breakdown on that side compared to the opposite side. Based on the measured effect of a shallow centerline spline on the vortex formation above a thick delta wing with triangular cross section,[14] the asymmetry observed on the 65-deg delta-wing-body configuration (inset in Fig. 1a) in tests at $\alpha = 30$ deg by Cipolla and Rockwell[15] at $Re = 0.0324 \times 10^6$ (Fig. 3) could be expected.[16,17] In spite of the symmetric flow conditions at $\alpha = 30$ deg and $\phi = 0$, the helical flow structure downstream of the spiral vortex breakdown was found to be asymmetric.[18] Of course, when the top-side centerbody is off center,[13] it should be expected to cause the observed static vortex asymmetry.

Conclusions

The significant effects on delta-wing aerodynamics of subtle changes in the centerbody geometry need to be fully understood when designing future unmanned combat air vehicles and low-observable configurations, having wings with sharp leading edges that generate vortices likely to be influenced to a unanticipated degree by the presence of an apparently insignificant fuselage.

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Trajectory Analyses of External Store Separation by Using the Euler Equations

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Introduction

THE prediction of the separation behavior for an external store released from a military aircraft is most concerned about the flight safety. The individual aerodynamic loads that acted on the store, however, possibly can cause the released stores to impact the aircraft. Thus, accurate predictions for the trajectory of external store such as bombs, tanks, and missiles released from the aircraft is one of the important missions for the design engineer. In general, there are three kinds of methods commonly used in determining the store separation characteristics. They are captive-trajectory system (CTS), free flight test, and numerical analysis. The CTS test can provide some useful data for regarding store carriage, but it is severely limited by the scaling effects and practical design considerations. The free flight test is an option, but without extensively analytical or experimental results for evaluating flight possibility in advance the test can cause unpredictable danger during the flight mission. In recent years the availability of modern computer systems has made the analytical methods become more efficient for the store separation prediction.[1–3] Thus, the numerical approach for the store separation prediction is employed in the present study.

To treat complex configuration, composite grid techniques commonly use two or more meshes to discretize the space domains. Although the disadvantage of composite meshes is that the flow solver must be modified, the bookkeeping that tracks relationships among the meshes will be more complicated. It is well known that the use of a multiple grid approach can yield a better grid resolution, simplify the application of boundary conditions, and alleviate the task of grid generation. In 1986, Steger and Benek developed an overset grid technique for solving unsteady body motion problems.[4] In their technique one component grid can move with respect to the rest of the components. The bookkeeping technique in their packages is fully capable of tracking the overset relationship about the moving mesh with the fixed grids. Successful calculations for the three-dimensional calculation have been presented in the Ref. 5. In this Note the use of the multiblock overset grid method combined with an iterative time-accurate Euler solver is presented for the trajectory prediction about a centerline fuel tank separation. The analytical flows include subsonic, transonic, and supersonic regimes.

Numerical Approach

Iteration of Euler Solver and Multiblock Overset Grid Scheme

The three-dimensional Euler equations and an implicit approximate factorization scheme for inviscid calculation are used in the present numerical approach. Details about the expression of three-dimensional Euler equations and formulation of the implicit factorization finite difference forms are shown in the Ref. 6. As mentioned in the Introduction, the original Euler solver must be modified to track the bookkeeping of multiple meshes and the "hole" points that

Received 12 July 2001; revision received 15 April 2002; accepted for publication 15 April 2002.

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result from the grid points of one mesh fall within the body boundaries of another.[4] These hole points must be blanked or excluded from the solution calculation.

Time Relaxation Method

In the current work a relaxation method is proposed to maintain a time-accurate solution for the unsteady flow calculation. This relaxation method is coupled with the earlier approximate factorization algorithm to correct the calculation values within a time step:

$$\left[I + h\delta_\xi A^{(m)}\right]\left[I + h\delta_\eta B^{(m)}\right]\left[I + h\delta_\varsigma C^{(m)}\right]\Delta Q^{(m)} = -h\left(\delta_\xi E^n + \delta_\eta F^n + \delta_\varsigma G^n\right) \tag{1}$$

$$Q^{(m+1)} = Q^{(m)} + \omega_{\text{in}} \Delta Q^n, \qquad m = 1, 2 \tag{2}$$

The mathematical symbols expressed in the Eq. (1) have been prescribed in Ref. 6. For the sake of simplification, we are not shown the detailed formations of the Eq. (1) again. Here, we just further introduce a relaxation technique that can achieve the time-accurate solution. For the present calculation Eq. (1) is combined with Eq. (2) within one time-step iteration. In general, several cycles for Eqs. (1) and (2) are performed to obtain a convergence solution. At the end of the time step, an outer relaxation is introduced.

$$Q^{n+1} = Q^n + \omega_{\text{out}} \Delta Q^{(m)} \tag{3}$$

The coefficients ω_{in} and ω_{out} presented in Eqs. (2) and (3) are the inner and outer relaxation parameters. The value ω_{out} must be chose as 1.0 for the unsteady flow computation.

