JOURNAL OF AIRCRAFT
Vol. 39, No. 5, September–October 2002

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).

Nonlinear Flutter Characteristics of Composite Missile Wing in Transonic/Low-Supersonic Flows

Dong-Hyun Kim* and In Lee†
Korea Advanced Institute of Science and Technology, 373-1 Taejon 305-701, Republic of Korea

Introduction

ADVANCED composite materials offer an attractive potential for reducing the structural weight of modern aircraft. Using composite materials enables one to construct weight-saving aircraft structures that satisfy several important design requirements. Flight vehicle wings that operate in transonic flow experience increased susceptibility to critical flutter or limit-cycle oscillation (LCO) phenomena. In transonic speeds, aerodynamic nonlinearities generally become dominant due to the effect of shock waves on the wing surface. Thus, in practice, the development of a nonlinear aeroelastic analysis code using advanced computational techniques such as computational structural dynamics and computational fluid dynamics is needed to design the weight-efficient wings.

In recent years, several studies have shown good results on flutter and divergence analyses of composite wing models.[1–4] Substantial effort has also been made in developing mathematical theories, finite element methods, and corresponding parametric analyses of composite wing structures. These studies primarily focused on the structural effect of aeroelastic characteristics, and most of the wing models were assumed to be either a cantilevered composite beam or plate. The theoretical approach based on the beam and plate model is an efficient method to perform various parametric studies. Recently, Eastep et al.[5] studied the effects of fiber orientations on optimized weight while satisfying constraints on strength, roll-reversal velocity, and flutter velocity. However, these studies concentrated almost exclusively on the application of incompressible aerodynamic theories to composite wing structures. From this perspective, the authors intend to show the important nonlinear effects of fiber orientations on the transonic and supersonic flutter characteristics of a composite missile wing model.

Computational Background

The aeroelastic equations of motion for an elastic wing can be formulated in terms of generalized displacement response vector $\{q(t)\}$, which is a solution of the following equation:

$$[M_g]\{\ddot{q}(t)\} + [C_g]\{\dot{q}(t)\} + [K_g]\{q(t)\} = \{Q(t, q, \dot{q})\} \tag{1}$$

where t is the physical time, $[M_g]$ is the generalized mass matrix, $[C_g]$ is the generalized damping matrix, $[K_g]$ is the generalized stiffness matrix, and $\{Q\}$ is the vector of unsteady generalized aerodynamic forces in the time domain. These forces are directly computed by integrating the pressure distributions on the wing surface as

$$Q(t)_i = \frac{1}{2}\rho_\infty U_\infty^2 c_r^2 \iint_S [Cp_L(x, y, t) - Cp_U(x, y, t)]\psi_i(x, y)\frac{\mathrm{d}S}{c_r^2} \tag{2}$$

where ρ_∞ is the freestream air density; U_∞ is the freestream velocity; c_r is the reference chord length; S is the wing area; C_p is the unsteady pressure coefficient on the arbitrary wing surface; subscripts L and U mean the lower and upper surface, respectively; and ψ_i is the ith natural mode shape vector. In this study, the coupled-time integration method is used to fully consider the nonlinear characteristics of aeroelastic responses. A general transonic small disturbance (TSD) code[6] is used to calculate unsteady aerodynamic forces in the time domain. The details of the theory used in this study can be found in Ref. 7.

The flutter conditions can also be obtained by the transient pulse method.[8] In the pulse analysis, the generalized aerodynamic forces are computed indirectly using fast Fourier transform for the response of the flowfield due to a pulse varying smoothly with exponential shape. Also, classical subsonic doublet-lattice and supersonic doublet-point numerical techniques are applied to calculate the linear generalized aerodynamic forces in the frequency domain. Then, the classical P–k method is used to determine the linear flutter solutions. For the structural vibration analysis of the composite wing model, a displacement field finite element method, based on the first-order shear deformation plate theory, is applied to a laminated composite plate with various fiber angles.

