Engineering Notes

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Conical Euler Simulation of Wing Rock for a Delta Wing Planform

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Introduction

IN recent years, the understanding and prediction of the complex flows about modern aircraft at high angles of attack have been research topics that have generated much interest within the fluid dynamics community.[1,2] These aircraft typically have thin highly swept lifting surfaces, such as delta wings, that produce a vortical flow over the leeward side of the vehicle at high angles of attack α. This vortical flow can have beneficial effects on performance, such as lift augmentation at high α, but may also have adverse effects, such as structural fatigue due to tail buffet, and also stability and control problems, such as wing rock, wing drop, nose slice, and pitch-up.[3] Considerable research has been conducted into the wing-rock phenomenon, which is a self-induced limit cycle rolling oscillation with, in some cases, a coupled yaw oscillation. Both experimental[4-8] and computational[9-12] methods have been used in efforts to better understand the basic flow physics involved in this type of unsteady vortical flow. Use of the more modern computational fluid dynamics (CFD) techniques that solve the Euler and Navier Stokes equations,[13] although applicable to general time-dependent vortical flow phenomena, have yet to be applied to problems such as wing rock.

The objective of the current research is to study unsteady vortex-dominated flowfields by using the conical Euler equations as an efficient first step to investigating the full three-dimensional problem. Assuming that the flow about a delta wing is conical in nature for supersonic speeds allows the three-dimensional problem to be reduced computationally to a two-dimensional problem. This, in turn, reduces significantly the amount of computer resources required for a calculation. Therefore, the conical method is used as an efficient first step to treating the full three-dimensional problem. The purpose of this Note is to report the first CFD calculation of a conical Euler solution for a delta wing undergoing wing-rock motion. The flow solver used for this calculation is that of Ref. 14, which involves a Runge-Kutta time-stepping scheme and a finite-volume spatial discretization suited for an unstructured grid. The code was modified to allow for the additional analysis of the free-to-roll case by the inclusion of the rigid-body equation of motion for simultaneous time integration with the governing flow equations. The Note presents a brief description of the conical Euler flow solver and free-to-roll analysis, along with results demonstrating the computational simulation of a type of wing-rock phenomenon.

Euler Solution Algorithm

The unsteady conical Euler equations are solved using a multistage Runge-Kutta time-stepping scheme similar to that of Ref. 14. This algorithm uses a finite-volume spatial discretization for solution on an unstructured grid made up of triangles. The algorithm is a cell-centered scheme whereby the flow variables are stored at the centroids of the triangles. The artificial dissipation is added explicitly to prevent oscillations near shock waves and to damp high-frequency uncoupled error modes. The algorithm also employs enthalpy damping, local time stepping, and implicit residual smoothing to accelerate convergence to steady state. A time-accurate version of the residual smoothing is also used for global time-stepping during unsteady applications of the code. With respect to boundary conditions, freestream conditions are applied along the far-field boundary, and a reasonably large computational grid is used so that the bow shock is captured as a part of the solution. A flow tangency (or slip) condition is applied to the inner boundary representing the wing. Also, for unsteady calculations, the grid is moved as a rigid body to conform to the instantaneous position of the wing. In this application, grid speeds are computed at the nodes and are included in the governing equations to account for the relative motion between the grid and the fluid.

Free-to-Roll Analysis

The equation of motion for a rolling delta wing can be expressed as

$$I_{xx}\ddot{\phi} = \ell - \mu_x\dot{\phi} \tag{1}$$

where ϕ is the roll angle that is positive clockwise when viewed from aft, I_{xx} is the mass moment of inertia about the longitudinal axis, ℓ is the aerodynamic rolling moment (also positive clockwise), and μ_x is a structural damping term (dot superscripts indicate differentiation with respect to time). The structural damping term is added to simulate a sting bearing mount. This type of bearing was used in the low-speed wind-tunnel investigations of wing rock reported in Refs. 4-7. In order to nondimensionalize Eq. (1), the angular rates are multiplied by the root chord of the delta wing c and divided by the freestream speed of sound a_∞. The rolling moment coefficient is defined as

$$C_\ell = \ell/q_\infty Sc \tag{2}$$

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where q_∞ is the freestream dynamic pressure and S is the planform area. The nondimensional rolling equation of motion can then be written as

$$\phi'' = C_1 C_\ell - C_2 \phi' \tag{3}$$

where

$$C_1 = M_\infty^2 Sc^3 \rho_\infty / 2I_{xx}$$

$$C_2 = \mu_x c / a_\infty I_{xx} \tag{4}$$

The prime superscripts indicate differentiation with respect to nondimensional time.

