the unsteady computation, the modes that were calculated by finite element analysis in Ref. 10 were mapped onto the CFD surface grid points, by use of the interface method of Refs. 13 and 14. Figure 2 shows the wing's elastic modes, already mapped to the CFD surface grids, indicating the associated modal frequency. The modes can be characterized as first bending, first torsion, second bending, and second torsion.



a) b)

Fig. 1 Steady-state pressure contours on the upper surface, at zero angle of attack, at freestream Mach numbers of a) 0.96 and b) 1.141.

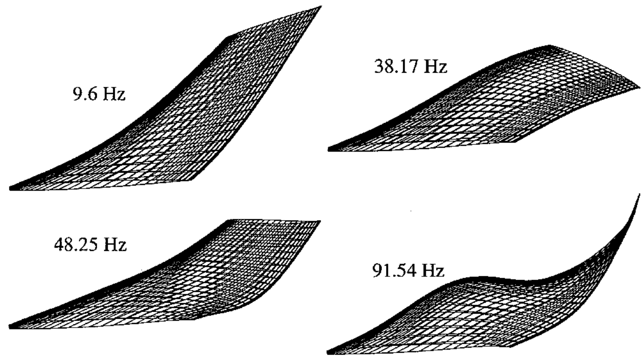


Fig. 2 AGARD 445.6 wing first four elastic mode shapes mapped into the CFD surface grids.

Next, a step-response database was constructed for Mach number of 0.96. A dimensionless time step of 0.01 was used, together with a modal step amplitude of 0.001. The criteria used to choose these input parameters were as follows:

1) The time step was chosen to be small enough to achieve adequate resolution of the response. Because the step response is used to construct the frequency response, the time step should be small enough to ensure enough samplings per cycle. A dimensionless time step of 0.01 results in 1000–100 samplings per cycle for reduced frequencies of 0.1–1.0.

2) In accordance with the chosen time step, the modal step amplitude was chosen such that the resulting grid displacements and velocities are of an order of magnitude that the CFD code can handle without blowing up.

3) The grid displacements and velocities should be kept small in accordance with the basic assumption of linear perturbations about the steady-state condition. A modal displacement of 0.001 in the first bending mode results in maximum displacements of about 0.1% of the root chord. In the first wing torsion mode, the same modal displacement results in a maximum tip torsion angle of about 0.3 deg.

Figure 3 shows the first wing bending mode step response, that is, the time-dependent generalized forces in all four modes, recorded from the CFD in response to a unit modal step applied to the first mode. The sea-level far-field pressure of $p_\infty = 2116.22$ lb ft^2 was used to compute the dimensional forces in Fig. 3. When the dynamic-pressure-independent GAFs are calculated, these responses are normalized by the dynamic pressure used to calculate them ($q = 1/2\gamma M_\infty^2 P_\infty$). Therefore, the value of p_∞ used in the CFD analysis is meaningless and can be taken as unity, or γ^{-1}, as normally is the case in CFD analyses.

The modes of the AGARD 445.6 wing are weakly coupled, that is, the first mode is mainly a bending mode, whereas the second mode is mainly torsion. Therefore, when the first mode is excited,

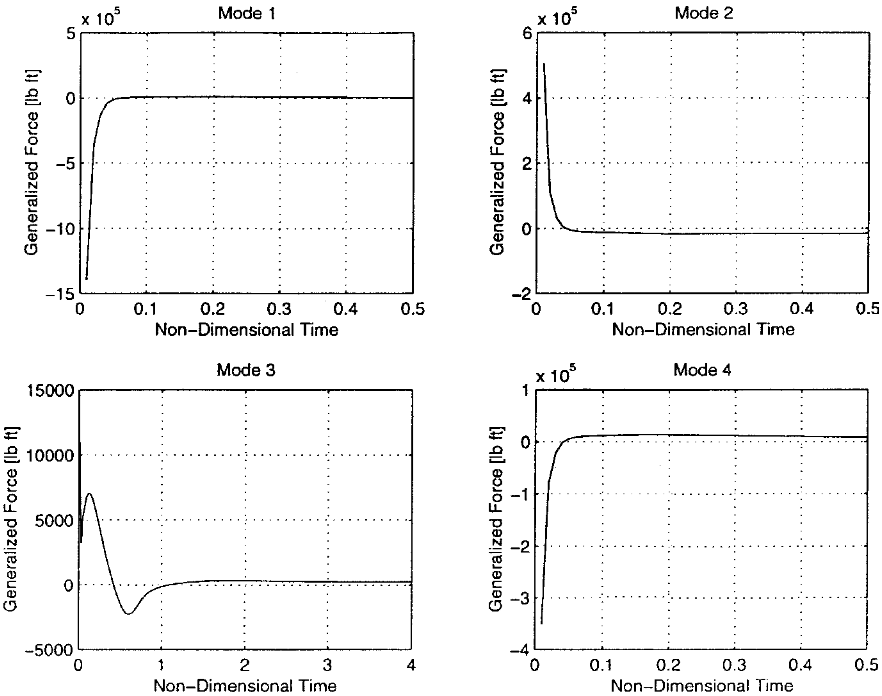


Fig. 3 Recorded CFD response to a step input in the first wing bending mode, Mach 0.96.

