PREDICTION OF STORE SEPARATION CHARACTERISTICS USING CFD AND VALIDATION WITH FLIGHT TEST RESULTS

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Abstract

The design, integration and certification of a store configuration to a fighter aircraft involve extensive and expensive wind tunnel and flight testing with the objective of determining the operational and deployment envelopes for safe separation. Computational trajectory prediction techniques have shown to have the potential not only to reduce the number of flight/wind tunnel tests but also to design an intelligent test matrix. In this paper a Cartesian grid based Euler code-PARAS coupled with trajectory evaluation module (a 6-DOF time integration module) developed at ADA has been used to predict the separation trajectory of an external store from Jaguar fighter aircraft. Coupled 6-DOF Cartesian grid based methods provide reasonably accurate results with low turnaround time. A traditional multi block structured grid usually provides a better result, however handling qualities and robustness in terms of complexity of configuration and range of flight conditions makes Cartesian grid based methods an ideal choice. The current method is capable of simulating store separations without user interventions. Trajectory from the flight test has been generated using photogrammetric methods, data for which has been generated using on-board high speed camera fitted on the special POD. The computed store trajectory results are validated with flight tests and found to be in good agreement. This computational approach is further applied to predict the trajectory for higher Mach number release configurations.

Key Words: *Store separation, Euler code, 6-DOF, Trajectory*

Nomenclature

φ = roll of the store w.r.t inertial frame
θ = pitch of the store w.r.t inertial frame
ψ = yaw of the store w.r.t inertial frame
M = free stream Mach number
X = positive towards rear
Y = positive towards starboard
Z = positive downward

Introduction

One of the most important tests in the certification of a new store/weapon on a fighter aircraft is a safe separation test performed to demonstrate that the weapon can be deployed safely and effectively. Such tests typically involve evaluation of various flight conditions and flight configurations throughout a defined operational envelope. To reduce the size of a flight test program, wind tunnel tests or computational methods are used to predict potential "hot spots" or troubled areas within the defined envelope. After analyzing the predictions, a flight test matrix is developed to test the worst case conditions. Once the flight tests have been successfully completed, a deployment envelope is recommended to the fleet. The basic characteristics of store separation analysis are the presence of a body that moves in computational domain as a result of its interaction with the computed flow field.

Over several years, efforts to validate, demonstrate and accelerate the insertion of CFD methods into the store certification process of external store carriage and release have been undertaken. In 1989 the clearance of the JSOW from the F-18 at Mach 0.95 took more than 400 hours of wind tunnel testing and twenty flights. In 2000, the MK-83 JDAM was cleared after 60 hours of wind tunnel testing and five flights to the full F-18 aircraft envelope of Mach

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1.3. This reduction occurred because of wider application of numerical simulation techniques, including CFD method [1].

Several methodologies have been proposed over the years for 6-DOF rigid body simulations including structured overset grid [2], unstructured dynamic remeshing, meshless and Cartesian embedded boundaries. Each scheme has its own strengths and weaknesses. PARAS employs Cartesian grid based methods with an option to integrate a 6-DOF module [3]. In this approach a, the aerodynamic prediction module (PARAS code), that computes the forces and moments acting on the store and trajectory evaluation module (a 6-DOF time integration module) is coupled into an automated program and hence there is no user intervention during the trajectory computation.

The primary objective of this ongoing study is 1) to gain confidence in PARAS's capability to accurately predict store trajectories and 2) to apply PARAS to different ADE specific store-pylon-aircraft combinations.

One configuration (Jaguar a/c-centre line pylon release) for which flight data was available was chosen to compare the results with those obtained from the PARAS integrated 6-DOF code. The results were validated and secondly the same methodologies for the same configuration were adopted for estimation of trajectory for higher Mach number release conditions.

Simulation Approach

Computational simulations of store separation using Cartesian based Euler methods involve a multi-step process from grid generation to setting us the model and obtaining a solution. The following section briefly describes these steps.

Geometry and Computational Mesh

Jaguar Aircraft: The geometry of Jaguar aircraft is modeled using a preprocessor tool GAMBIT. The fuselage, wing and the tail components of Jaguar aircraft are modeled. The air intakes are faired at the entry and there is no flow through the intakes. The fuselage bottom center line pylon is modeled wherein the airborne Store is mounted at the rear end. The geometry of the aircraft, pylon and the store are modeled to simulate the computations close to the real geometry to the extent possible. Fig.1(a) and Fig.1(b) show the actual geometry and computational geometry of Jaguar aircraft.

