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# Separation Dynamics of Air-to-Air Missile and Validation with Flight Data

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**ABSTRACT**

Prediction of flight characteristics of a store in the vicinity of an aircraft is vitally important for ensuring the safety of the aircraft and effectiveness of the store to meet the mission objective. Separation dynamics of an agile air-to-air-Missile from a fighter aircraft is numerically simulated using an integrated store separation dynamics suite. Chimera cloud of points along with a grid-free Euler solver is used to obtain aerodynamic force on the missile and the force is integrated using a rigid body dynamics code to obtain the missile position. In the present work, the suite is applied to a flight test case and sensitivity of trajectory variables on launch parameters is studied. Further, the results of the suite are compared with the flight data. The predicted body rates and Euler angles of missile compare well with the flight data.

**Keywords:** Grid-free method; Chimera cloud; Store separation dynamics; Rigid body dynamics; Validation

## 1. INTRODUCTION

Store separation study involves the estimation of flight characteristics of a missile in close proximity of an aircraft and other stores. A missile launched from an aircraft traverses through a highly non-uniform and complex flow fields. There are large velocity gradient regions due to shock waves emanating from the aircraft nose, leading edges of canards and wings. Further, the missile experiences severe flow angularities due to downwash from the deflected aircraft canard and side wash from the swept back wing. Even though the region of non-uniform flow is limited to near the aircraft, the effects are highly significant. The flow field complexities may induce the store to exhibit certain behaviour that compromises safety of the aircraft or effectiveness of the missile. A store separation trajectory must be safe and not to exhibit any threatening motion toward the aircraft and the transitory effects of the separation must not compromise the ability of the store to achieve the intended mission. In some cases, lateral motion is the primary concern due to tight tolerances between the store and the adjacent aircraft components or additional stores[1,2]. If the store escapes the aircraft flow field with increasing separation distance, then the trajectory is considered safe.

The store separation studies are generally carried out using flight testing[3], experimental methods[4,5] and computational fluid dynamics (CFD) methods[6]. Integrated or online method[7] and grid or off-line method[8,9] are generally used in store separation dynamics studies. In the first method, a rigid body dynamics code (RBD) is integrated with a CFD code. The aerodynamic forces are obtained on the missile using the CFD code and the forces are integrated using RBD code to obtain the new position of missile with respect to the aircraft. The above cycle is repeated till the missile reaches a safe distance. Main difficulty in the store separation dynamics using CFD methods is the grid generation around complex geometries of flight vehicles. Cartesian grid solvers[10], Unstructured Dynamic Grid solvers[11], Overset grid methods[12] and Grid-free methods[13] are successfully applied to study the store separation dynamics. Apart from the non-linear flow field, the uncertainties due to variations in missile properties, wing, fin and thrust misalignments also contribute to the unsafe separation or undesirable flight characteristics of the missile. Osman[14], *et. al.* have used unstructured dynamic mesh to carry out store separation studies for generic store separating from F-16 aircraft. They have observed that the quasi steady approach results compare well with the experimental data. Berglind and Tysell[15] have carried out the store separation studies including the aircraft manoeuvre and they have observed that the store separation is safer during manoeuvre due to the simultaneous movement of the air vehicle away from the store and the fact that the influence on the trajectory is weak. Perillo and Atkins[16] have pointed out that there is a growing importance of store separation studies due to rapidly diminishing store size and weight but increased store complexity and often less stable configuration. Kapulu and Tekinalp[17] presented simulation results to predict the behaviour of stores after being released from a helicopter. The effect of various inflow models on the collision of the store with the helicopter body is given. It is shown that the simulation code can predict unsafe cases and can be used as an important analysis tool to determine critical flight conditions before carrying out actual flight tests. Recently, hybrid RANS/LES models are employed to predict the store separation from weapons bays[18].

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In the present work, an integrated store separation dynamics (SSD) tool[19], that consists of a Grid-free Euler solver, a pre-processor and a RBD code, is used to simulate store separation dynamics of an agile air-to-air missile from a fighter aircraft at various launch conditions. The objective of the present work is to demonstrate that the SSD suite could predict the aircraft flow field effects on the trajectory of an unguided missile launched from the aircraft in flight. The objective was met by comparing the trajectory parameters of the missile including body rates and Euler angles of the missile with the measured flight data. This is a critical step of validating the SSD suite for the complex flow field to build confidence on the prediction capability and application of the SSD suite for the launch envelope expansion studies of the missile.

