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APPLICATION OF NAVIER-STOKES ANALYSIS TO STALL FLUTTER*

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ABSTRACT

A solution procedure has been developed to investigate the two-dimensional, one- or two-degree-of-freedom flutter characteristics of arbitrary airfoils. This procedure requires a simultaneous integration in time of the solid and fluid equations of motion. The fluid equations of motion are the unsteady compressible Navier-Stokes equations, solved in a body-fitted, moving coordinate system using an approximate factorization scheme. The solid equations of motion are integrated in time using an Euler implicit scheme. Flutter is said to occur if small disturbances imposed on the airfoil attitude lead to divergent oscillatory motions at subsequent times.

The flutter characteristics of airfoils in subsonic speed at high angles of attack and airfoils in high subsonic and transonic speeds at low angles of attack are investigated. The stall flutter characteristics were also predicted using the same procedure. Results of a number of cases are included and compared with numerical and experimental data where available. The effects of mass ratio, initial perturbation, mean angle of attack, viscosity, and shape and thickness, on the flutter boundary are also investigated.

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GOVERNING EQUATIONS

The fluid equations of motion used in the present formulation are the compressible Navier-Stokes equations. These equations are written below in a conservative form. These are solved in a body-fitted, moving coordinate system using an appropriate factorization scheme.

$$\delta_t q + \delta_x E + \delta_y F = Re^{-1}(\delta_x R + \delta_y S)$$

WHERE

$$q = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ e \end{bmatrix}, \quad E = \begin{bmatrix} \rho u \\ \rho u^2 + P \\ \rho uv \\ u(e + P) \end{bmatrix}, \quad F = \begin{bmatrix} \rho v \\ \rho uv \\ \rho v^2 + P \\ v(e + P) \end{bmatrix}, \quad R = \begin{bmatrix} 0 \\ \tau_{xx} \\ \tau_{xy} \\ R_4 \end{bmatrix}, \quad S = \begin{bmatrix} 0 \\ \tau_{xy} \\ \tau_{yy} \\ S_4 \end{bmatrix}$$

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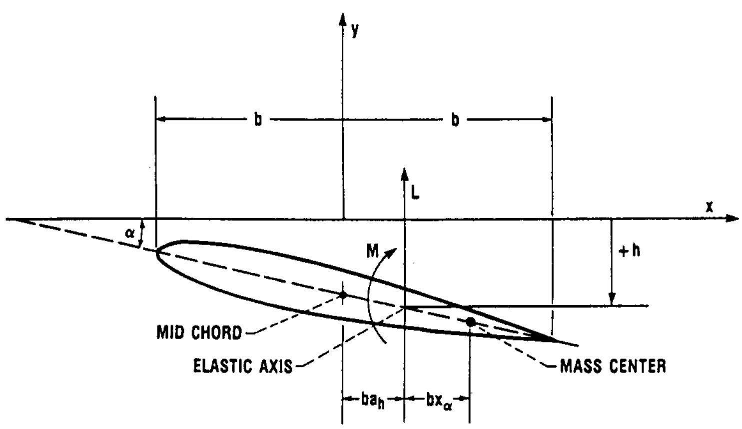
STRUCTURAL MODEL FOR 2-DOF SYSTEM

The structural dynamic model considered is a 2-DOF (pitching and plunging motion) system. An Euler implicit scheme was used to integrate the structural governing equation. The fluid and the solid equations were simultaneously integrated in time to monitor how lift, moment, and drag vary with time.



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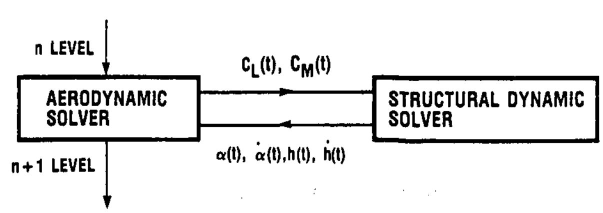
GOVERNING EQUATION OF THE 2-DOF STRUCTURAL MODEL

$$I\ddot{\alpha} + S\ddot{h} + g_\alpha \dot{\alpha} + K_\alpha \alpha = M(t)$$

$$m\ddot{h} + S\ddot{\alpha} + g_h \dot{h} + K_h h = -L(t)$$

- EULER IMPLICIT SCHEME FOR $\dot{h}$, $\ddot{h}$, etc.

