Turbulent Study of Roll Pitch Yaw Phenomena for a Finned Store Released from a Wing Regarding Different Values of Angle of Attack

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Abstract

In this article, the commercial software CFD FASTRAN is applied to study the roll, pitch and yaw phenomena of turbulent flows around a finned store released from a wing regarding different values of angle of attack. The three-dimensional, unsteady Navier-Stokes equations and standard $k$-$\varepsilon$ turbulent model are solved in the Cartesian coordinate system. The Chimera two-block grid system is utilized, and grid communication among two blocks are automatically implemented. To evaluate the accuracy of the present calculation, the calculated instantaneous trajectories of center of gravity of store, angles of roll, pitch and yaw, velocities and angular rates are compared with those of experimental data. The satisfactory agreement is achieved. Then, computations of different values of angle of attack applied on the store are carried out to investigate the unsteady roll, pitch and yaw phenomena of the separated store. Longitudinally clockwise roll angle of store from pilot’s viewpoint and yaw angle toward the wing tip decrease as the angle of attack increases. Maximum value of pitch angle increases as the angle of attack increases, and the time of maximum value of pitch angle increases as well.

Keywords: Store; Wing; Turbulent flows; Angle of attack; Yaw

1. Introduction

Physical phenomena of multi-body separation in the atmosphere are complicated and challenging. Typical...
applications are store separation from an aircraft, stage separation from a launch vehicle, canopy separation, and simulation of flight control systems. Significant attention has been given to the store separation from the aircrafts in recent years. Regarding the release of store from the aircraft, it is important that the target is hit and destroyed by the stores. However, it will not be allowed and expected if the mother aircraft is hit and damaged by the store it releases. Consequently, smooth separation of store and aircraft is also concerned. As mentioned by Pamadi et al [1], the aerodynamic characteristics of the relatively small-sized store were influenced by the proximity of the aircraft, but those of the aircraft were virtually not affected. A similar case was the separation of the X-15 research vehicle from the B-52 carrier aircraft [2]. The aerodynamic characteristics of the relatively smaller X-15 research vehicle were influenced by the proximity of B-52 aircraft, but not vice versa. The carriage and release of stores from fighter aircraft are of primary importance to Air Force. Accurate prediction of the trajectory of a store release from an aircraft is critical in assessing whether the store can be released safely as well as if it will accurately reach its target [3]. In general, there are three kinds of method commonly used in determining the store separation characteristics [4]. 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 consideration. The free flight test is an option, but it can cause unpredictable danger during flight mission without extensively analytical and experimental results for evaluating flight possibility in advance. Due to the increasing capability of computer facility as well as the advancement of computational fluid dynamics, numerical simulation of store separation becomes more efficient and reliable [3-18].

A computational fluid dynamic technique [3] was demonstrated for a time-accurate store separation event at transonic speeds, where an overlapping grid approach was used coupled with an implicit Euler flow solver with a flux-difference split scheme based on Roe’s approximate Riemann solver and a six-degree-of-freedom trajectory code. Three sources of error were identified and discussed. Liu [4] presented the multi-block overset grid method combined with an iterative time-accurate Euler solver to study the trajectory prediction about a centerline fuel tank separation. The flight Mach number for the mission of empty 275-gal fuel tank separation was suggested to be 0.85. The Beggar code [5] used blocked and overset grid techniques and combined the grid assembly, flow solution, and six-degree-of-freedom trajectory calculation processes into a single code with reduced user input. Single-store separation trajectory calculations at transonic Mach number were compared with wind tunnel data, and the generality and ease of use were further illustrated by a three-store ripple release simulation. A complete, complex aircraft, the F/A-18C, was modeled with actual stores in their carriage position [6]. Cobalt, a parallel, implicit unstructured flow solver, was used to calculate the flowfield and resultant aerodynamic loads on grids composed of tetrahedral cells. The resulting carriage loads were used in a separate six-degree-of-freedom rigid-body motion code to generate store trajectory. A numerical technique [7] for simulating the separation dynamics of strap-on boosters jettisoned in the dense atmosphere was presented. Six-degree-of-freedom, rigid-body equations of motion were integrated to the 3D unsteady Navier-Stokes solution procedure to determine the dynamic motions of strap-ons, and an automated chimera overset grid technique was introduced. Vertical and pitching motions of a thin body of revolution separating from a rectangular cavity in a subsonic stream were investigated to simulate store separation from weapons bay cavity [8]. Body trajectory dependencies on initial conditions, body parameters, and freestream velocity were studied. The grid survey approach was adopted to predict trajectory characteristics of a body-tail configuration separating from a clipped delta wing at transonic speed [9]. Coupled computational fluid dynamics with six-degree-of-freedom trajectory predictions using an automated Cartesian method were demonstrated by simulating a GBU-31/Joint Direct Attack Munition store separating from an F/A-18C aircraft [10], and the standalone six-degree-of-freedom package [11] were incorporated.