## 2. STORE SEPARATION DYNAMICS SUITE

Studies on store separation dynamics in the present work are carried out using a store separation dynamics (SSD) suite consists of a pre-processor, a grid-free Euler solver and a RBD code. The grid-free solver operates on a distribution of points and in the present work, an overlapped unstructured grids are used to get the distribution of points. The grids are used to mainly to get the desired point distribution that conforms to local feature of components and with appropriate clustering near the body. The grids are generated around the aircraft and the store separately and the grids are overlapped to get a chimera cloud of points. Even though the overlapped grids are used, the grid-free method, unlike overset grid method, does not require any interpolation for solution transfer across the overlapping grids and the solver is applied at all points except for the points fall within the solid component. Therefore, there is no specific requirement on cell size or absence of flow discontinuity in the overlapping region. Presence of thin gaps between the missile and deflected fins or aircraft and store in the captive position can be modelled efficiently without any special consideration on the individual component grids.

### 2.1 Pre-processor

The pre-processor accepts unstructured grids around the components and places appropriately to define the unstructured grids around the whole geometry. It identifies the points that lie inside the solid components (solid points), and removes them from the domain. The remaining points form a cloud of points around the geometry. The pre-processor identifies a set of neighbours, known as stencil or local cloud, around each point. The points in the overlapping region have neighbours from all the overlapping grids. There is an option in the pre-processor to optimize the overlapping region using wall distance (distance of a field point from the closest wall point). The points in the excess overlapping regions are also removed like solid points to form cloud of points with minimal overlap. This concept is followed from the overset grid method to reduce the overlapping region and, in turn, to reduce the computation time. A detailed discussion on the capability of the pre-processor is available in[20].

### 2.2 Grid-free Solver

The grid-free Euler solver, based on entropy variables least squares kinetic upwind method[21], is applied on the above distribution of points. The governing partial differential equations are solved in the differential form and the spatial derivatives are discretised using least squares method. Simple discretisation using least squares method, similar to central difference scheme, is inherently unstable. Therefore, the stencil is divided into sub-stencils and the least squares method is applied on the split fluxes evaluated at those points in the sub-stencils to obtain the flux derivatives such that it satisfies the upwinding property for the local flow field. The data structure of a grid-free solver consists of a cloud of points and a set of neighbours around each point. The simple data-structure allows making the solver to run on multi-core and/or processor systems efficiently. The cloud of points is divided into smaller sub-domains using graph partitioning software MeTis[22] and each sub-domains are solved in each core. The points, whose neighbours are in other cores, are duplicated in the respective cores and the values of those points are exchanged through message passing interface[23] calls. Further, to accelerate the computation, few cycles of Lower-Upper Symmetric Gauss Seidel method[24] is applied in each domain and the domain boundary values are exchanged after every cycle. At the end of iteration, the surface values are collected in one of the cores and the skin friction coefficient is evaluated at each point on the surface using van Driest method[25]. The surface pressure and skin friction are integrated to obtain aerodynamic forces on the aircraft and the missile. The store separation dynamics is fundamentally unsteady, since the store position and angle continuously change with the time. The unsteady method involves time accurate simulation of movement of store along with appropriate unsteady boundary conditions. The time step in RBD is same as that of fluid flow, which is generally very small. In the present case, a quasi steady method (similar to experimental technique of Captive Trajectory System) is employed where, the store is positioned relative to the aircraft and steady state simulations are carried out to obtain the aerodynamic loads on the store at that position. The force is integrated to obtain new location of missile using RBD code and the store is moved to the new location. This process is repeated till the store reach safe position. Here, the time step in the RBD code is considerably large compared to that of fluid flow. Therefore, the data structure generation is not that frequent as in the unsteady simulation.