$$\dot{h} = \frac{h^{n+1} - h^n}{\Delta t}, \qquad \ddot{h} = \frac{h^{n+1} - 2h^n + h^{n-1}}{\Delta t^2}$$



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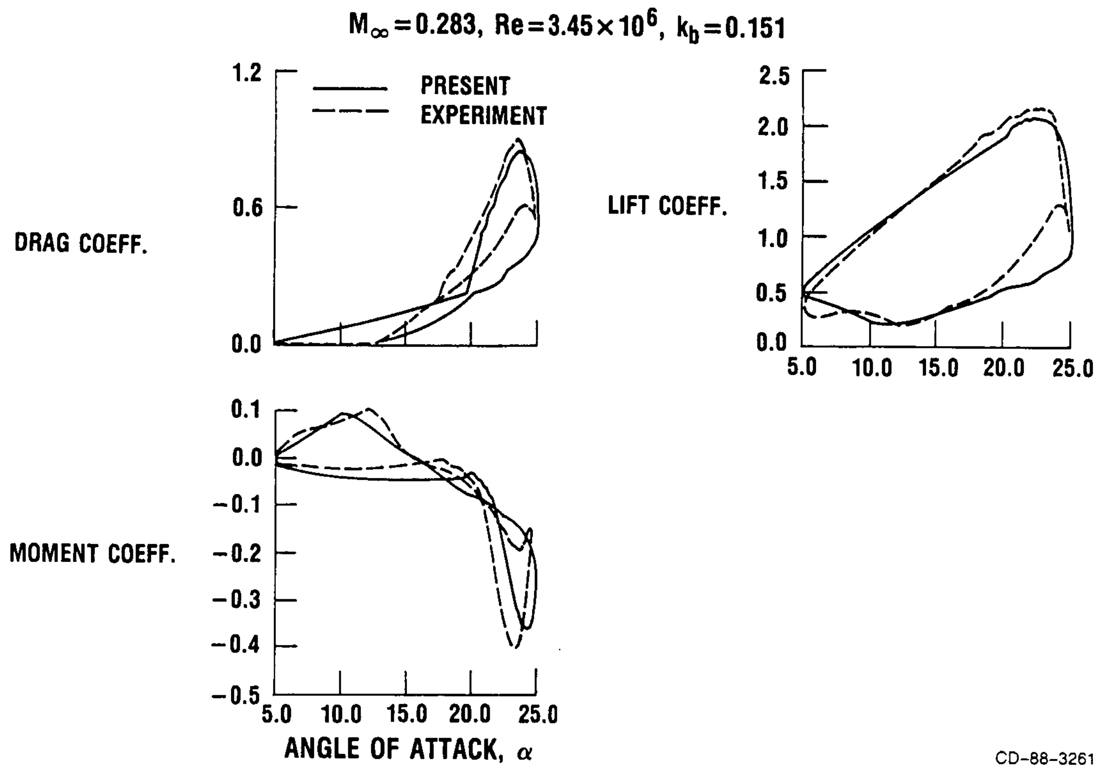
COMPARISONS OF UNSTEADY AIRLOADS ON A NACA 0012
AIRFOIL EXPERIENCING DYNAMIC STALL

The present Navier-Stokes solver is able to obtain time-accurate results in highly separated flows. The lift, drag, and moment hysteresis loops are shown here and compared with experiments by McAlister et al (1982). The case is shown of a NACA 0012 airfoil oscillating in pitch with the mean angle of oscillation 15 degrees and 10 degrees of amplitude of oscillation. The solver correctly predicts (1) the near-linear increase in lift during the upstroke; (2) the dynamic stall which causes rapid variations in lift, drag, and moment alike; and (3) the post stall recovery phase of the flow during the downstroke.