Store: The airborne store is also modeled using a CFD preprocessor tool GAMBIT. Store has a cruciform canard, main body and a flip-out tail fin unit. The fins have flip-out extended fins for giving enough stability to the bomb. The outboard fins are folded inside the inboard fins portions during carriage and release from the aircraft and the outboard fins are deployed immediately after separation phase from the aircraft. The configuration modeled for the CFD analysis of store separation is shown in Fig.3. Percentage of flip out opening in terms of its span is shown in this figure. Only 25% and 50% fin opening were simulated in this study for initial release period of about 1 sec. to establish the behavior.

Flow and Trajectory Calculations

A store trajectory prediction program comprises mainly of two distinct modules, namely (i) an aerodynamic prediction module (that computes the forces and moments acting on the store), and (ii) a 6-DOF time integration module (that computes the trajectory of a store given the forces and moments acting on the store and its inertial properties, such as mass and moments of inertia).

In the present study forces and moments acting on released store are computed using a computer code PARAS [3]. PARAS (PARallel Aerodynamic Simulator) is an Euler code that works on Cartesian grids. The effort involved in Cartesian grid generation is a few orders of magnitude lower than that required for more traditional structured multi-block grids. Also, PARAS code can easily handle configurations typical of the separating store problem.

A six degree of freedom (6-DOF) code [4] developed in ADA has been used here for predicting the motion of the store released from Jaguar aircraft. The aerodynamic prediction module (PARAS) and trajectory evaluation module (a 6-DOF time integration module) are coupled into an automated program and hence there is no user intervention during the trajectory computation.

A critical parameter in the store separation analysis is the miss distance [5]. The miss distance is defined herein as the minimum distance (as a function of time) between any part of the store and parent aircraft during the early part of the trajectory. Based on miss distance calculation it can be decided whether released store is safe for the aircraft or not.

A program has been developed to compute the miss distance. The miss distance code is based on a methodology whereby, the parent aircraft and the store are represented by discrete points. The store is positioned based on the corresponding displacements and orientation at each time step, and the miss distance is computed.

An algorithmic perspective to the trajectory and miss distance simulation approach is presented in Fig.2. Solution is started at the instant of store release, t=0. At this instant twelve state variables (SV) are evaluated. Aerodynamic forces and moments are evaluated by first creating an input file for generation of Cartesian grid and executing the PARAS code. There is no explicit correction for viscous effects. Values of SV along with aerodynamic data are used to obtain SV time-derivatives from the equations of motion. These equations are then integrated by 2nd order Runge-Kutta method in two steps to obtain SV at time $t^{n+1} = t^n + \Delta t$. In the first step SV is obtained at time $t^{n+(3/4)\Delta t} = t^n + (3/4)\Delta t$, with $t^0 = 0$. Aerodynamic forces and moments are evaluated at this stage again by generating Cartesian grid and executing the PARAS code. In the second step, using current values of SV along with aerodynamic data, time derivatives of SV are obtained from the equations of motion. After integrating the equations SV are obtained at time $t^{n+1} = t^n + \Delta t$. Grid is regenerated and using PARAS code, aerodynamic forces and moments are evaluated at this time step and the computation cycle is repeated. The process continues till the store leaves aircraft interference zone. Once the trajectory computation is completed the miss distance for all the time steps are computed using the miss distance program.

Description of the 6-DOF Equations: The six-degree-of freedom equations of motion are stated here in the reference frame of the moving body and are nonlinear. They describe evolution with time of twelve parameters defining the instantaneous state of the moving body, namely translational velocity (3 parameters), angular velocity (3), Euler angles (defining orientation of body-fixed frame w.r.t. an inertial frame -3 parameters), and position (w.r.t. inertial frame- 3). These variables are function of, apart from themselves (nonlinearity), the mass, moments-of-inertia, and instantaneous forces and moments (aerodynamic/propulsive/thrustor generated). The equations are in a very general form but do not include special cases like gust effects. They are reproduced from the text suggested by Stevens and Lewis [6].

The set of equations may be stated as

$$\dot{X} = f_1(X) + g_1(U, V) \tag{1}$$

$$\dot{U} = f_2(X, \dot{X}, C) \tag{2}$$

The state variable time derivatives $\dot{X}$ may be expressed explicitly in terms of current states X, aerodynamic inputs U, and inertial inputs V (mass, moments of inertia, center of gravity), as in equation (1). Equation (2) shows that the aerodynamic forces and moments U are functions of states X and state derivatives of X, as also of control surface deflections C that are, in turn, dependent on guidance and control laws.