A low-order model was derived to capture the dominant mechanisms that governed the store trajectory with and without microjets and conditions under which unsafe and safe departures occurred were predicted [12]. This model included separate components to predict the pitch and plunge motion of the store when it was inside the cavity, passing through the shear layer at the mouth of the cavity, and completely outside the cavity. The ballistic separation effect in an aircraft flowfield was predicted via the direct direction of incremental coefficient [13], and the incremental coefficients were computed according to the difference between the aerodynamic coefficients. An analysis was made about the flow characteristics and the rocket motion during supersonic separation of an air-launching rocket from the mother plane [14]. The design parameters such as fin size and location of center of gravity of the rocket are essentially important factors for safe separation. The prediction of the separation movements of the external store weapons carried out on military aircraft wings under transonic Mach number and various angles of attack is an important task in the aerodynamic design area in order to define the safe operational-release envelopes.
Using computational fluid dynamics, unsteady flow-field related to multi-store separating from aircraft was researched, and the simulated results indicated that the movement of border upon stores had severe aerodynamic interfere action. The sequence and distance of multi-store had determinant influence for safe operation. Based on the dynamic hybrid grids, a parallel implicit finite-volume flow solver for 3D unsteady Navier-Stokes equations was developed to deal with problems of multi-body separation. The integration of the rigid-body, six-degree-of-freedom equations of motion was coupled in the same framework of the flow solver. In the authors’ previous study, the commercial software CFD FASTRAN was applied to study the parametric effects of inviscid flows around a store with fins released from a wing. The three-dimensional, unsteady Euler equations were solved in the Cartesian coordinate.

In this article, the commercial software CFD FASTRAN is applied to study the roll, pitch and yaw phenomena of turbulent flows around a finned store released from a wing regarding different values of angle of attack. The three-dimensional, unsteady Navier-Stokes equations and standard k-ε turbulent model are solved in the Cartesian coordinate system. Computations of different values of angle of attack applied on the store are carried out to investigate the unsteady roll, pitch and yaw phenomena of the separated store.

2. Governing Equation

In this paper, the three-dimensional, unsteady Navier-Stokes equations with moving domain effects and a two-equation standard k-ε turbulence model will be solved. The integral form can be written as

\[ \frac{d}{dt} \int_V \rho \left( \mathbf{u} \cdot \nabla \right) \theta dV + \int_S \left( \mathbf{F}_C - \mathbf{F}_D - \mathbf{F}_B \right) \cdot \mathbf{n} dS = \int_S \mathbf{F}_D \cdot \mathbf{n} dS \]

where \( \mathbf{Q} \) is the conserved variable vector, \( \mathbf{F}_C \) is the convective flux, \( \mathbf{F}_D \) is diffusive flux, \( \mathbf{v}_g \) is the volume surface velocity and \( \Omega \) is the source term.

As for the CFD FASTRAN commercial software, Roe’s approximate Riemann solver with the addition of Osher-Chakravarthy limiter is applied. The spatial accuracy is upgraded to third order. Regarding the time marching scheme, the fully implicit Jacobi-point iterative method is utilized. The temporal accuracy is equal to second order.

In the present calculations, no-penetration and adiabatic wall conditions are imposed on the store or wing surface. The velocity of surface of the non-moving wing is equal to zero, while the velocity of surface of the moving store is set to be the corresponding surface grid speed. Pressure and temperature are obtained by extrapolation from the values at the interior cells. Density is obtained from the equation of state. Considering the computational block of the wing, the freestream conditions are specified on the incoming boundary and space extrapolation is applied on the outgoing boundary.

The 6-DOF motion model requires additional information to determine how its body moves based on the physical properties and forces and movements. It is achieved through the general equations of unsteady motion. The 6-DOF module involves solving the six scalar equations to obtain the displacements and rotations of the moving body.