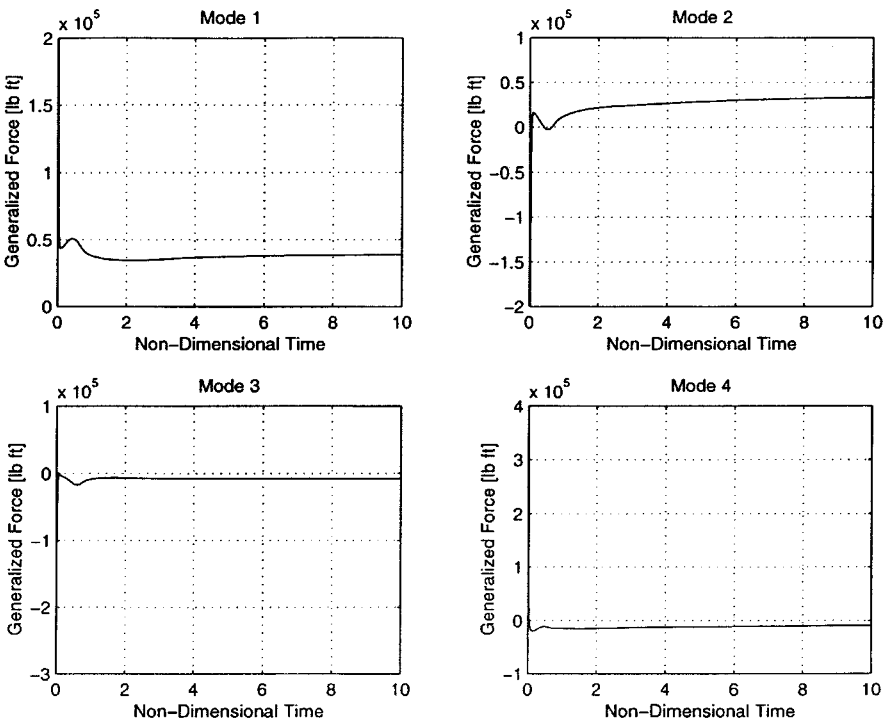


Fig. 4 Recorded CFD response to a step input in the first wing torsion mode, Mach 0.96.

generalized forces develop in response to modal velocity rather than in response to modal displacement. This can be seen in Fig. 3: Vertical velocity exists only in the first time step, and it causes large generalized forces to develop. These forces then rapidly decay, and at the steady state the generalized forces are almost zero. Contrarily, when the second mode is excited by a modal step, the modal displacement changes the local angles of attack, leading to nonzero forces at the steady state, as seen in Fig. 4.

Nonlinear GAFs

Next, the GAFs computed by the convolution of Eq. (5) are compared to the forces obtained directly from the CFD analysis in response to a forced-harmonic excitation. For the forced-harmonic response, a sinusoidal modal displacement was prescribed to each mode, in a time-accurate simulation, which was restarted from the steady-state flow conditions of Mach 0.96 and zero angle of attack. The time step for the forced harmonic analysis was chosen as 0.0279, and the modal amplitude was chosen as 0.01, which is 10 times larger than the modal amplitude that was used to calculate the step response but still in the amplitude range that results in a linear response (in most cases). Comparisons of the convolved and the direct responses were repeated for a large range of oscillation frequencies, for all four elastic modes. Figure 5 shows the convolved and direct forces in all of the modes in response to an oscillation of the first wing bending

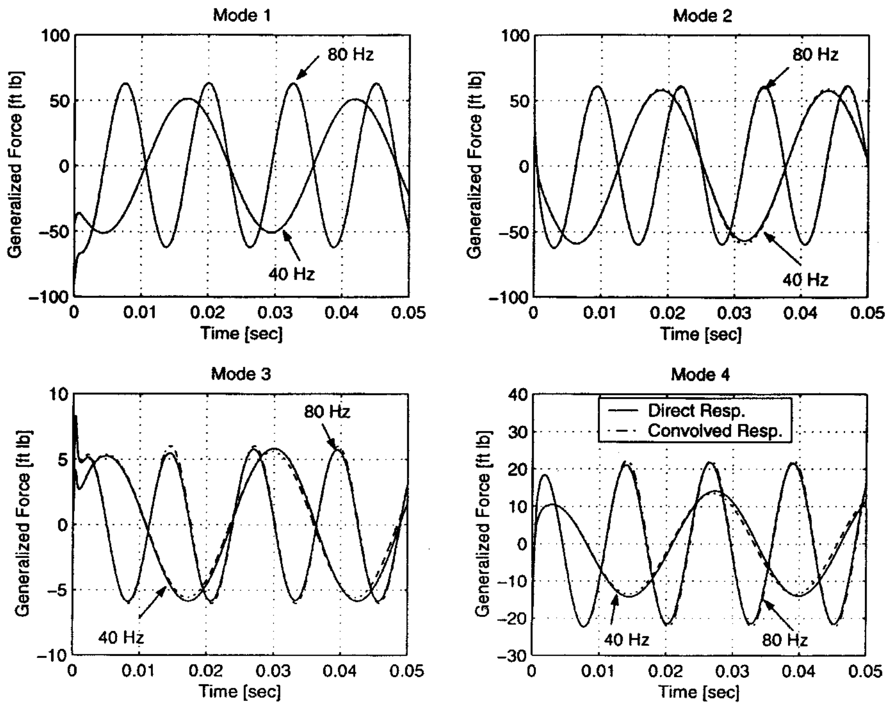


Fig. 5 Convolved vs direct response to sinusoidal excitation of the first wing bending mode at frequencies of 40 and 80 Hz, modal amplitude of 0.01, and Mach 0.96.