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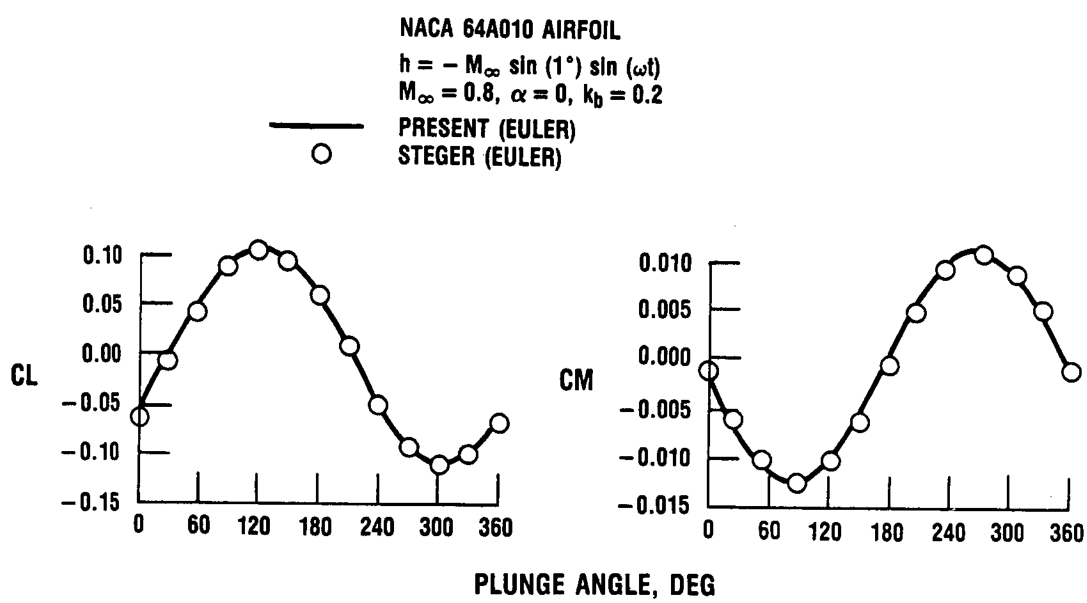
VARIATION OF LIFT AND PITCHING MOMENT COEFFICIENT
FOR PLUNGING MOTION

The present code's ability to handle unsteady, transonic flows in a time-accurate manner is illustrated in the figure below. The case is shown of a NACA 64A010 airfoil oscillating sinusoidally in plunge at a free stream Mach number of 0.8 at zero mean angle of attack. The lift and pitching moment history are plotted as a function of phase, and are compared with the Euler calculations performed by Steger (1978). Very good agreement is observed between the two solvers.



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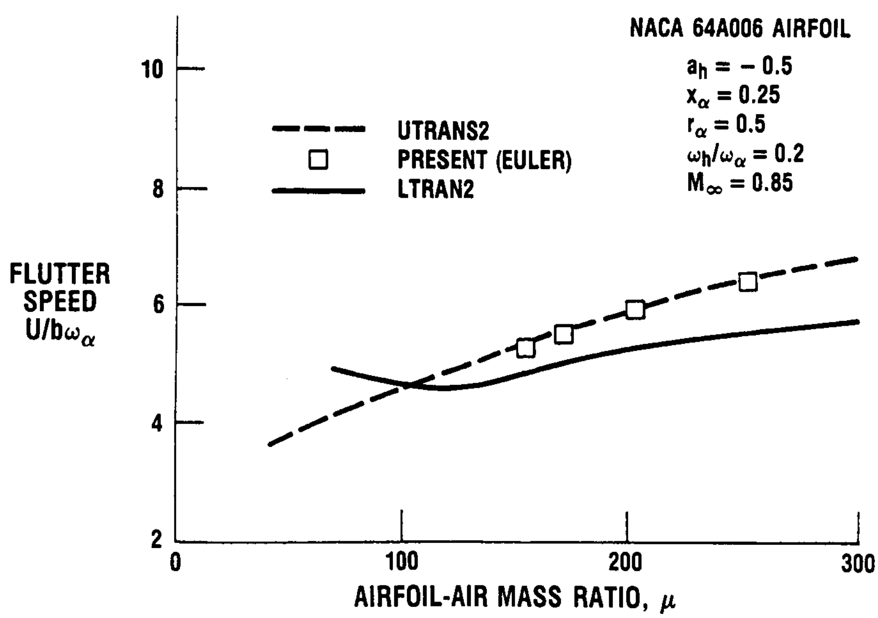
EFFECTS OF AIRFOIL-AIR MASS RATIO ON FLUTTER SPEED

The present technique for the prediction of stall flutter was validated for transonic flutter calculations where reliable numerical solutions exist. The airfoil is a NACA 64A006 airfoil at a free stream Mach number 0.85, and the flow was assumed to be inviscid. The flutter speed predicted by the present theory is plotted as a function of the airfoil-air mass ratio (Wu et al., 1987). For comparison, the results from the LTRAN2 and UTRANS2 (Ballahus, 1978) and UTRANS2 (Farr et al., 1974) codes are shown. It is seen that the Euler results agree very well with the prediction of the UTRANS2 code, while only a qualitative agreement between the present results and the LTRAN2 code could be found.