3. Results and Discussion

In this flow problem, the free stream Mach number, angle of attack and altitude are set to be 0.95, 0.0 deg, and 8000 meters, respectively. The wing-pylon-store configuration in Figure 1(a) consists of a clipped delta wing with a 45-degree sweep and a constant NACA 64A010 airfoil section. The geometry of store plotted in Figure 1(b) is an ogive-cylinder-ogive cross section shape, whereas the geometry of pylon is an ogive-flat plate-ogive cross section shape. The configurations of pylon had been generated in the authors’ previous Euler calculations. The fins of store consist of a clipped delta wing a 45-degree sweep and a NACA 0008 airfoil section. The benchmark wind-tunnel data were generated at Arnold Engineering Development Center. Regarding the computational domain, the x (longitudinally forward), y (laterally toward the wing tip) and z (vertically downward) axes are depicted in Figure 2, and far-field planes are set at least 10 times the length of root chords away from the wing.
Figure 1. (a) The wing-pylon-store configuration and (b) geometry of the finned store.

Figure 2. X (longitudinally forward), Y (laterally toward the wing tip) and Z (vertically downward) axes of the computational domain.

Initial conditions are set as $U=292.7045 \text{ m/s}$, $P=35652 \text{ N/m}^2$, $T=236.22 ^\circ \text{K}$, $K=4.283796 \text{ m}^2/\text{s}^2$, $\varepsilon=14216.24727 \text{ m}^2/\text{s}^3$, and other characteristic values are listed in Table 1.

Table 1. The characteristic values for turbulent flows around a finned store released from a wing

| Weight of the store       | 907.18 kg                     |
|---------------------------|-------------------------------|
| Center of gravity         | 1.41732 m aft of store nose   |
| Aft ejector location      | 1.746504 m aft of store nose  |
| Aft ejector force         | 4354.464 kg                   |
| Forward ejector location  | 1.237488 m aft of store nose  |
| Forward ejector force     | 1088.616 kg                   |
| Ejector store length      | 0.100584 m                    |
| Roll moment of inertia, Ixx| $27.11653932 \text{ kg-m}^2$ |
| Pitch moment of inertia, Iyy| $488.0977077 \text{ kg-m}^2$  |
| Yaw moment of inertia, Izz | $488.0977077 \text{ kg-m}^2$  |
| Aircraft angle of attack  | 0 deg                         |
| Pressure Altitude         | 8000m                         |
| $u$                       | 292.7045 m/s                  |
| $v$                       | 0 m/s                         |
| $w$                       | 0 m/s                         |
| $T$                       | 236.22 °K                     |
| $P$                       | 35652 N/m²                    |

The global and local views of Chimera two-block overset grid for turbulent flows around a finned store released from a wing is plotted in Figure 3, where 2507468 computational cells are generated. The major wing C-H type grid
consists of 1867396 computational cells, while the minor store C-O type grid consists of 640072 computational cells. The hole cutting capability and grid communication among two blocks are automatically implemented. The calculated instantaneous trajectories of center of gravity of store, angles of roll, pitch and yaw, velocities and angular rates will be compared with those of experimental data [3] to evaluate the accuracy of the present calculation. Furthermore, computations of different values of angle of attack applied on the store will be carried out to investigate the unsteady roll, pitch and yaw phenomena of the separated store.

In this paper, three different values of angle of attack -2 deg., 0 deg. and 2 deg. are calculated. In order to evaluate the accuracy of the present calculations, the calculated results of zero angle of attack are compared with those of experiment [3]. The runtime required for a typical simulation on ASUS A500 personal computer is about one month. Concerning the store, distributions of positions of center of gravity, angles, velocities and angular rates are plotted in Figure 4(a)-(d). As shown in Figure 4(a), the x-axis (longitudinally forward) movement of store for different values of angle of attack -2 deg., 0 deg. and 2 deg. at t=0.35 second are equal to -1.05ft, -0.999ft and -1ft, respectively. The longitudinally backward movement varies slightly as the angle of attack increases. As for the y-axis (laterally to the wing tip) direction, the lateral movement toward the wing tip for different values of angle of attack -2 deg., 0 deg. and 2 deg. at t=0.35 second are equal to -0.381ft, -0.301ft and -0.133ft, respectively. The lateral movement toward the wing tip increases as the angle of attack increases, and the difference between different angles of attack is slight. As shown in Figure 4(a) for zero angle of attack, the calculated distributions of positions of center of gravity in three axes compare very well with those of experiment [3]. The accuracy of the present calculations is evaluated.