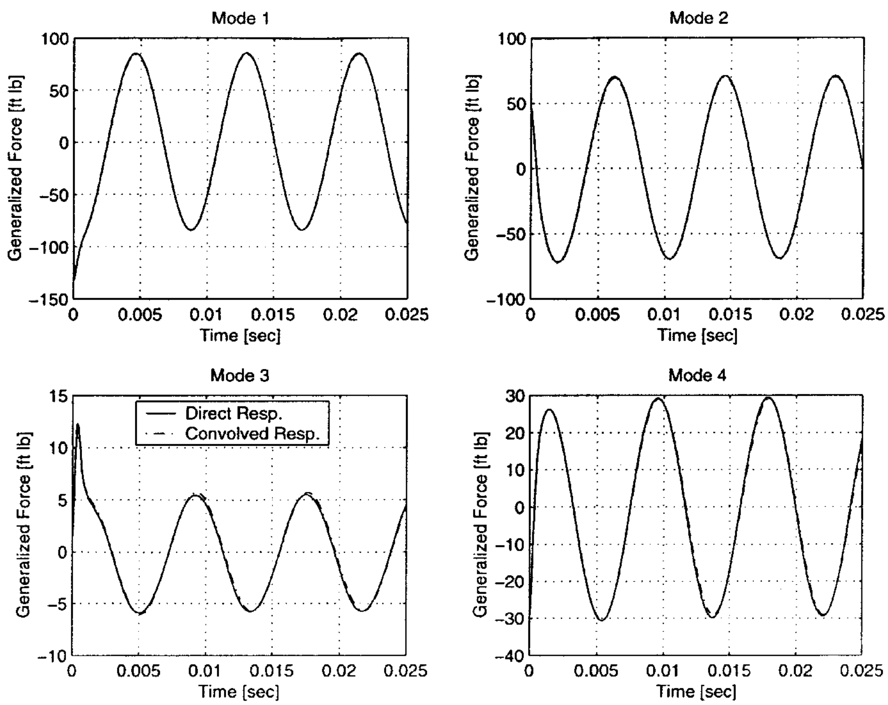


Fig. 6 Convolved vs direct response to sinusoidal excitation of the first wing bending mode at a frequency of 120 Hz, modal amplitude of 0.01, and Mach 0.96.

mode, at frequencies of 40 and 80 Hz (which correspond to a reduced frequencies of 0.23 and 0.47, respectively). Figure 6 shows the 120-Hz response (corresponds to a reduced frequency of 0.7). Figure 7 shows the convolved vs the direct response to an oscillation of the first wing torsion mode at a modal amplitude of 0.025 and frequency of 40 Hz. In this case, the oscillation amplitude is 25 times larger than the amplitude used to construct the step response. In all cases, the convolved response compares very well with the direct response, which demonstrates the wide range of application of the ROM.

Comparisons were made for several Mach numbers (0.678, 0.96, 1.141). In all cases in which the direct response was linear, it was very well predicted by the ROM. Among the studied cases, some of the direct responses were nonlinear, typically as a response to high-amplitude inputs and at the low-frequency range (5–10 Hz). In those cases, there were discrepancies between the direct and convolved responses, as can be seen, for example, in Fig. 8, which corresponds to excitation of the first torsion mode at Mach 1.141, at frequency of 10 Hz (reduced frequency of 0.059). When the direct input amplitude was decreased, such that the direct response was linear, a

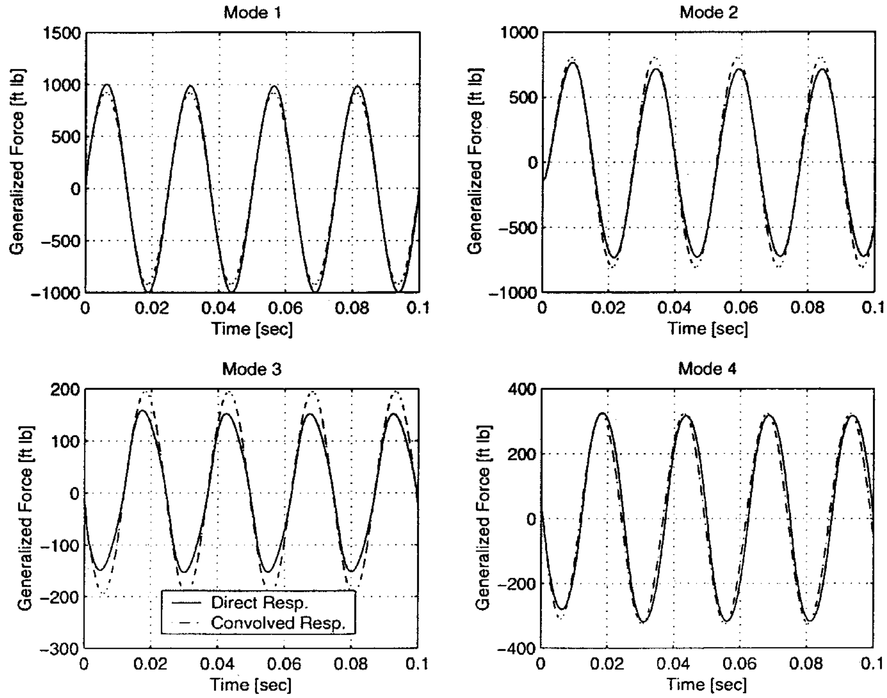


Fig. 7 Convolved vs direct response to sinusoidal excitation of the first wing torsion mode at a frequency of 40 Hz, modal amplitude of 0.025, and Mach 0.96.