Results and Discussion

In this study, the wing structure is assumed as a cantilevered laminated composite plate for the purpose of considering the effect of fiber orientation. Parametric studies for various fiber orientations are presented to investigate unusual flutter characteristics. The wing is constructed of a T300/5208 graphite/epoxy core and 5% biconvex plastic foam. The material constants for T300/5208 are $E_1 = 138.0$ GPa, $E_2 = 9.7$ GPa, $G_{12} = 5.5$ GPa, $\upsilon_{12} = 0.28$, and $\rho = 1580$ kg/m^3. The thickness of each lamina is 0.125 mm. The wing model is modeled as a $[\theta_2/0_2]_s$ laminate, where θ is the fiber angle selected to examine the effect of fiber orientation and is measured counterclockwise from the midspan line. The root chord length of the wing model is 0.2 m, the airfoil is 5% biconvex, and the leading-edge sweptback angle is 40 deg. Although this laminate presents a thin model, it serves the purpose of examining the properties of a sweptback missile wing made of composite materials. Because the stiffness and mass effects of plastic foam are relatively small, the structural properties of plastic airfoil form can be ignored for the structural analysis. However, the aerodynamic thickness effect is required for unsteady aerodynamic analysis using the computational fluid dynamics technique.

Received 9 March 2001; revision received 21 June 2002; accepted for publication 21 June 2002.

*Postdoctoral Research Associate, Department of Aerospace Engineering, Kusong-dong, Yusong-gu. Member AIAA.

†Professor, Department of Aerospace Engineering, Kusong-dong, Yusong-gu. Senior Member AIAA.

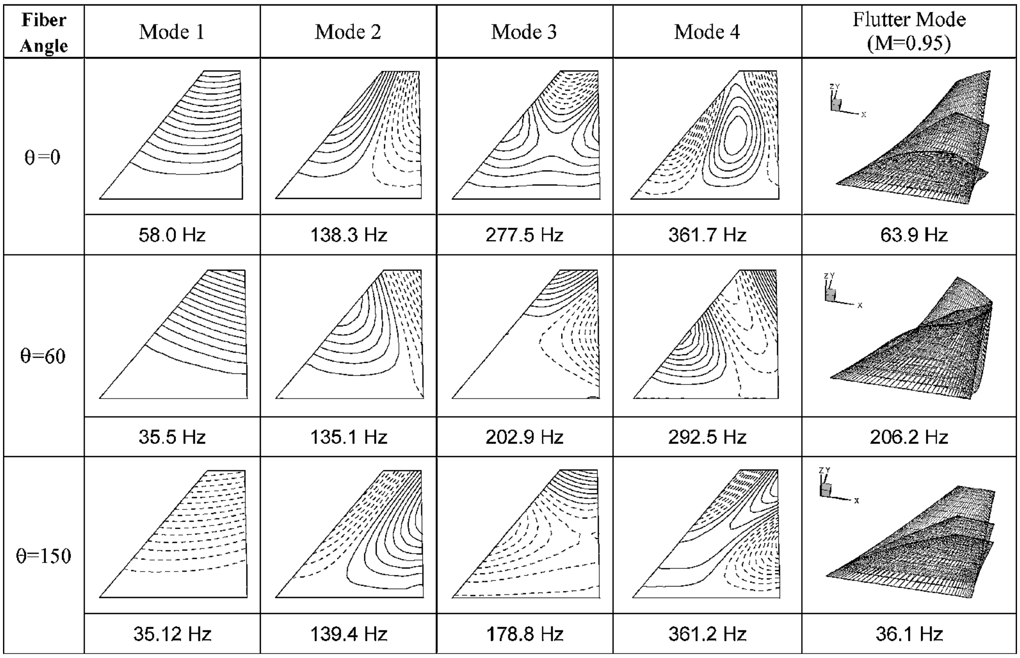

Fig. 1 Comparison of natural vibration and flutter mode shapes for different fiber angles.