Variations of angle of store are plotted in Figure 4(b). Roll angles of the store shown in Figure 4(b) for different values of angle of attack -2 deg., 0 deg. and 2 deg. at t=0.35 second are equal to 6.68 deg., 5.34 deg. and 1.25 deg., respectively. The longitudinally clockwise roll angle of store from pilot’s viewpoint decreases as the angle of attack increases, and the tendency becomes obvious after t=0.04 second. Regarding the angle of pitch of store shown in Figure 4(b) for angle of attack -2 deg., it attains the maximum value of 4.77 deg. at t= 0.18 second and thereafter decreases gradually during time evolution. The pitch angle for angle of attack -2 deg. at t=0.35 second is equal to -0.323 deg.. Considering zero angle of attack, pitch angle achieves the maximum value of 5.47 deg. at t= 0.2 second and thereafter decreases gradually during time evolution. The pitch angle for zero angle of attack at t=0.35 second is equal to 1.73 deg. As for the angle of attack 2 deg., pitch angle achieves the maximum value of 6.41 deg. at t= 0.22 second and thereafter decreases gradually during time evolution. The pitch angle for angle of attack 2 deg. at t=0.35 second is equal to 3.16 deg. Maximum value of pitch angle increases as the angle of attack increases, and the time of maximum value of pitch angle increases as the angle of attack increases as well. Yaw angles of the store shown in Figure 4(b) for different values of angle of attack -2 deg., 0 deg. and 2 deg. at t=0.35 second are equal to 12.8 deg., 12.3 deg. and 9.44 deg., respectively. It is apparent that the yaw angle toward the wing tip decreases as the angle of attack increases. After comparing the calculated roll, pitch and yaw angles of zero angle of attack in Figure 4(b)
with those of experiment [3], the satisfactory agreement is achieved and the accuracy of the present calculations is confirmed.

The x-axis (longitudinally forward), y-axis (laterally toward the wing tip) and z-axis (vertically downward) instantaneous velocities plotted in Figure 4(c) are u, v and w, respectively. The longitudinal velocity u for different values of angle of attack -2 deg., 0 deg. and 2 deg. at t=0.35 second are equal to -6.15 ft/sec., -5.82 ft/sec. and -5.84 ft/sec., respectively. The longitudinally backward velocity varies slightly as the angle of attack increases. Regarding the lateral velocity v shown in Figure 4(c) for angle of attack -2 deg., it reaches the minimum value of -1.71 ft/sec. at t= 0.18 second and thereafter increases gradually during time evolution. The lateral velocity of angle of attack -2 deg. at t=0.35 second is equal to 0.0253 ft/sec. Considering zero angle of attack, the lateral velocity achieves the minimum value of -1.43 ft/sec. at t= 0.19 second and thereafter increases gradually during time evolution. The lateral velocity of zero angle of attack at t=0.35 second is equal to 0.28 ft/sec. As for the angle of attack 2 deg., the lateral velocity attains the minimum value of -0.85 ft/sec. at t= 0.16 second and thereafter increases gradually during time evolution. The lateral velocity for angle of attack 2 deg. at t=0.35 second is equal to 0.785 ft/sec. The lateral velocity increases as the angle of attack increases, and its minimum value increases as well. Concerning the vertically downward velocity w shown in Figure 4(c) for angle of attack -2 deg. it increases linearly with higher acceleration of 216 ft/sec.\(^2\) from zero up to 10.8 ft/sec. at t= 0.05 second and thereafter increases at a smaller averaged acceleration of 22 ft/sec.\(^2\) during time evolution. The vertically downward velocity for angle of attack -2 deg. at t=0.35 second is equal to 17.4 ft/sec. Considering zero angle of attack, the vertically downward velocity increases linearly with higher acceleration of 216 ft/sec.\(^2\) from zero up to 10.8 ft/sec. at t= 0.05 second and thereafter increases at a smaller averaged acceleration of 19.6667 ft/sec.\(^2\) during time evolution. The vertically downward velocity for zero angle of attack at t=0.35 second is equal to 16.7 ft/sec. As for angle of attack 2 deg., the vertically downward velocity increases linearly with higher acceleration of 218 ft/sec.\(^2\) from zero up to 10.9 ft/sec. at t= 0.05 second and thereafter increases at a smaller averaged acceleration of 17.667 ft/sec.\(^2\) during time evolution. The vertically downward velocity for angle of attack 2 deg. at t=0.35 second is equal to 16.2 ft/sec. Maximum value of vertically downward velocity decreases as the angle of attack increases. Comparing the calculated velocities in three axes of zero angle of attack in Figure 4(c) with those of experiment [3], similar trend is demonstrated.