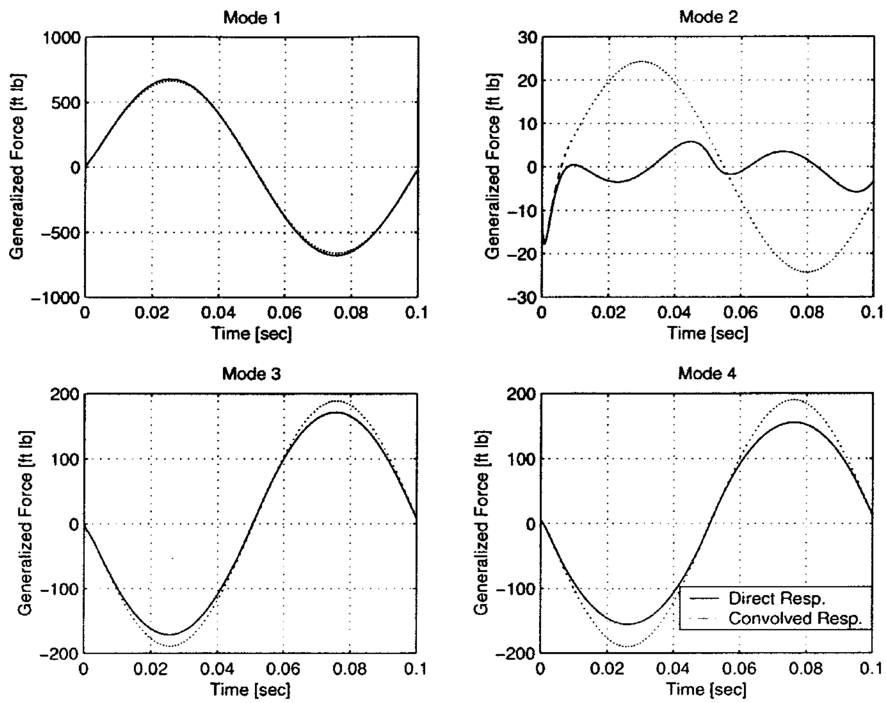


Fig. 8 Convolved vs direct response to sinusoidal excitation of the first wing torsion mode at a frequency of 10 Hz, modal amplitude of 0.01, and Mach 1.141.

good matching appeared (Fig. 9). The difference between Figs. 8 and 9 does not suggest any improvement of the ROM, but rather demonstrates that the first-order ROM is accurate for predicting responses to small perturbations about the nonlinear mean flow. Because the aeroelastic equation for flutter analysis [Eq. (9)] is already cast as a linear stability problem, there is no significance to the displacement amplitudes in determining the system's stability. A ROM made of a database of step responses, computed with small displacement/velocity amplitudes, can be used to evaluate the nonlinear GAF matrices at a large range of reduced frequencies as shown next.

The evaluation of the unsteady aerodynamic forces by convolution offers a great computational time saving compared to the direct response. For the AGARD 445.6 wing, creating the step-response database at a specific Mach number for all four modes required 4000 CFD iterations. Then, the evaluation of the forces along a range of frequencies was performed within a few minutes. For comparison, the direct evaluation of the forces during one cycle at a frequency of 5 Hz required approximately 8000 CFD iterations.

Nonlinear GAFs were computed for a range of reduced frequencies and compared to linear GAFs computed by the ZAERO's

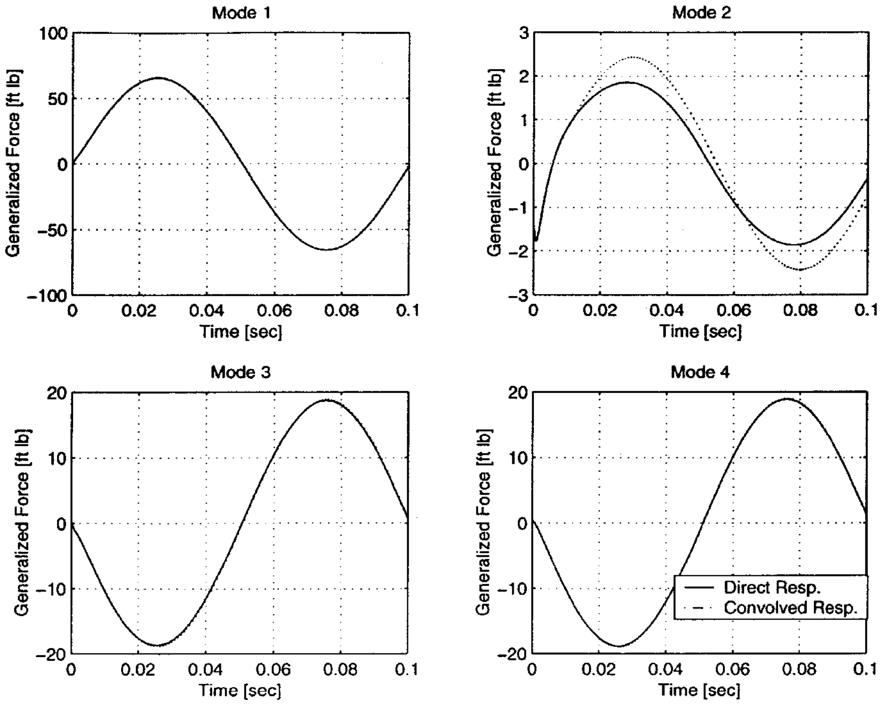


Fig. 9 Convolved vs direct response to sinusoidal excitation of the first wing torsion mode at a frequency of 10 Hz, modal amplitude of 0.001, and Mach 1.141.