### 2.3 Wall Boundary Condition

In the quasi-steady method, the relative velocity and body rates of store with respect to aircraft are not simulated. Due to relative velocity and body rates, the store experiences additional induced angle of attack. The aerodynamic force and moment due to the induced angle of attack will reduce the relative velocity and body rates and therefore, they are referenced to aerodynamic damping. The aerodynamic damping is modelled by rotating the store with an angle equal to the induced angle of attack. Sometime, such an angle of attack may lead to interference of the store with the aircraft. Therefore, in the present work, the relative velocity and the body rates are imposed as a transpiration boundary condition to model the relative motion of the store with respect to the aircraft which simulates the aerodynamic damping also. Generally, in the inviscid simulations, the slip wall boundary condition is imposed on the solid wall boundaries which implies that the velocity of fluid normal to the surface is zero, i.e., no mass flow pass through the solid wall. In store separation studies, the relative velocity and body rates of missile with respect to aircraft is imposed using transpiration boundary condition (TBC)[26]. In the TBC, the velocity of fluid normal to the surface is set as projection of local body velocity normal to the surface. This condition modifies the local flow field due to the missile linear and angular velocity in addition to the orientation of the missile with respect to the aircraft. This boundary condition creates additional force and moment that caused by the induced angle of attack due to missile velocity and they oppose the body rates of missile. Therefore, the TBC also models the effect of aerodynamic damping of the missile. The estimation of roll damping coefficient of a finner configuration and comparison with wind-tunnel results are presented in[19].

### 2.4 Rigid Body Dynamics

The force and moment of the missile are obtained using grid-free solver is integrated using RBD code to obtain the position and velocity of the missile. The aerodynamic force and moment obtained are in inertial frame. They are transformed to body frame and the forces due to gravity, thrust and misalignments are added to the basic aerodynamic force. Then, the six degrees-of-freedom of equations of motion are solved in the body frame using RBD code to obtain the missile new position and velocity. The body velocity and position are transformed to inertial frame and the cloud of points around the missile is correspondingly moved to the new position. The connectivity is regenerated for the new position of missile using the pre-processor. The transformation of vectors from body frame to inertial frame and vice versa are carried out using quaternion. The body velocity and angular rate are used in the TBC to model the relative motion of missile with respect to aircraft. The process is repeated till the missile reaches a safe distance.

## 3. APPLICATION OF SSD SUITE

The SSD suite was validated for a generic store separating from a wing[13]. The surface pressure distribution on the store at different time instants and the trajectory of the store compare well with the experimental results. The SSD tool was applied to an air-air missile (AAM) attached to a complex fighter aircraft[27] to predict the captive loads of the AAM. The captive loads were estimated on three set of distribution of points to obtain the grid independent results and the results compare well with a finite volume based commercial CFD solver. Then, the SSD tool was successfully applied on optimal grid to predict the trajectory of the AAM separating from the aircraft[28]. The effect of time step, aerodynamic damping, tip-off rates and skin friction on the trajectory of the AAM was studied and the results were compared to get appropriate simulation parameters.

### 3.1 Separation Dynamics

In the present work, the SSD tool is applied to the AAM at different launching conditions to get the trajectories of the missile. The axis system and the geometries are shown in Fig. 1. The chimera cloud of points is generated by overlapping distribution of points around aircraft and store. The distribution of points in a cross-section and a pitch plane passing through the missile and the aircraft wing are shown in Fig. 2. The grid-free Euler solver is applied on this cloud of points to get aerodynamic forces on the missile and the aircraft. Mach contours in a cross-section and a pitch plane are shown in Fig. 3. The forces and moments due to thrust, wing and fin misalignments are included in the RBD code. As the missile traverses along the rail, due to clearance between the rail and the missile, the missile experiences high body rates with rapidly varying contacts. This part of motion is simulated using transient dynamic analysis using ANSYS 3-D finite element model. The aerodynamic forces are obtained using SSD at different position of missile along the rail. The aerodynamic forces are used in the transient dynamic analysis to simulate the motion of the missile along the rail and the missile trajectory parameters at the end of rail phase are obtained[29]. The tip-off parameters, thus obtained, are used as initial conditions for