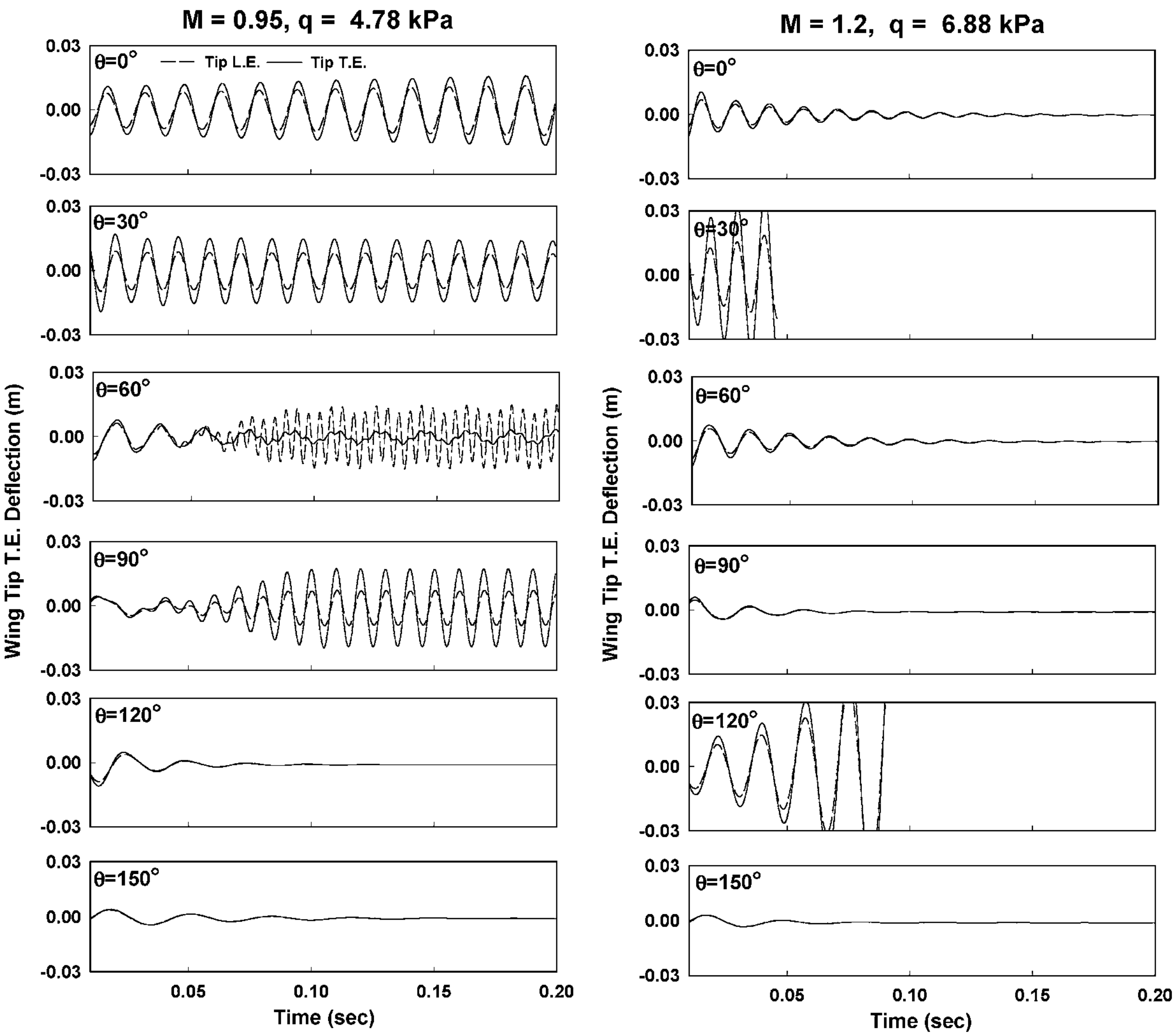

Fig. 2 Comparison of physical aeroelastic responses at Mach 0.95 and 1.2.