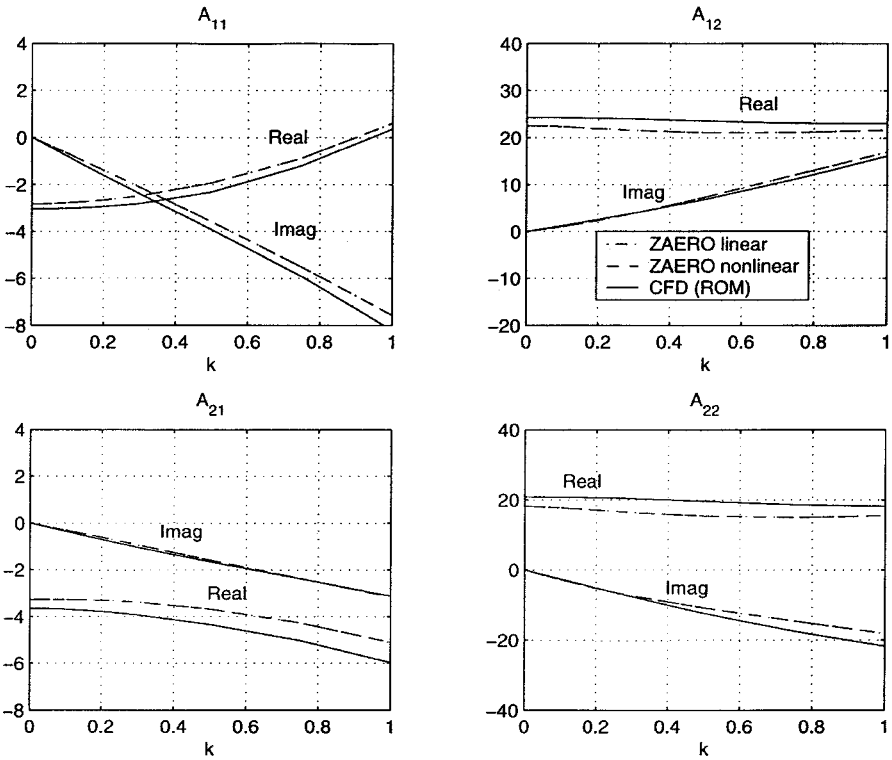


Fig. 10 Comparison of linear and nonlinear GAFs for the first two modes, Mach 0.678.

ZONA6 and ZONA7 aerodynamic modules. Where data was available, a comparison was also made with GAFs computed by ZTAIC,[16] ZAERO's nonlinear transonic method, in which steady pressure distributions from CAP-TSD analysis were used to introduce nonlinear effects into the GAFs.[21] Figures 10–13 show the GAFs in the form of complex numbers, for the first two modes. At Mach number of 1.141, the real part of the CFD-based A_{22} element is very small compared to the linear one, and the real part of the CFD-based A_{12} element is significantly different than the linear one. The same phenomenon was reported in Refs. 19 and 22, in which the decrease of the A_{22} term was attributed to the aft motion of the aerodynamic center due to the shock wave. Apparently, the shock predicted by the Euler analysis for this case is stronger than in reality, and a Navier–Stokes analysis is required to produce more realistic GAF matrices.[19]

Flutter Analysis

The nonlinear GAFs of the first four modes were used in a g-method flutter analysis within ZAERO, replacing the linear GAFs. For each Mach number, the density was kept fixed at a value equal