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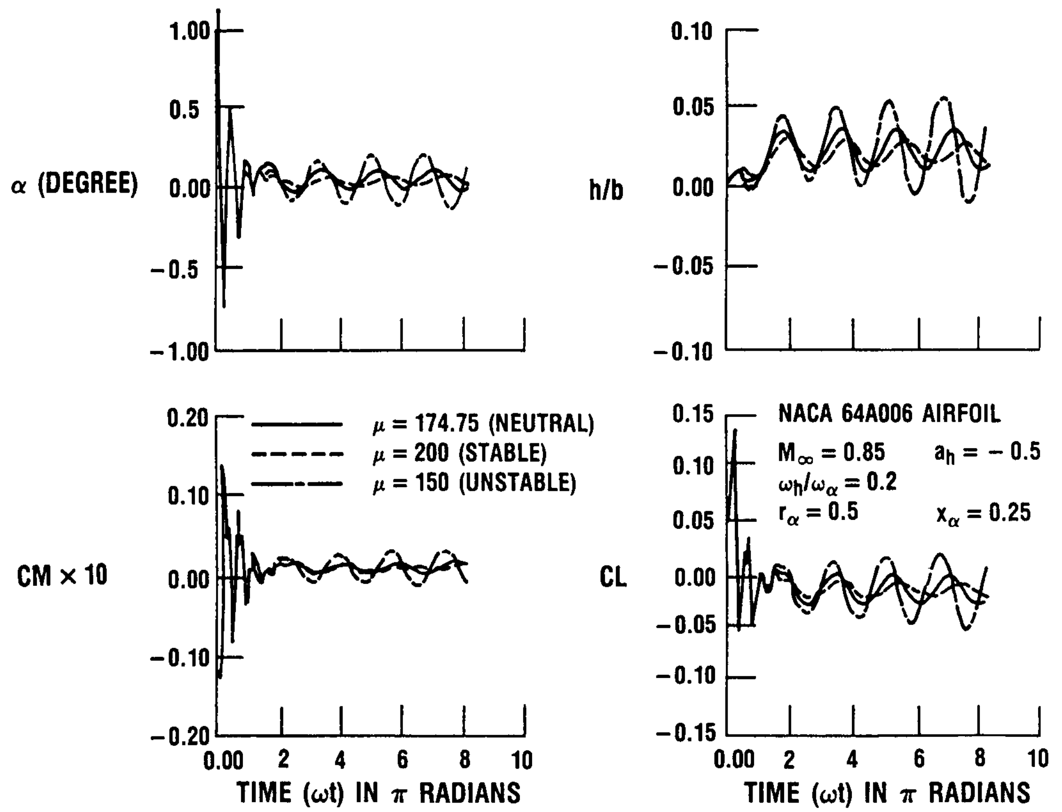
RESPONSES OF THE 2-DOF SOLID-FLUID SYSTEM AS A FUNCTION OF TIME

The following figure illustrates the time responses of a 2-DOF flutter calculation. The flow is assumed to be inviscid at free stream Mach number 0.85. A NACA 64A006 airfoil was released after the forced sinusoidal oscillation and was allowed to follow pitching and plunging motions dictated by the structural dynamic equations. By parametrically varying the airfoil air mass ratio during this phase of the calculations, it led to damped oscillations, neutral oscillations, stable oscillations, or divergent (flutter) oscillations.