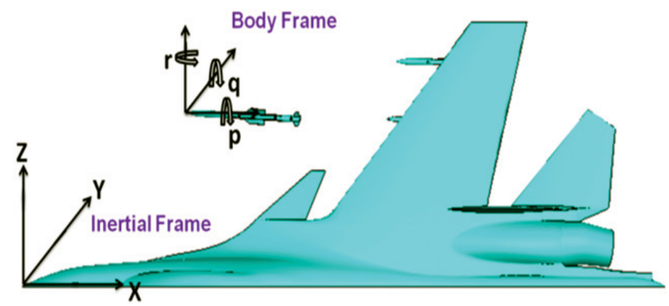
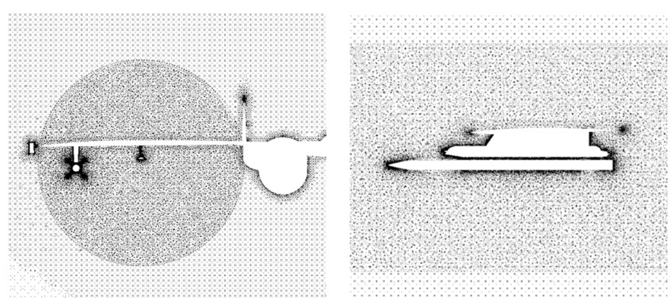
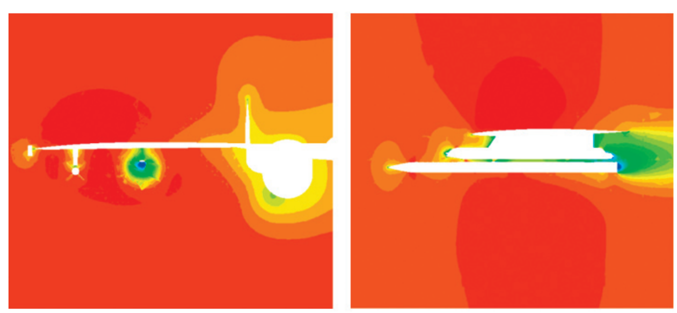



**Figure 1. Axis system.**



(a) (b)

**Figure 2. Chimera cloud of points; Distribution of points in a (a) cross-section and (b) pitch plane.**



(a) (b)

**Figure 3. Mach contours in a : (a) cross-section and (b) pitch plane.**

further separation dynamics study in the present work. The trajectory of missile predicted at a transonic Mach number, altitude of 5 km and angle of attack of -1.5° is shown in Fig. 4. The trajectory is simulated till the missile crosses the nose of the aircraft when the control is initiated. It can be observed the missile travels slightly downward due to higher gravity force in comparison with aerodynamic normal force of missile and missile moves slightly inward due to side slip angle.

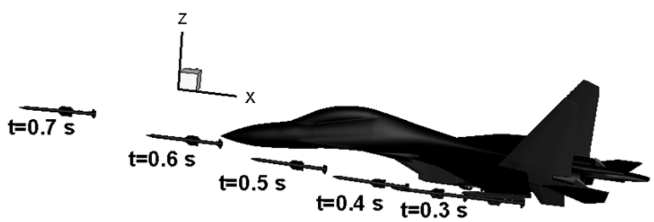



**Figure 4. Trajectory of missile.**

### 3.2 Sensitivity of Launch Parameters

Sensitivity study of various launch parameters on the missile trajectory is carried out. Even though the tip-off parameters should change with the launch parameters, in the present study, the tip-off parameters are fixed for relative comparison study. The effect of launch angle of attack on the missile trajectory parameters are given in Fig. 5. The aircraft angle of attack has been varied from -3° to 3°. Figure 5(a) shows the missile pitch rate at different angles of attack. Initially the missile has pitch down rate due to tip-off and as soon as the missile comes out of the rail, it pitches up due to stability of the missile and later pitches down due to the missile weathercock mode. The rise of pitch rate increases with the increase in angle of attack. Figure 5(b) shows the vertical displacement of the missile which indicates that the missile traverses down due to higher gravity force compared to the missile normal force at lower angle of attack. The displacement increases with the angle of attack as expected due to increase in normal force. The missile yaw rate and the lateral displacement at different angles of attack are given in Figs. 5(c) and 5(d), respectively. The missile yaw rate is positive, that is the missile nose turns away from aircraft, due to the cross-flow induced by the swept back wing of the aircraft. As the missile traverses, the yaw rate reduces due to stability of the missile. At negative angles of attack, initially the missile yaw rate is negative and as the missile crosses the wing influence the yaw rate increases. The displacement figure indicates the missile traverses away from the aircraft. Hence, the safety of the aircraft is ensured at all angles of attack. Further, the trajectories of missile are simulated at different launch altitudes from 1 km to 11 km and the corresponding missile pitch rate and yaw rate are given in Fig. 6. The effect of altitude on the missile pitch rate is given in Fig. 6(a). As mentioned earlier, from the initial tip-off pitch down rate, the missile pitch rate increases and later, the pitch rate decreases due to the stability of missile. As altitude increases, the dynamic pressure decreases and hence the aerodynamic moment also decreases. Therefore, the rate of increase in pitch rate reduces with the increase in altitude. A similar feature is observed in the yaw rate of the missile as shown in Fig. 6(b).