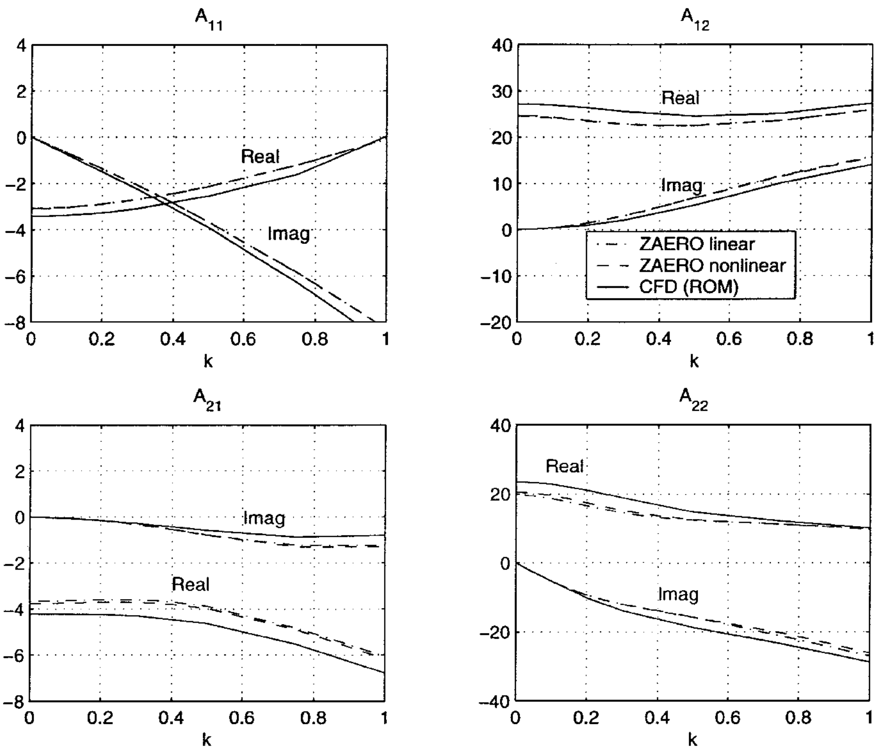


Fig. 11 Comparison of linear and nonlinear GAFs for the first two modes, Mach 0.9.

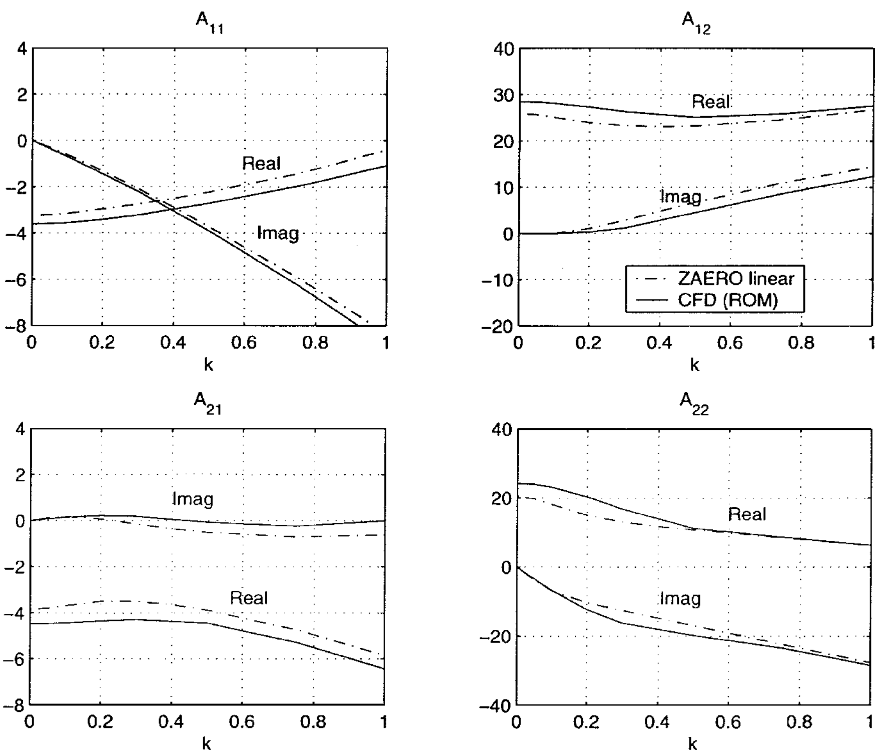


Fig. 12 Comparison of linear and nonlinear GAFs for the first two modes, Mach 0.96.

to the flutter density reported in Ref. 10 and the velocity was varied. Figure 14 shows the computed flutter characteristic of the AGARD 445.6 wing, compared with wind-tunnel test results reported in Ref. 10. Flutter characteristics are presented in terms of the flutter speed index $U_f/b\omega_\alpha\sqrt{\mu}$ and the flutter frequency ratio ω/ω_α, where U_f and ω are the flutter velocity and frequency, respectively, b_s is the streamwise semichord measured at the wing root, ω_α is the natural frequency of the wing's first torsion mode, and $\mu = m/\rho V$ is the mass ratio defined as the ratio between the wing mass and the mass of air contained within a volume V of a conical frustum having streamwise root chord as lower base diameter, streamwise tip chord as upper base diameter, and panel span as height.

At the transonic regime (Mach 0.9 and 0.96) the flutter characteristics are in good agreement with wind-tunnel test results. At Mach number 1.141, the flutter analysis based on the nonlinear GAFs resulted in no flutter of the first wing bending and wing torsion modes. In Ref. 19, flutter at Mach 1.141 is reported with GAFs that are similar to those of the current study; however, the flutter char-