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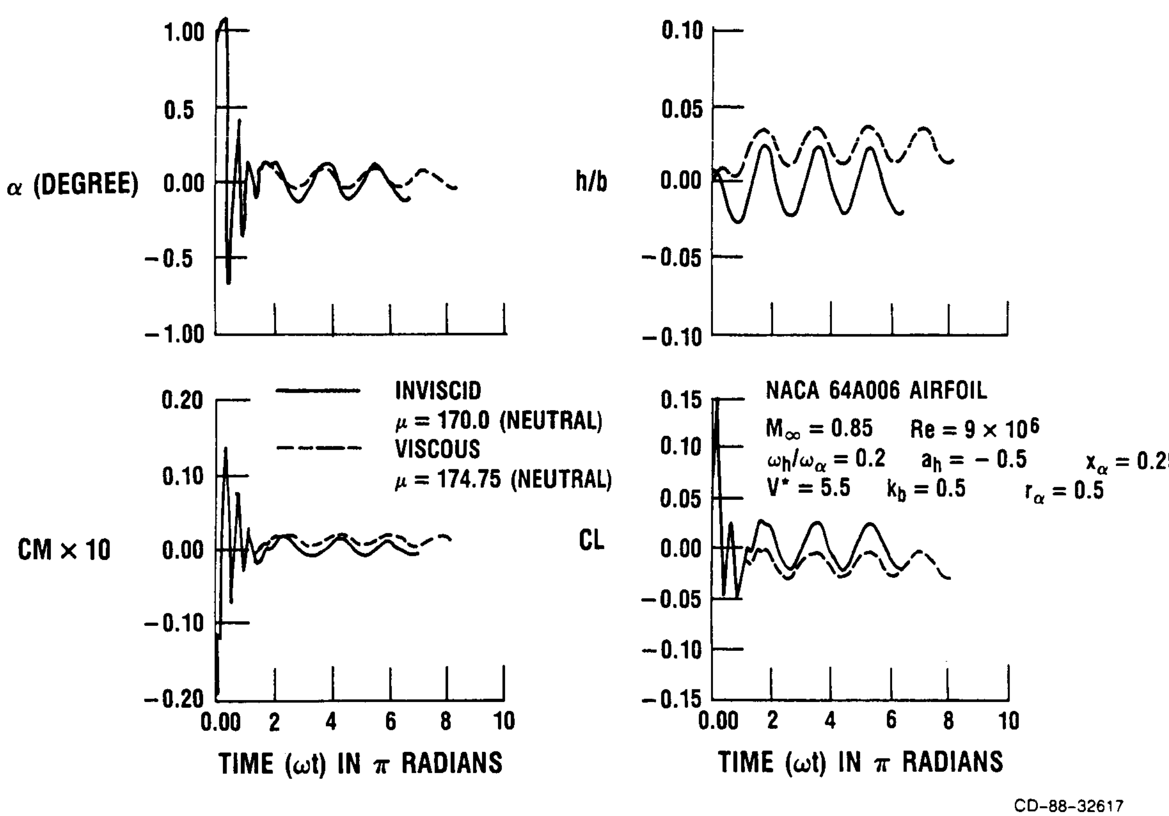
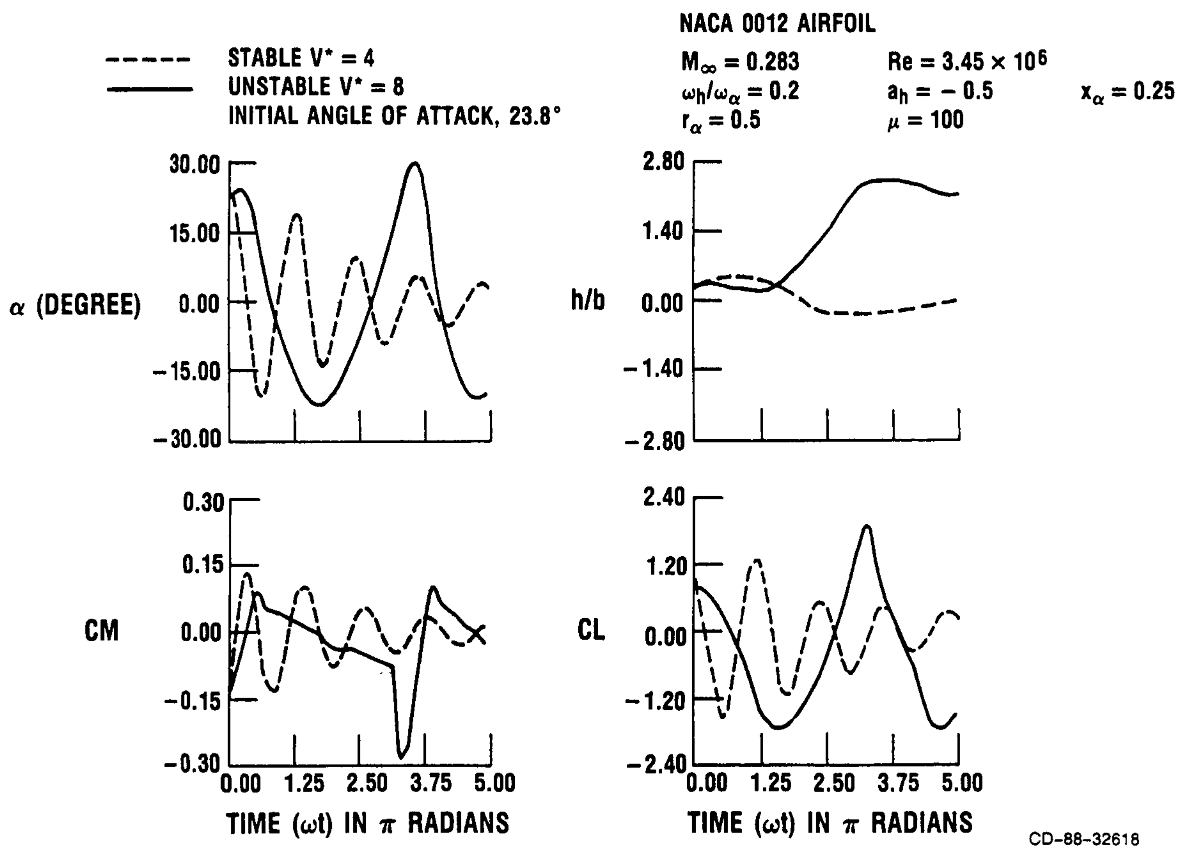
EFFECTS OF VISCOSITY ON THE TIME RESPONSE