Results and Discussions

Full 275-gal Fuel Tank Separation

In the first case a fighter with a full 275-gal fuel tank separation at flight height 15k ft is conducted. The flight Mach number and angle of attack are specified as $M_\infty = 0.85$ and $\alpha = 2.5$ deg. The principle moments of inertia for the full fuel tank are specified as $I_{xx} = 31.3$ slug-ft, $I_{yy} = 770.79$ slug-ft, and $I_{zz} = 771.75$ slug-ft. Also, the initial conditions of the tank with downward velocity and pitch rate are given as 9.85 ft/s and 0 deg/s, respectively. In the present calculation the preceding conditions and initial data are same as the CTS test. As shown in Fig. 1, the trajectory path of the dropped full fuel tank is displayed. From the figure a good comparison for the present calculation with the CTS data is achieved. Because of the 275-gal tank contains full fuel, the variation of pitch angles is very small during the tank separation.

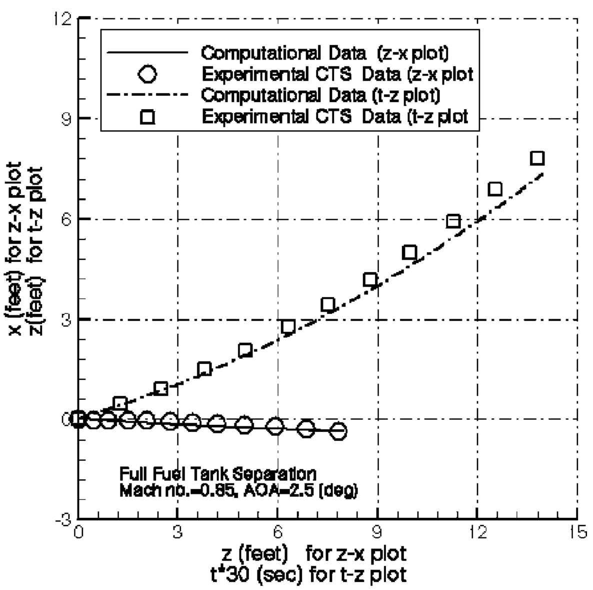

Fig. 1 Trajectory path of the full 275-gal fuel tank separation by the z–x and t–z plots.

Empty 275-gal Fuel Tank Separations

Further, trajectory calculations for an empty 275-gal fuel tank released from the fighter are investigated. In the present study three flight conditions of flight speed and angle of attack are chosen as $M = 0.7$, $\alpha = 2.5$ deg, $M = 0.85$, $\alpha = 2.5$ deg, and $M = 1.2$, $\alpha = 0.0$ deg. The principle moments of inertia of the empty fuel tank are set as $I_{xx} = 5.87$ slug-ft, $I_{yy} = 134.73$ slug-ft, and $I_{zz} = 134.73$ slug-ft. Also, the initial conditions for the downward velocity and pitch rate are given as 21.5 ft/s and -68.8 deg/s. The empty fuel tank is released from the aircraft at altitude 15k ft. By using the overset grid method, the trajectory data for the transonic case are displayed in Fig. 2. As shown in this figure, the satisfactory agreement is obtained when comparing the data with the flight and CTS results. Besides the displacement of the tank along the x and z directions (shown in the Fig. 2a), the numerical solution is compared well with the flight-test data. Except for the z–x and t–z curves, there are some discrepancies existing for both CTS and computations in the z–θ data when comparing the two results with the flight test (shown in the Fig. 2b). This is caused by the initial pitch rate for both computation, and CTS tests are different from the practical flight test. As the result, curve behavior of θ for the computation and experiment are only qualitatively similar to the flight test. As the