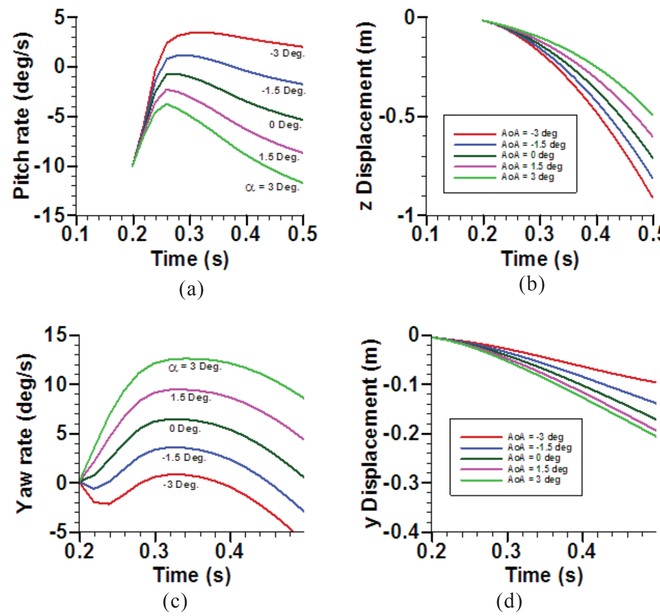



**Figure 5. Effect of angle of attack of aircraft on missile trajectory; (a) pitch rate, (b) vertical displacement, (c) yaw rate, and (d) lateral displacement.**

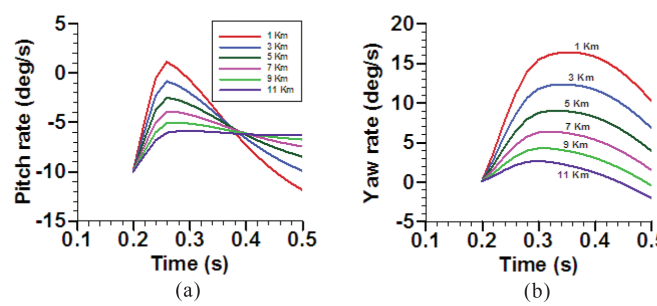
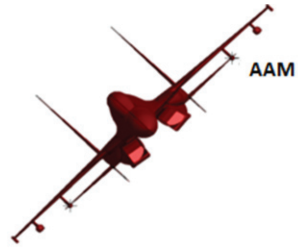


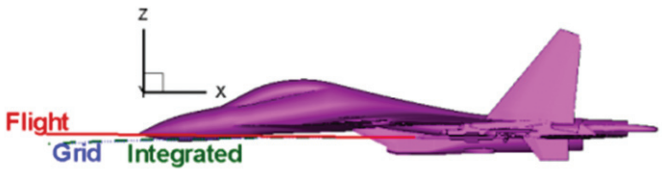

**Figure 6. Effect of launch altitude on missile trajectory: (a) pitch rate and (b) yaw rate.**

## 4. VALIDATION OF SSD SUITE WITH THE FLIGHT DATA

The air launch of the AAM is conducted at high subsonic Mach number during level turn of 1.45 g of aircraft with moderate angle of attack and side slip angle as shown in Fig. 7(a). The measured telemetry data includes the translational accelerations and angular velocities. The displacement and Euler angles are obtained by integrating the above measured data. The separation dynamics of the AAM is carried out using SSD for the same launch condition after the flight trial from the time instant the last launch shoe of the missile leaves the rail to the time instant of control initiation when the nose of the missile crosses nose of the aircraft. The initial conditions (such as tip-off rates) of the store separation studies are taken from the flight data. The wing, fin and thrust misalignments were measured before the flight test. The aerodynamic force and moment coefficients due to wing and fin misalignments and the force due to thrust misalignments are added to the aerodynamic coefficients of the basic configuration. The total force and moment are integrated to obtain the trajectory of the missile and are compared with the flight data. The relative displacement obtained using SSD compares well with




(a)