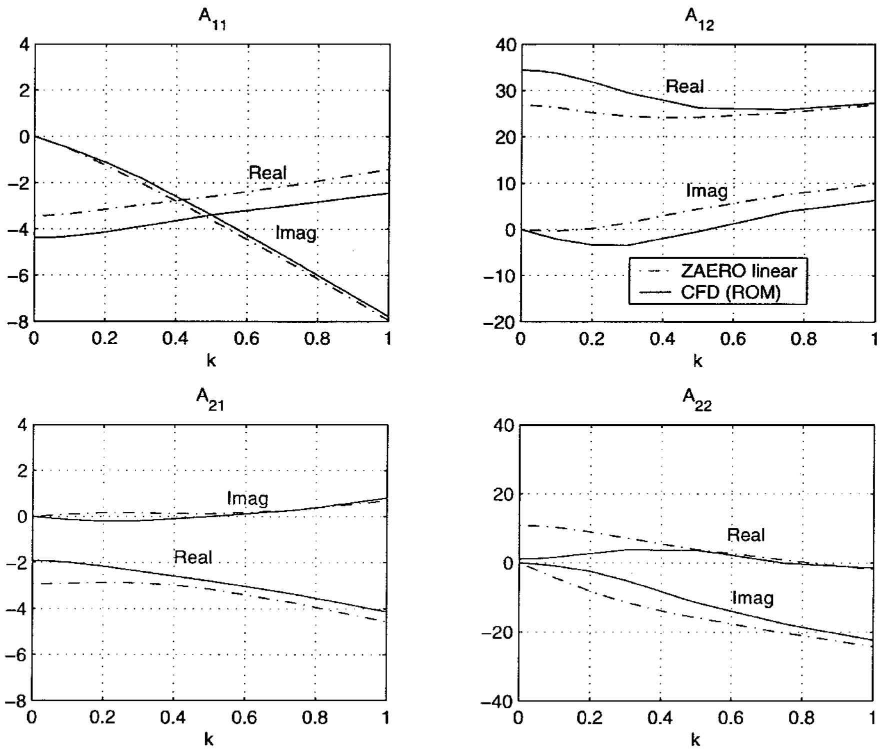
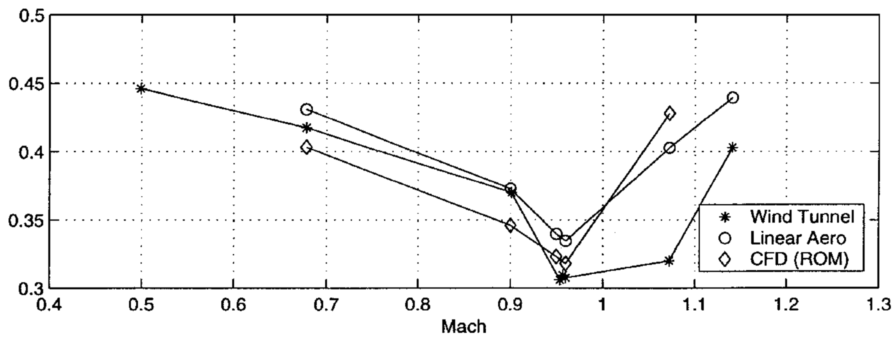
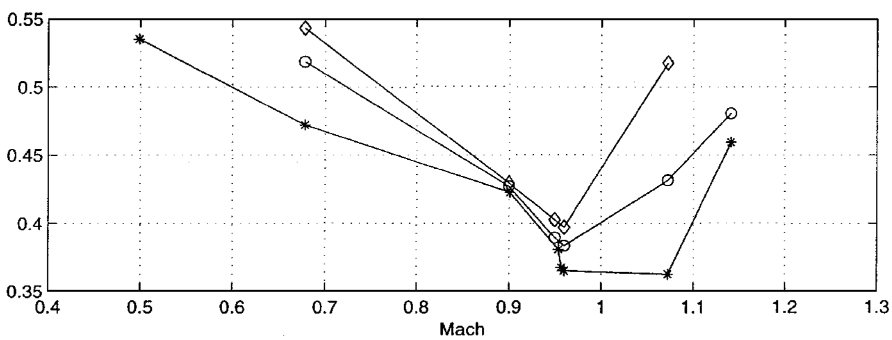


Fig. 13 Comparison of linear and nonlinear GAFs for the first two modes, Mach 1.141.



Flutter speed index



Flutter frequency ratio

Fig. 14 Computed vs wind tunnel tests flutter characteristics for the AGARD 445.6 wing.

acteristics are significantly different than those of the wind-tunnel test. In general, it was found that the flutter characteristics of the AGARD 445.6 wing at these conditions are not only sensitive with respect to the GAF values but also with respect to the method used for flutter analysis (not presented in this paper).

Conclusions

The paper presented a novel method to evaluate nonlinear transonic GAFs from a CFD Euler code for flutter analysis. A set of CFD modal step responses served as a first-order Volterra series ROM, and GAF matrices were computed by convolution of sinusoidal signals, in different reduced frequencies, with the ROM. Comparison of the GAFs computed from the ROM with those computed by direct sinusoidal excitation demonstrated that for the linear response regime, that is, for small amplitudes of excitation, the ROM is capable of evaluating the unsteady aerodynamic forces very accurately. For larger amplitudes, for which the response is nonlinear, the ROM suggested in this paper is not adequate for accurate prediction of the response. For applications where the response to large displacements is required, for example, limit-cycle oscillation prediction, the

ROM can be enhanced to include second- and higher-order kernel elements. Computing the GAFs over a range of reduced frequencies by the ROM provided a significant computational time saving compared to the forced-harmonic method. Flutter analysis performed by the g-method with nonlinear GAFs provided flutter characteristics at Mach numbers of 0.678–1.141. The transonic flutter characteristics were found to be in good agreement with those reported from wind-tunnel tests and in less close agreement in other flow regimes. At Mach number 1.141, it was found that the Euler analysis is inadequate for the prediction of the flowfield.