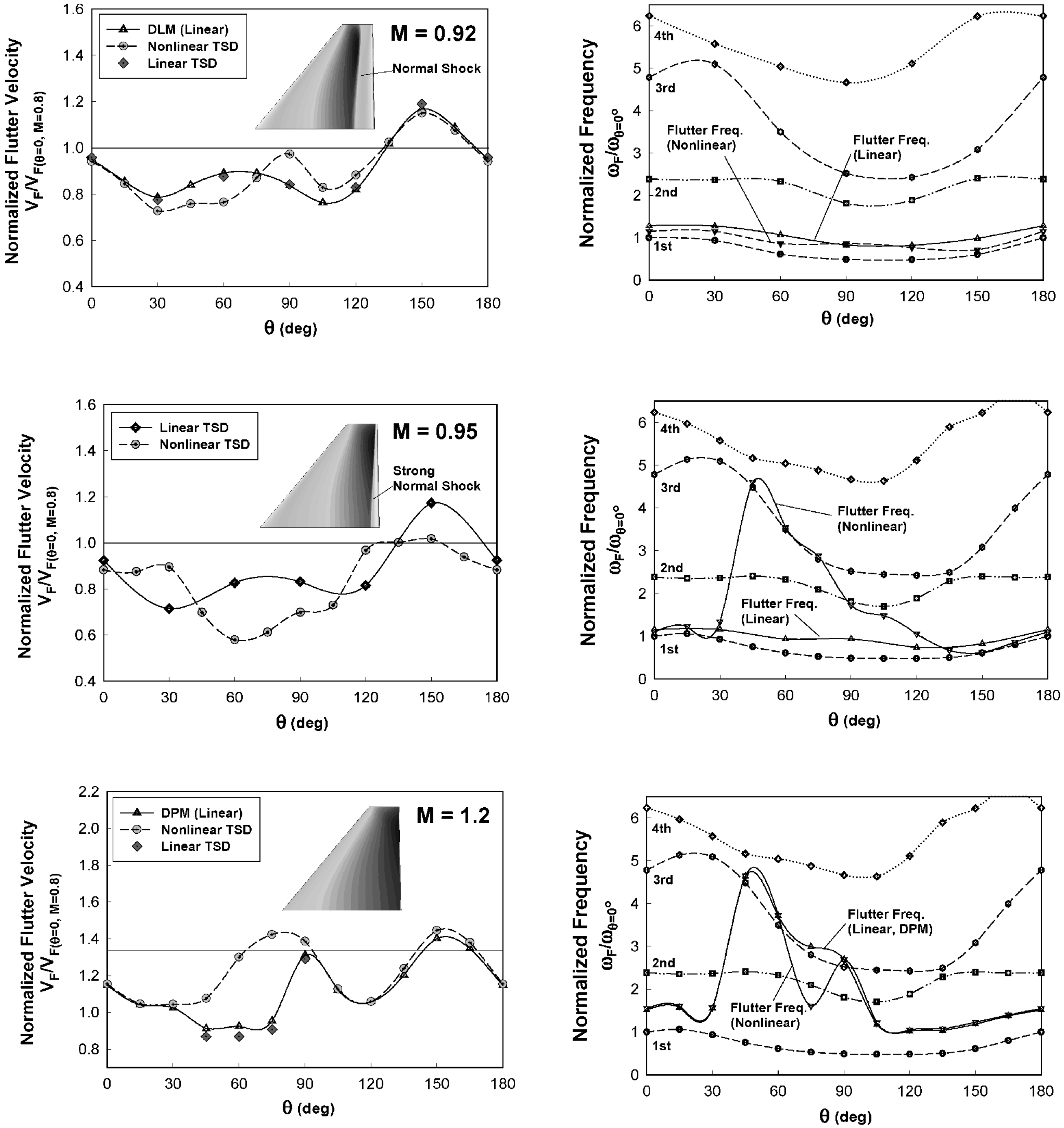

Fig. 3 Comparisons of normalized flutter velocity and frequency for various laminates.

Figure 1 shows representative plots of natural vibration and flutter mode shapes for various fiber angles. Because the flutter characteristics are related to the natural mode shapes and frequencies, it is important to investigate these free-vibration characteristics. The predicted flutter mode shape is also plotted for the case of Mach 0.95. These three-dimensional flutter modes are extracted from the animation data for each case. Flutter vibration shapes show different patterns because the dominant flutter mode is influenced by a combination of natural vibration modes coupling with the effects of unsteady aerodynamics.