The solution procedure for the time integration of Eq. (3) is based on a finite-difference representation of the time derivatives. The time derivatives are expressed in terms of second-order-accurate finite-difference approximations. After substituting these expressions into Eq. (3), the roll angle at time level $n+1$ can be expressed in terms of the roll angle at previous time levels as

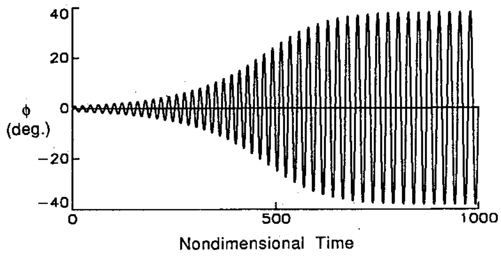
$$\phi^{n+1} = [C_1 C_\ell^{n+1} \Delta\bar{t}^2 + (5+2C_2\Delta\bar{t})\phi^n - (4 + \tfrac{1}{2}C_2\Delta\bar{t})\phi^{n-1} + \phi^{n-2}]/[\tfrac{3}{2}C_2\Delta\bar{t} + 2] \tag{5}$$

where the nondimensional time $\bar{t}$ is defined by $a_\infty t/c$. The rolling moment at time level $n+1$, C_ℓ^{n+1}, is estimated from a linear extrapolation of C_ℓ at the previous two time levels. This predicted value of C_ℓ is used to determine the roll angle at time level $n+1$, ϕ^{n+1}. The flowfield is then calculated about the wing at this roll angle, and the actual value of the rolling moment coefficient is determined. The rolling moment coefficient is then updated for use in the next time step. Because of the explicit time-marching formulation of the Euler code used in this study, the time steps required for stability were small, and, thus, it was not necessary to iterate between the roll angle calculation and the flowfield calculation at each time step. For a free-to-roll calculation, steady-state initial conditions are specified for ϕ^{-1}, ϕ^0, C_ℓ^{-1}, and C_ℓ^0. An initial angular velocity is imposed to provide an initial perturbation to the wing.

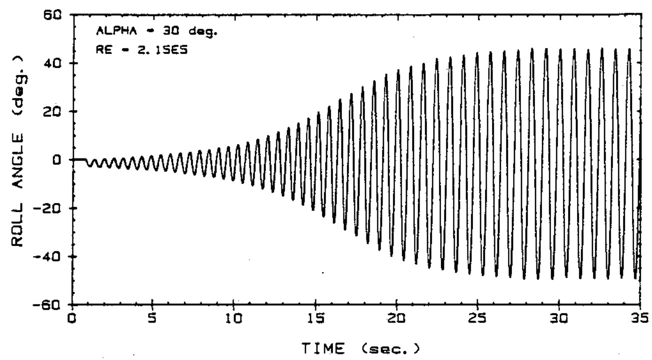
Results and Discussion

Calculations were performed for a 75-deg delta wing at a freestream Mach number of 1.2 and an angle of attack of 30 deg. The wing has thickness and sharp leading edges. The thickness-to-span ratio at the computational cross section is 0.025, and the bevel angle is 10 deg. The grid, which was generated using an advancing-front method,[15] has a total of 4226 nodes and 8299 elements.