The effect of flow viscosity on the flutter characteristics for a 2-DOF system was studied using the present solver operating in the Navier-Stokes mode. The airfoil is a NACA 64A006 airfoil at a free stream Mach number 0.85. Viscous solution corresponds to a Reynolds number of 9×10^6. The flutter boundaries predicted by the viscous and inviscid calculations were within 2 percent of each other, which means that in high Reynolds number transonic flutter studies, inviscid calculations would suffice.



TIME RESPONSES OF A 2-DOF SYSTEM EXPERIENCING STALL FLUTTER

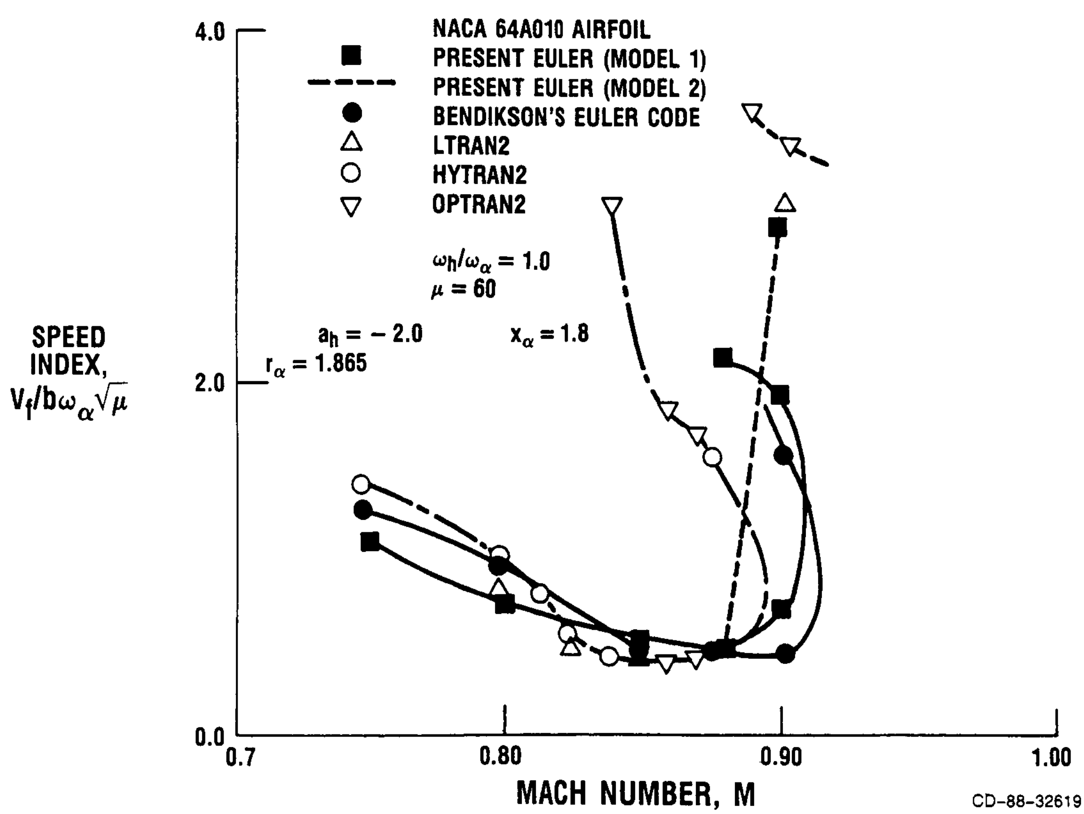
The stall flutter calculations are carried out using the Navier-Stokes/structural dynamics solver. The case considered was a NACA 0012 airfoil, initially subjected to a sinusoidal pitching oscillation between 5 and 25 degrees. During the downstroke, around 23.8 degrees, the airfoil was released and was allowed to follow a pitching and plunging motion dictated by the structural dynamic equations. Two dimensionless speeds V*, 4 and 8, were considered. At the lower speed, the airfoil began to undergo a damped sinusoidal oscillation and reached a stable condition eventually. The time history for the speed V* equal to 8, however, showed a rapidly growing oscillating motion indicative of dynamic stall flutter.