Physical aeroelastic responses at Mach 0.95 and 1.2 are presented in Fig. 2. Air density and sonic speed are assumed to be 0.3108 kg/m^3 and 295.02 m/s, respectively. For the same dynamic pressure at Mach 0.95, the physical aeroelastic responses at the wing tip show different patterns because of the nonlinear shock wave effect. At Mach 0.95, the $[120_2/0_2]_s$ and $[150_2/0_2]_s$ laminates show stable response, the $[60_2/0_2]_s$ and $[90_2/0_2]_s$ laminates show LCO, and the $[0_2/0_2]_s$ laminate shows a divergent response. However, at Mach 1.2, the $[30_2/0_2]_s$ and $[120_2/0_2]_s$ laminates are unstable, whereas all other cases show stable responses.

Figure 3 compares normalized flutter velocities and frequencies for the various fiber angles at Mach 0.92, 0.95, and 1.2. The flutter velocities are normalized by the results of the $[0_2/0_2]_s$ laminate at Mach 0.8, and the frequencies are normalized by the first natural frequency of the $[0_2/0_2]_s$ laminate. The divergence velocities for all cases are significantly higher than the flutter velocity; thus, these are not specified herein. The flutter velocities and frequencies using both linear and nonlinear aerodynamic theories, though not presented in this Note showed very good correlations at Mach 0.8 because of aerodynamic linearity. However, for higher Mach numbers, aerodynamic nonlinear effects are observed.

At Mach 0.92, the most unstable flutter condition predicted by nonlinear TSD equation is observed on the $[30_2/0_2]_s$ laminate, but linear flutter analysis indicates the $[105_2/0_2]_s$ laminate. The flutter frequencies for both linear and nonlinear analyses are similar for this case, and all flutter frequencies are located between mode 1 and 2. Physically, this means that the flutter phenomena for this Mach number is dominantly coupled by the first bending and torsion modes (Fig. 1). At Mach 0.95, the linear and nonlinear results are quite different because of the effect of a strong rearward shock wave. The $[60_2/0_2]_s$ laminate has the lowest flutter velocity and is approximately 58% of the reference value. In general, for an isotropic wing model, the nonlinear flutter analysis that includes shock effects gives a lower (conservative) flutter velocity than those of the linear flutter analysis. It is noted that LCO are observed for several fiber orientations at Mach 0.92 and 0.95; thus, some of the presented flutter velocities are, in reality, the lowest values in which LCO response is present. The computed flutter frequencies are quite different for the fiber angle range of 45–105 deg because the flutter mode is significantly changed by the effect of nonlinear unsteady aerodynamics. At Mach 1.2, the more unstable cases predicted by the nonlinear analysis are shown at about $\theta = 15$, 30, and 120 deg. However, the linear analysis shows much lower flutter velocities than those of the nonlinear analysis on the $[45_2/0_2]_s$, $[60_2/0_2]_s$, and $[75_2/0_2]_s$ laminates, whereas the others show similar results compared to the nonlinear analysis. Comparisons of the flutter frequencies found from linear and nonlinear analyses are very similar except for the $[75_2/0_2]_s$ laminate. Finally, note from the linear and nonlinear analyses that the $[150_2/0_2]_s$ laminate commonly shows good flutter performance in both transonic and supersonic flows.

Conclusions

The authors examined the flutter characteristics of a sweptback composite missile wing in transonic and supersonic flows. Detailed comparisons of the effect of fiber orientation were presented to show the dynamic response and flutter stability characteristics of a laminated composite wing model. Comparisons were conducted within the transonic regime at Mach 0.92, 0.95, and 1.2. It was observed that the effect of fiber angle on the flutter stability is related to an inherent aerodynamic nonlinearity related to strong shock motions in transonic and low-supersonic flows. It was also observed that flutter frequencies change substantially due to the change of the flutter mode, which is related to the shock motions. It has been shown that there may be at least one lamination configuration for the missile wing that satisfies good flutter performance in both transonic and supersonic flows.

Acknowledgments

This work was supported through funding from the Korea Ministry of Science and Technology. The authors acknowledge the support (Subject 2000-N-NL-01-C-250) of the National Research Laboratory Program.

References

[1]Weisshaar, T. A., "Aeroelastic Tailoring of Forward Swept Composite Wings," *Journal of Aircraft*, Vol. 18, No. 8, 1981, pp. 669–676.