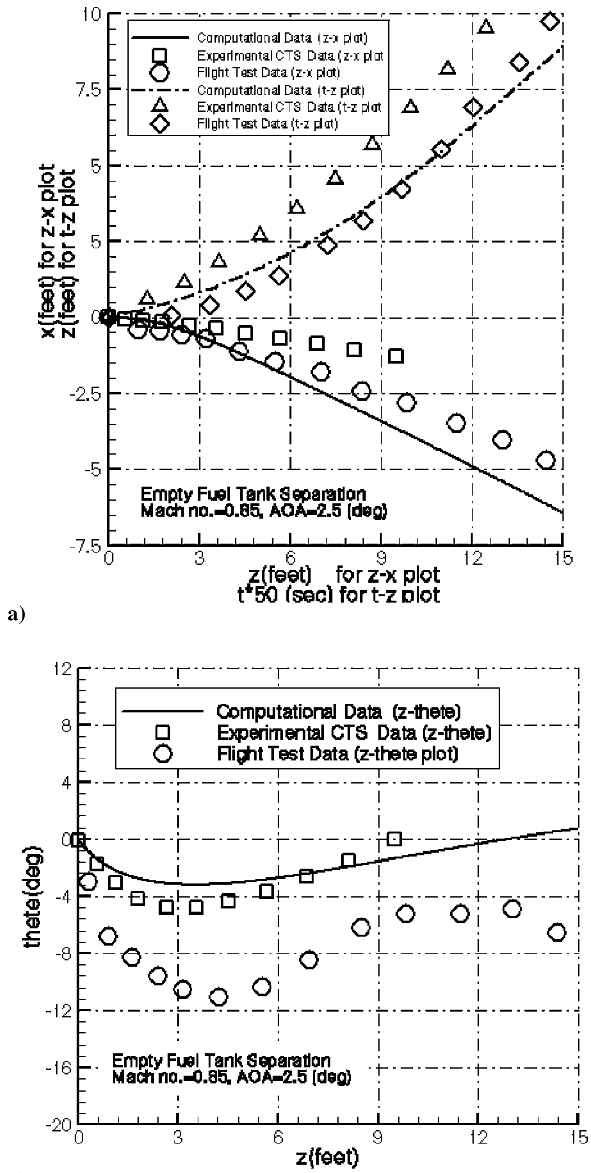

Fig. 2 Trajectory path of the empty 275-gal fuel tank separation by the a) z–x, t–z and b) z–θ plots.

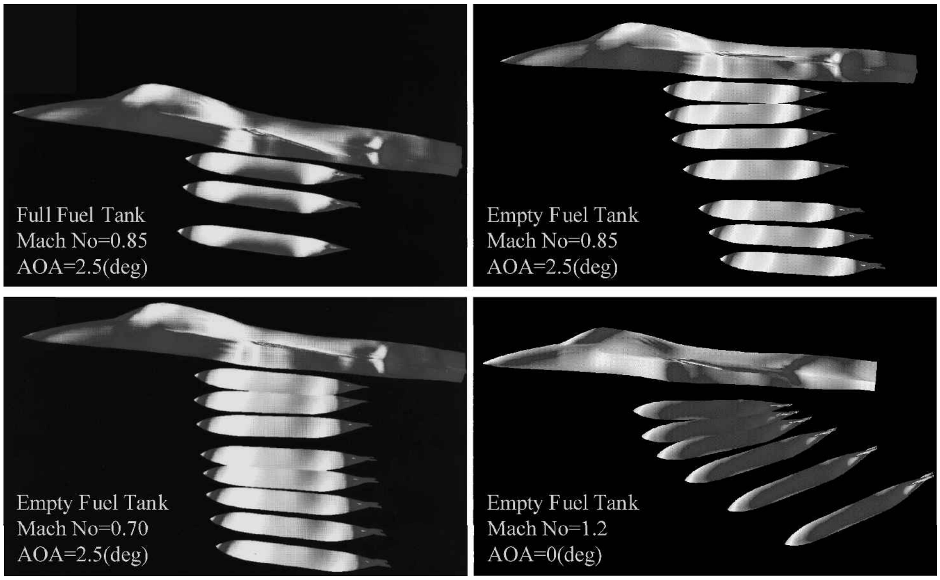

Fig. 3 Trajectory demonstrations of the full/empty 275-gal fuel tank separation at four kinds of flight condition (M_∞ = 0.7–1.2 and α = 0–2.5 deg).

flight speed increases to supersonic regime, the aerodynamic effect acted on the empty tank will hugely dominate the tank trajectory. The pressure drag produced by the oblique shock waves on the body and fin surfaces will make certain that the tank has a large movement backward from the flight direction. The overall trajectories for the preceding three cases are depicted in Fig. 3. It is apparent that the tank body pitched nose down first, followed by a nose up in the subsonic and transonic flows, while the fuel tank moved backward and pitched down rapidly as a result of the large pressure drag in the supersonic flow. As studied in the subsonic and transonic cases, the empty tank has a wave-like pattern in the pitch motion during separation process. Nevertheless, in the supersonic case the tail fins of the tank cannot produce large enough pitch-up moment to correct the pitch-down attitude. Thus, the tail tank body moves upward rapidly and can be potentially dangerous for impacting the aircraft. In addition, in the real flight the initial dropped pitch rate for the fuel tank could not be controlled accurately, and also some uncertified factors or flow disturbances could not be predicted completely in advance. This flight mission about safety should be more concerned in the supersonic store separation. Throughout this numerical analysis we suggested the fight Mach number for the empty 275-gal fuel tank separation should be limited to 0.85.

Conclusions

The application of the unsteady program, which consists of the Euler solver, the overset grid method, and time-accurate relaxation method, has shown the capabilities for unsteady motion analysis that related the external store separation problem. In this Note the predicted trajectories for the 275-gal fuel tank in the full and empty fuel conditions are analyzed. Also, the numerical data are presented for the comparison with the CTS test and free flight test. From the numerical study we can obtain a safe Mach-number limit for the external tank separation. In the present study the flight Mach number for the mission of empty 275-gal fuel tank separation is suggested to 0.85.

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Sensitivity Analysis to a Forced Landing Maneuver

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Introduction

FLIGHT simulators are becoming more sophisticated in replicating actual flying maneuvers and conditions. Despite the advancement of technology, a flight simulator cannot perfectly represent a particular aircraft in all aspects. For example, the

Received 20 February 2002; revision received 1 August 2002; accepted for publication 18 September 2002.

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