Strictly, only equation (1) represents the equations of motion and is explained below. To evaluate the trajectories, however, equations (1) - (2) have to be solved together. Equation (2) incorporates the effect of guidance and control on trajectory evolution. However, in the present formulation these effects have not been considered explicitly.

Integration of Equations of Motion: The equations of motion, as expressed in the previous section, are a set of ordinary differential equations in time. They are not amenable to close-form solution and need to be solved numerically.

For an equation system of the general form

$$\dot{X} = F(X, t) \tag{3}$$

The solution at time t+Δt may be obtained from a Taylor's series expansion as

$$X(t+\Delta t) = X(t) + \Delta t\,\dot{X}(t)$$

$$+ \left((\Delta t)^2 / 2\,! \right) \ddot{X}(t) + \left((\Delta t)^2 / 2\,! \right) \dddot{X}(t) + \ldots \tag{4}$$

provided higher order derivatives of $X(t)$ with respect to time are available. But all that is available is the first derivative in the form of equation (3). Hence numerical schemes are developed to relate the first derivative in above equation to the higher derivatives in equation (4).

One of the best known numerical time-integration techniques is the higher order Runge-Kutta (RK) method that marches from one time step to the next by a series of intermediate evaluations of the right hand side of equation (3). The second order RK scheme that is used here, may be expressed for the general system in equation (3) as

$$k_1 = \Delta t\, F(X, t)$$

$$k_2 = \Delta t\, F(X + 3/4\, k_1\, , t + 3/4\, \Delta t)$$

and

$$X(t + \Delta t) = X(t) + 1/3\, k_1 + 2/3\, k_2 \quad (5)$$

An important feature of the Runge-Kutta equations is that they do not need values at previous time steps.

Flight Tests

ADE has conducted a number of flight trials for evaluating the performance of this store in the recent past. The store was carried and released from Jaguar aircraft fuselage bottom center line pylon over the test range at ITR Balasore. The store was released from Jaguar at MNo. 0.7 from 3 to 5 km altitude with 8ft/sec downward ejection velocity. The store release trajectories were checked for safe separation characteristics from the aircraft in the trials.

During the flight data has been obtained by different sources like, onboard telemetry data, EOTS data from ground stations, Video images from onboard cameras mounted on the pod, Video images from chase aircraft.

Some of the typical images captured during flight trials [7] by the on board high speed cameras for release at MNo. 0.7, 3km alt, Vz = 8ft/sec from Jaguar fuselage CLP are shown here in Fig.4. These images captured by the high speed cameras were used to get the separation characteristics of the store separated from the parent aircraft. Parameters like vertical displacement and pitch attitude during release phase were deduced from these images using photogrammetric techniques and were used for comparison with the computational results.

Results and Discussions

Trajectory generations are performed for separation cases of the airborne store released from the fuselage center line pylon of the Jaguar. The trajectory parameters examined are time evolution of X, Y, Z positions of bombs' C.G. and the store Euler angles pitch (θ), yaw (ψ) with respect to inertial frame. The inertial frame corresponds to the parent aircraft body axes at the instant of store release, considered as t = 0. Fig.5 shows the released store axes system where X, Y, and Z are considered positive towards rear, to starboard and downwards respectively. The roll, pitch and yaw angles are considered positive right wing down, nose up, and nose to right respectively.

Figures 7-8 shows the predicted trajectory of the airborne store released at MNo. 0.7, α = 0 (deg.), altitude = 3km and ejection velocity = 8 ft/sec.

Validation: Fig.7a and 7b show the displacement of airborne Store's cg in Z direction and development of pitch angle with time for the above flight condition. The bomb rear fins have a fixed portion and a flip-out portion. The flip-out fins are folded and housed inside the fixed fins during carriage and release from the aircraft. After the release around 200 milli seconds the flip-out fins start opening. The trajectories are computed considering two different bomb's rear flip-out fins opening timings- (i) fins start opening at t = 0.2 sec and (ii) fins start opening at t = 0.4 sec, see Fig.6. It has been observed that the bomb keeps on moving in downward direction from the parent aircraft. It has also been observed that the effect of bomb's rear fin opening timings in movement of bomb in Z direction is not very significant. The development of pitch angle with time is little slower for the case where fins start opening at t = 0.2 sec compared to the case where the fins start opening at t = 0.4 sec. The present result has been compared with flight test data. A good agreement has been obtained in Z motion. Whereas during initial stage the comparison of pitch angle is good but later on CFD result slightly deviates from flight test data.