The free-to-roll results were obtained for the inertial and structural parameter values and flow conditions listed here: $c = 0.282$ m, $I_{xx} = .1776 \times 10^{-3}$ Kg m^2, $\mu_x = 0.0$ Kg m^2/s, $\rho_\infty = 0.526$ Kg/m, and $a_\infty = 312$ m/s. The initial angular velocity imposed on the wing was $\phi' = 0.003$. The resulting roll angle response is shown in Fig. 1a. This response indicates that initially the oscillatory response diverges for small values of roll angle. As the maximum roll amplitude increases to around 35 deg, the rate of divergence decreases, and, finally, the response reaches a maximum amplitude of motion at $\phi = 38$ deg corresponding to a limit cycle. The reduced frequency (based on one-half of the root chord) of the limit cycle motion is $k = 0.103$. Although there is no supersonic experimental data for comparison purposes, these results are similar in nature to the results, shown in Fig. 1b, obtained by Arena and Nelson[7] for an 80-deg swept delta wing at 30-deg angle of attack in a low-speed experimental investigation of wing rock. The reduced frequency of the limit cycle in Fig. 1b is approximately $k = 0.125$. Noting that the freestream Mach number and the leading-edge sweep angle considered in the present study are different from that of Ref. 7, the similarities between the two



a) Conical Euler solution for a 75-deg swept delta wing at $M_\infty = 1.2$ and $\alpha = 30$ deg



b) Low-speed experimental results for an 80-deg swept delta wing at $\alpha = 30$ deg (Ref. 7, reprinted with permission from Professor Robert C. Nelson, Notre Dame University)

Fig. 1 Comparison of free-to-roll time histories.

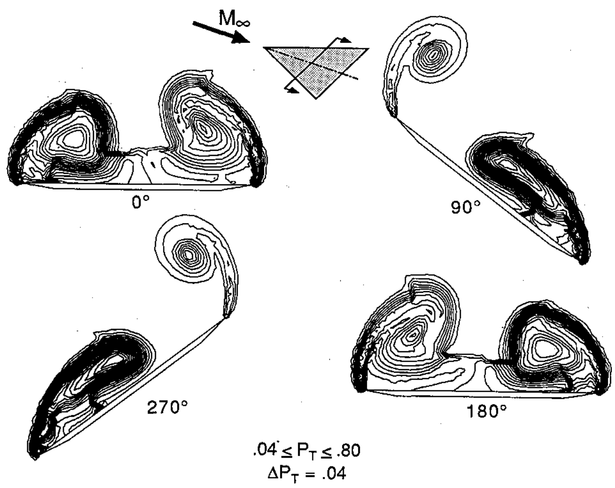


Fig. 2 Total pressure loss contours during a wing-rock cycle for a 75-deg swept delta wing at $M_\infty = 1.2$ and $\alpha = 30$ deg.

sets of results are still noteworthy and give credibility to the present calculation with respect to wing-rock damping, frequency, and amplitude. It is important to note that the same free-to-roll calculation performed at a lower angle of attack of $\alpha = 10$ deg produced a stable (convergent) roll response.[16] This transition from a stable to unstable wing-rock response with increasing angle of attack is consistent with the low-speed experimental results. The unsteady vortex motion during the wing-rock cycle is illustrated in Fig. 2 by the changes in the crossflow total pressure loss P_T contours. The crossflow contours are shown at four points in time during the wing-rock cycle, corresponding to the 0-, 90-, 180-, and 270-deg cycle positions. Figure 2 shows that as the left leading edge moves through zero roll angle and continues to the maximum position (90 deg), the left vortex weakens and lifts off the wing, while the right vortex strengthens and moves inboard. As the right leading edge moves up to its maximum position (270 deg), the opposite occurs. The vortex liftoff is believed to be the source of the change in aerodynamic damping that stabilizes the wing response, thus producing a limit cycle oscillation. However, the details of the fluid mechanisms that produce the wing-rock phenomena are still under investigation.

Concluding Remarks

Modifications to an unsteady conical Euler code for the free-to-roll analysis of highly swept delta wings were described. The modifications involved the addition of the rolling rigid-body equation of motion for its simultaneous time integration with the governing flow equations. The flow solver utilized in the Euler code included a multistage Runge-Kutta time-stepping scheme that used a finite-volume spatial discretization on an unstructured mesh made up of triangles. A free-to-roll calculation was presented for a 75-deg swept delta wing at a freestream Mach number of 1.2 and an angle of attack of 30 deg. The free-to-roll case exhibited a wing-rock-type response produced by nonlinear aerodynamics associated with the leading-edge vortex motion. Similarities with wing-rock time history from a low-speed wind-tunnel test were noted.

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