COMPARISON OF CALCULATED FLUTTER BOUNDARIES

A comparison of flutter boundaries with the boundaries obtained by various codes presented by Bendikson et al. (1987) is shown below. Two artificial viscosity models were used in the present calculations (Reddy et al., 1988). The artificial viscosity in the present code is based on pressure gradient. In model 1, the pressure gradient was scaled by a constant coefficient, whereas in model 2, it was scaled by the spectral radius.

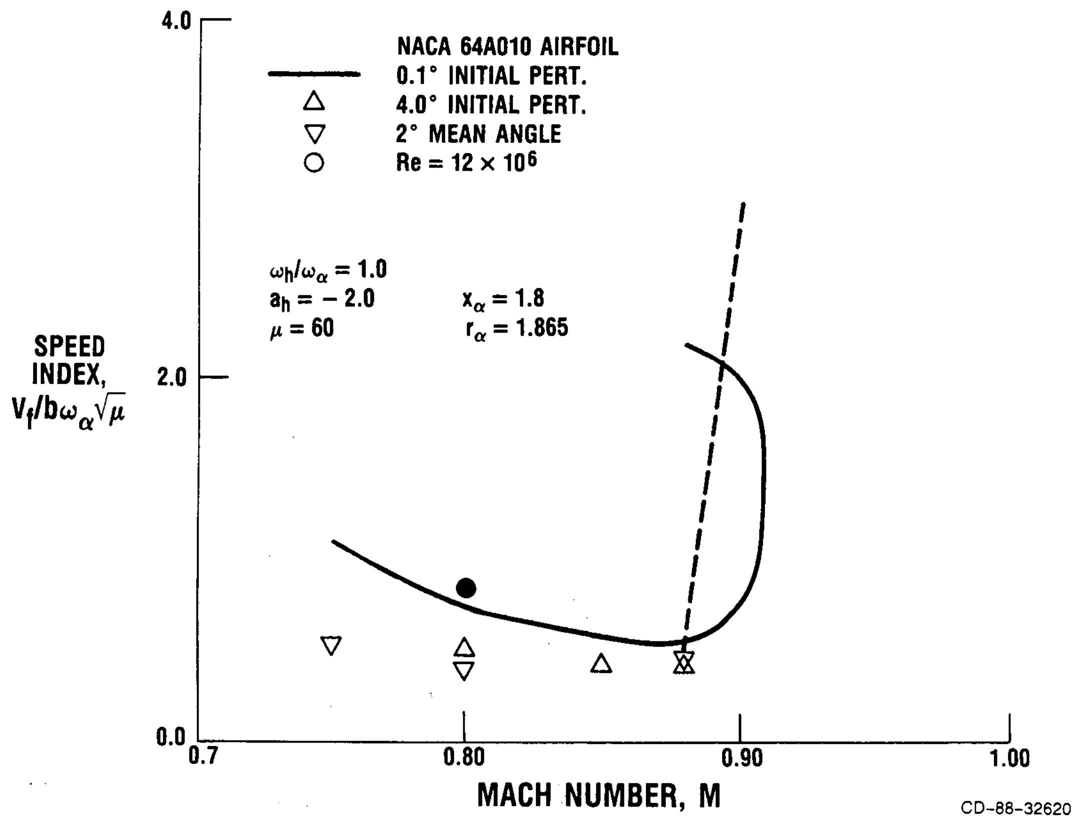
The rotational effects of the flow behind the shock wave have strong effect on the transonic flutter speed, depending on the chordwise location of the shock. Neglecting the flow rotation effects results in predicting a higher flutter speed.