Figure 8 shows the comparison of miss distance time history between flight test data and computed results for the above cases. The miss distance plots show that the bomb steadily moves farther from the parent aircraft. The comparison of computed miss distance with flight test data is found to be in good agreement.

Results: Figs 9-10 shows the predicted trajectory of the airborne Store (fins start opening at t = 0.4 sec) released at MNo. 0.8, α = 0 (deg.), altitude = 3km and ejection velocity = 8 ft/sec.

Figure 9a and 9b show the translational and angular states of the bomb for the above flight condition. The bomb c.g. moves in Z direction at a much faster rate than in the X and Y directions. The bomb initially exhibits a pitch down attitude and later on it has pitch up attitude. The development of yaw angle with time is very slow.

Figure 10 shows the miss distance time history for the above flight condition. The miss distance computation shows that the bomb steadily moves away from the parent aircraft.

Figures 11-12 shows the predicted trajectory of airborne Store (fins start opening at t = 0.4 sec released at MNo. 0.9, $\alpha = 0$ (deg.), altitude = 3km and ejection velocity = 8 ft/sec.

Figure 11a and 11b show the trajectory of airborne Store released from fuselage center line pylon of Jaguar at MNo. 0.9, $\alpha = 0$(deg.) and altitude = 3km. The trends of translational and angular states of the bomb are very similar to previous case.

Figure 12 shows the miss distance time history for the above flight condition. The trend of miss distance is also very similar to previous case.

Conclusion

This report presents the trajectory and miss distance of airborne Store released from fuselage center line pylon of Jaguar aircraft for MNo. 0.7, 0.8 and 0.9; $\alpha = 0$(deg.) and altitude = 3km. The trajectories have been predicted using Cartesian grid based Euler code PARAS and an in-house developed 6-DOF code. The predicted trajectory has also been validated with available flight test data. The comparison of predicted trajectory for MNo. 0.7 with flight test data is found very encouraging. The trajectory and miss distance predicted for release at higher speeds MNo. 0.8 and MNo. 0.9 also show that the separation of the bomb from Jaguar aircraft is safe.

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Fig.1a Actual Geometry of Full Aircraft-store Configuration

Fig.1b Computational Geometry of Full Aircraft-store Configuration

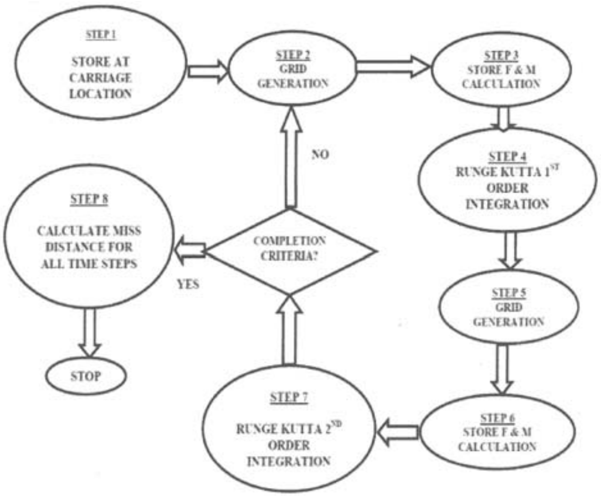

Fig.2 Store Trajectory and Miss Distance Prediction Process

Fig.3 Store Computational Models with Flip-out Fins (shown in + configuration for clarity)

Fig.4 Frame Photo of an Airdrop (on-board high speed camera)

Fig.5 Released Store Axes System as seen by the Pilot

Case - 1	
Time Duration (Sec) From Release	Fin Opening % in Terms of Flip out Fin span
0 - 0.2	0% (no fin opening)
0.2 - 0.4	25%
0.4 - 0.7	50%
0.7 - 1.1	75%
1.1 -	100%
Case - 2	
Time Duration (Sec)	Fin Opening %
0. - 0.4	0% (no fin opening)
0.4 - 0.7	25%
0.7 - 1.1	50%
1.1 - 1.6	75%
1.6 -	100%

Fig.6 Flip out Fin Opening Timings

Fig.7a Validation of Store Trajectory - Z Location

Fig.7b Validation of Store Trajectory - Pitch Angle

Fig.8 Validation of Miss Distance

Fig.9a Store Trajectory Computation - X, Y, Z Locations

Fig.9b Store Trajectory Computation - Pitch, Yaw Angles

Fig.10 Miss Distance Computations

Fig.11a Store Trajectory Computation - X, Y, Z Locations

Fig.11b Store Trajectory Computation - Pitch, Yaw Angles

Fig.12 Miss Distance Computation