[2]Lottai, I., "Flutter and Divergence Aeroelastic Characteristics for Composite Forward Swept Cantilevered Wing," *Journal of Aircraft*, Vol. 22, No. 11, 1985, pp. 1001–1007.

[3]Lin, K. J., Lu, P. J., and Tarn, J. Q., "Flutter Analysis of Cantilever Composite Plates in Subsonic Flow," *AIAA Journal*, Vol. 27, No. 8, 1989, pp. 1102–1109.

[4]Karpouzian, G., and Librescu, L., "Nonclassic Effects on Divergence and Flutter of Anisotropic Swept Aircraft Wings," *AIAA Journal*, Vol. 34, No. 4, 1996, pp. 786–794.

[5]Eastep, F. E., Tischler, V. A., Venkayya, V. B., and Khot, N. S., "Aeroelastic Tailoring of Composite Structures," *Journal of Aircraft*, Vol. 36, No. 6, 1999, pp. 1041–1047.

[6]Kim, D. H., and Lee, I., "Transonic and Low-Supersonic Aerodynamic Analysis of a Wing with Under Pylon/Store," *Journal of Aircraft*, Vol. 37, No. 1, 2000, pp. 189–192.

[7]Kim, D. H., and Lee, I., "Transonic and Supersonic Flutter Characteristics of a Wing-Box Model with Tip Stores," AIAA Paper 2001-1464, April 2001.

[8]Yang, S. M., Kim, D. H., and Lee, I., "Transonic Steady and Unsteady Aerodynamics for Wings Using Three-Dimensional Euler Equations," *Computational Fluid Dynamics Journal*, Vol. 10, No. 1, 2001, pp.44–54.

Parameter Estimation from Flight Data of an Unstable Aircraft Using Neural Networks

A. K. Ghosh* and S. C. Raisinghani†
Indian Institute of Technology Kanpur,
Kanpur 208 016, India

Introduction

THE maximum likelihood (ML) estimator in its several forms has been the most widely and successfully used for estimating aircraft stability and control derivatives (parameters) of a stable aircraft. However, for an unstable aircraft, difficulties can be expected because of 1) integration of equations of motion of the open-loop model generally resulting in diverging solutions, 2) the potential for correlation between input and output variables, 3) controllers suppressing the transients and thereby reducing information content in measured signals.[1] Although equation error methods do not face the preceding difficulties, they are not preferred mainly because of the need for accurate state reconstruction and biased estimates in the presence of measurement noise. Thus a need exists to find new approaches for estimating parameters of an unstable aircraft, and it is in this context that the present work explores the suitability of recently proposed Delta method[2,3] by applying it on simulated flight data as well as on flight data obtained via discretization of analog plots of real-flight data of an unstable aircraft.

Delta Method

The Delta method[2,3] is based on the understanding of what a stability/control derivative stands for; the stability/control derivatives represent the variation of the aerodynamic force or moment coefficients caused by a small variation in one of the motion/control variables about the nominal value, whereas all of the other variables are held constant. For example, to estimate $C_{m\alpha}$ the feed forward neural network (FFNN) is first trained to map the input file variables, say, α, q, and δ to the output variable C_m. Next, a modified network input file, wherein α values at each time point are perturbed by $\pm\Delta\alpha$ while all of the other variables retain their original values, is presented to the trained network, and the corresponding predicted values of the perturbed C_m (C_m^+ for $\alpha + \Delta\alpha$ and C_m^- for $\alpha - \Delta\alpha$) for each of the input-output samples are obtained at the output node. Now, the stability derivative $C_{m\alpha}$ is given by $C_{m\alpha} = (C_m^+ - C_m^-)/2\Delta\alpha$. If N is the number of input-output samples used by the network, then the estimated parameter is given by the average over N samples, and the sample standard deviation is an indicator of the accuracy of the estimates.[2,3]

Presented as Paper 2000-4102 at the AIAA Atmosphere Flight Mechanics Conference, Denver, CO, 14–17 August 2000; received 15 July 2001; revision received 1 May 2002; accepted for publication 10 May 2002.

*Assistant Professor, Department of Aerospace Engineering; akg@iitk.ac.in.

†Professor, Department of Aerospace Engineering; scr@iitk.ac.in. Senior Member AIAA.