EFFECT OF MEAN ANGLE OF ATTACK, INITIAL PERTURBATION, AND VISCOSITY ON THE FLUTTER BOUNDARY

The effect of initial perturbation, mean angle of attack, and viscosity are shown in the figure below.

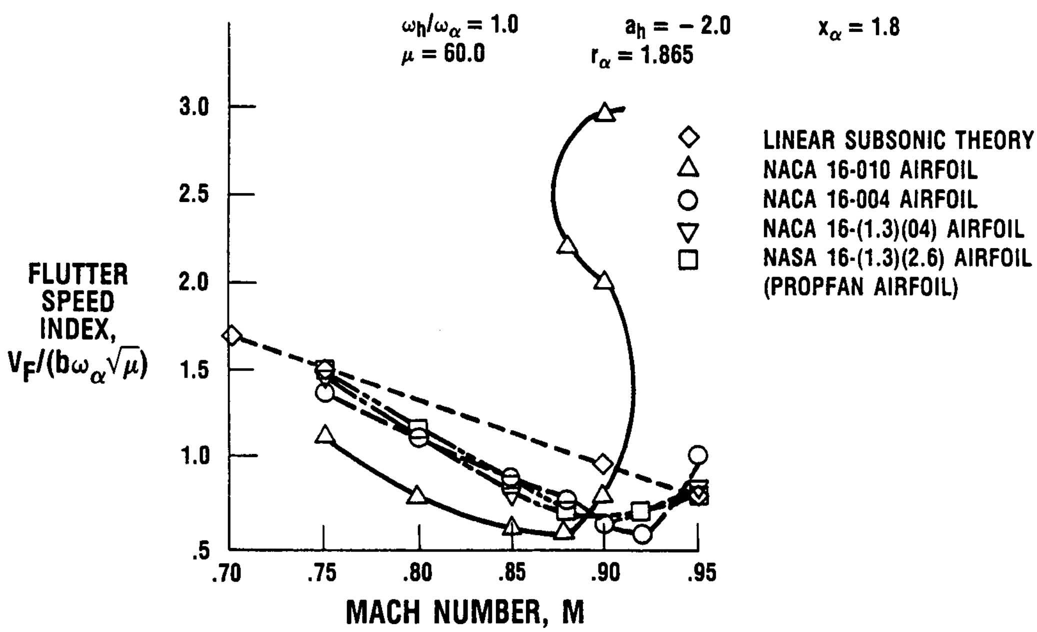
The effects of initial conditions, mean angle of attack, and viscosity on the minima of the transonic dip seem negligible. However, they have a significant effect away from the dip. Similar results for mean angle of attack were obtained by Edwards et al. (1983).



EFFECT OF AIRFOIL SHAPE AND THICKNESS ON THE FLUTTER BOUNDARY

The blade thickness and shape dictate the location and strength of shock, thereby affecting the flutter boundary. The transonic dip shifts to higher Mach numbers for symmetric airfoils with decreasing airfoil thickness to chord ratios. For very thin cambered airfoils, the transonic dip occurs at lower Mach numbers.

This effect is shown in this figure.



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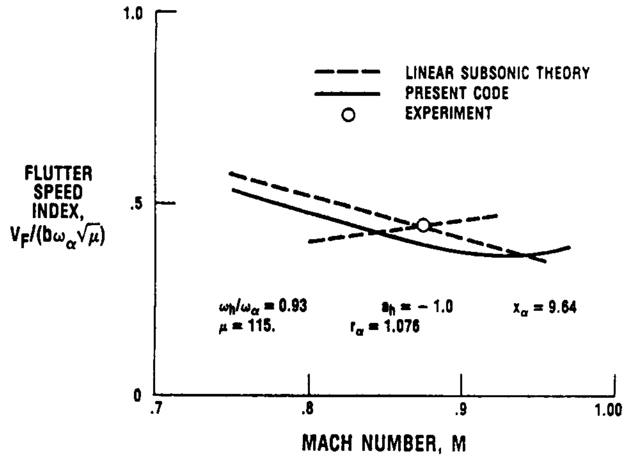
FLUTTER BOUNDARY FOR A SIMULATED SR5 TYPICAL SECTION STRUCTURAL MODEL

This figure shows the predicted flutter boundary of a simulated typical section model of an SR5 propfan blade. The flutter Mach number predicted by the present code is about 4.5 percent lower than that predicted by linear theory and experiment. This difference could be attributed to the simplified aeroelastic model used in the present analysis.



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