The nonlinear GAFs can be utilized in structural aeroelastic design applications based on the modal approach, where a limited, fixed set of structural modes of the baseline structure is used throughout the optimization process. With the modal-based design method, the GAFs would have to be evaluated only once, for the baseline structure. Structural design was not applicable with the AGARD 445.6 wing that served as the test case of this paper because a finite element structural model was not available to the authors. Structural design using nonlinear GAF matrices is, therefore, left for future applications.

References

[1]Dowell, E. H., Hall, K. C., Thomas, J. P., Florea, R., Epureano, B. I., and Heeg, J., "Reduced Order Models in Unsteady Aerodynamics," *40th Structures, Structural Dynamics, and Materials Conference*, AIAA, Reston, VA, 1999.

[2]Silva, W. A., "Reduced-Order Models Based on Linear and Nonlinear Aerodynamic Impulse Response," *International Forum on Aeroelasticity and Structural Dynamics*, NASA, Langley Research Center, Hampton, VA, 1999, pp. 369–379.

[3]Cowan, T. J., Arena, A. S., Jr., and Gupta, K. K., "Accelerating CFD-Based Aeroelastic Predictions Using System Identification," *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, AIAA, Reston, VA, 1998, pp. 85–93.

[4]Cowan, T. J., Arena, A. S., Jr., and Gupta, K. K., "Development of Discrete-Time Aerodynamic Model for CFD-Based Aeroelastic Analysis," *37th AIAA Aerospace Sciences Meeting and Exhibit*, AIAA 99-0765, AIAA, Reston, VA, 1999.

[5]Silva, W. A., "Application of Nonlinear Systems Theory to Transonic Unsteady Aerodynamic Responses," *Journal of Aircraft*, Vol. 30, No. 5, 1993, pp. 660–668.

[6]Silva, W. A., "Extension of a Nonlinear System Theory to General-Frequency Unsteady Transonic Aerodynamic Responses," *34th Structures, Structural Dynamics, and Materials Conference*, AIAA, Reston, VA, 1993, pp. 2490–2503.

[7]Silva, W. A., "Identification of Linear and Nonlinear Aerodynamic Impulse Response Using Digital Filter Techniques," *AIAA Atmospheric Flight Mechanics Conference*, AIAA, Reston, VA, 1997, pp. 584–597.

[8]Silva, W. A., "Discrete-Time Linear and Nonlinear Aerodynamic Impulse Responses for Efficient CFD Analyses," Ph.D. Dissertation, Faculty of the Dept. of Applied Science, College of William and Mary, Williamsburg, VA, Oct. 1997.

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

[10]Yates, E. C., Jr., "AGARD Standard Aeroelastic Configurations for Dynamic Response. Candidate Configuration I.—Wing 445.6," NASA TM-100492, 1987.

[11]Rugh, W. J., *Nonlinear System Theory The Volterra/Wiener Approach*, Johns Hopkins Univ. Press, Baltimore, MD, 1981.

[12]Krist, L., Biedron, R. T., and Rumsey, C. L., "CFL3D User's Manual (Version 5.0)," NASA TM 1998-208444, June 1988.

[13]Raveh, D. E., and Karpel, M., "Structural Optimization of Flight Vehicles with Computational-Fluid-Dynamics-Based Maneuver Loads," *Journal of Aircraft*, Vol. 36, No. 6, 1999, pp. 1007–1015.

[14]Raveh, D. E., "Integrated Aero-Structural Design of Maneuvering Flexible Flight Vehicles," Ph.D. Dissertation, Faculty of Aerospace Engineering, Technion—Israel Inst. of Technology, Haifa, Israel, Feb. 1999.

[15]Chen, P. C., "A Damping Perturbation Method for Flutter Solution: The g-Method," *International Forum on Aeroelasticity and Structural Dynamics*, NASA, Langley Research Center, Hampton, VA, 1999, pp. 433–441.

[16]*ZAERO Theoretical Manual*, 99-24.4 ed., Zona Technologies, Scottsdale, AZ, Nov. 1999.

[17]Cunningham, H. J., Batina, J. T., and Bennett, R. M., "Modern Wing Flutter Analysis by Computational Fluid Dynamics Method," *Journal of Aircraft*, Vol. 25, No. 10, 1988, pp. 962–968.

[18]Lee-Rausch, E. M., and Batina, J. T., "Wing Flutter Boundary Prediction Using Unsteady Euler Aerodynamic Method," *Journal of Aircraft*, Vol. 32, No. 2, 1995, pp. 416–422.

[19]Lee-Rausch, E. M., and Batina, J. T., "Wing Flutter Computations Using an Aerodynamic Model Based on the Navier–Stokes Equations," *Journal of Aircraft*, Vol. 33, No. 6, 1996, pp. 1139–1147.

[20]Raveh, D. E., Levy, Y., and Karpel, M., "Structural Optimization Using Computational Aerodynamics," *International Forum on Aeroelasticity and Structural Dynamics*, NASA, Langley Research Center, Hampton, VA, 1999, pp. 469–481.

[21]*ZAERO Applications Manual*, 99-24.3 ed., Zona Technologies, Scottsdale, AZ, Nov. 1999.

[22]Mohr, R. W., Batina, J. T., and Yang, H. T. Y., "Mach Number Effects on Transonic Aeroelastic Forces and Flutter Characteristics," *Journal of Aircraft*, Vol. 26, No. 11, 1989, pp. 1038–1046.