Distributions of angular rates of roll, pitch and yaw are demonstrated in Figure 4(d). The angular rate of roll for angle of attack -2 deg. attains the maximum value of 0.454 rad./sec. at t=0.1 second and thereafter decreases gradually during time evolution. The roll rate for angle of attack -2 deg. at t=0.35 second is equal to 0.205 rad./sec. Considering zero angle of attack, the roll rate achieves the maximum value of 0.322 rad./sec. at t= 0.11 second and thereafter decreases gradually during time evolution. The roll rate for zero angle of attack at t=0.35 second is equal to 0.218 rad./sec. As for the angle of attack 2 deg., the roll rate reaches the maximum value of 0.161 rad./sec. at t= 0.07 second and thereafter decreases gradually during time evolution. The roll rate for angle of attack 2 deg. at t=0.35 second is equal to -0.0954 rad./sec. The maximum value of roll rate decreases as the angle of attack increases. Regarding the pitch rate shown in Figure 4(d) for angle of attack -2 deg., it attains the maximum value of 0.903 rad./sec. at t= 0.05 second and thereafter decreases gradually during time evolution. The pitch rate for angle of attack -2 deg. at t=0.35 second is equal to -0.933 rad./sec. Considering zero angle of attack, the pitch rate achieves the maximum value of 0.907 rad./sec. at t=0.05 second and thereafter decreases gradually during time evolution. The pitch rate for zero angle of attack at t=0.35 second is equal to -0.843 rad./sec. As for the angle of attack 2 deg., the pitch rate reaches the maximum value of 0.969 rad./sec. at t=0.05 second and thereafter decreases gradually during time evolution. The pitch rate for angle of attack 2 deg. at t=0.35 second is equal to -0.828 rad./sec. The maximum value of pitch rate increases as the angle of attack increases. Concerning the yaw rate shown in Figure 4(d) for angle of attack -2 deg., it achieves the maximum value of 0.873 rad./sec. at t= 0.28 second and thereafter decreases gradually during time evolution. The yaw rate for Mach number 0.95 at t=0.35 second is equal to 0.796 rad./sec. Considering zero angle of attack, the yaw rate reaches the maximum value of 0.881 rad./sec. at t= 0.27 second and thereafter decreases gradually during time evolution. The yaw rate for zero angle of attack at t=0.35 second is equal to 0.797 rad./sec. As for the angle of attack 2 deg., the yaw rate reaches the maximum value of 0.652 rad./sec. at t= 0.23 second and thereafter decreases gradually during time evolution. The yaw rate for angle of attack 2 deg. at t=0.35 second is equal to 0.496 rad./sec. The time of maximum value of yaw rate shortens as the angle of attack increases. The tendency of calculated roll, pitch and yaw rates for zero angle of attack is very close to that of experiment [3] in Figure 4(d).
Figure 4. (a) Positions of center of gravity, (b) angles, (c) velocities and (d) angular rates of the store concerning different values of angle of attack for turbulent flows around a finned store released from a wing. ($M_\infty = 0.95$; angle of attack=-2°, 0° and 2°).

4. Conclusions

According to the comparison and analysis of the present solutions of different values of angle of attack, four conclusions of the separated store are listed as follows:

1. Longitudinally backward and vertically downward movements vary slightly as the angle of attack increases. Lateral movement toward the wing tip increases as the angle of attack increases.

2. Longitudinally clockwise roll angle of store from pilot’s viewpoint and yaw angle toward the wing tip decrease as the angle of attack increases. Maximum value of pitch angle increases as the angle of attack increases, and the time of maximum value of pitch angle increases as well.

3. Longitudinally backward velocity varies slightly as the angle of attack increases. Lateral velocity increases as the angle of attack increases. Maximum value of vertically downward velocity decreases as the angle of attack increases.

4. Maximum value of roll rate decreases as the angle of attack increases. Maximum value of pitch rate increases as the angle of attack increases. Time of maximum value of yaw rate shortens as the angle of attack increases.
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