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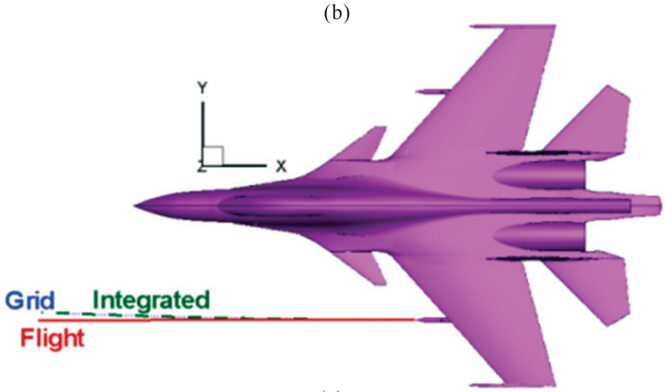
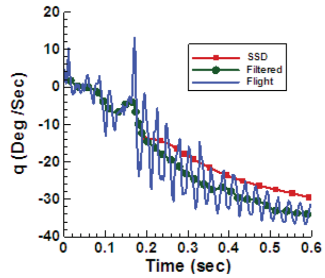


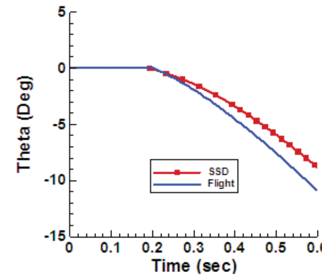

(c)

**Figure 7. Comparison of predicted displacement of missile with the flight data; (a) Level turn Manoeuvre, (b) Relative displacement (side view), and (c) Relative displacement (Top view).**

the flight data as shown in Figs. 7(b) and 7(c). The missile slightly moves inward and as well as downward, since the gravity force acts in that direction in the aircraft frame due to level turn of the aircraft. The time history of the pitch rate (p) and the pitch angle (θ) are compared in Figs. 8(a) and 8(b), respectively. The pitch rate of the missile is initially negative due to tip-off, since the centre of gravity of the missile is ahead of the last launch shoe of the missile. Then, the pitch rate is start increasing which indicate the inherent stability of the missile. There is an oscillatory behaviour of the pitch rate in the measurement which corresponds to the second mode of the structural vibration. The data is filtered to remove the structural frequency component. The structural frequency component is not predicted in the present rigid body simulation. However, the filtered body pitch rate compares well with that of the predicted pitch rate. Since, the missile rate is negative during this period, the missile pitch angle is continuously decreasing and the pitch angle is also comparing well. The yaw rate and yaw angle are compared in Figs. 8(c) and 8(d) and their behaviour are also similar to the pitch rate and the pitch angle. The predicted yaw rate and the yaw angle compare well with the filtered flight data. The roll rate and roll angles are compared in Figs. 8(e) and 8(f). The deviation is more in roll rate due to the prediction of rolling moment




(a)

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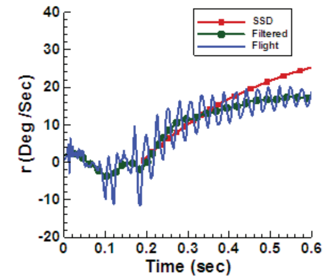
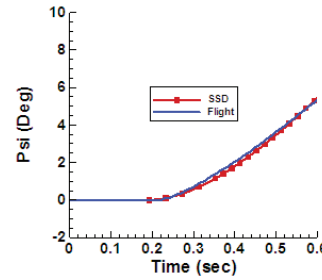
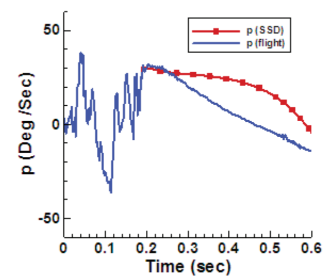


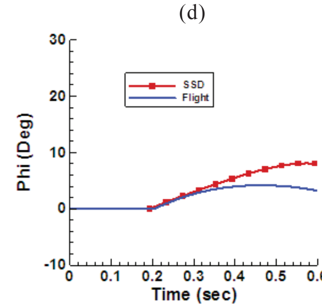

(c)




(d)




(e)




(f)

**Figure 8. Comparison of body rates and angles with the flight data; (a) pitch rate, (b) pitch angle, (c) yaw rate, (d) yaw angle, (e) roll rate, and (f) roll angle.**

by the CFD solver on asymmetric point distributions around the AAM. Although, the trends of predicted and measured roll rate and roll angle are similar, even a minor error in predicted rolling moment leads to considerable difference in roll rate due to low moment of inertia of the missile about the roll axis. Overall the predicted the missile trajectory compares well with the flight data.

## 5. CONCLUSIONS

An indigenous store separation dynamics suite has been developed and applied to separation dynamics studies of an AAM from a fighter aircraft for a flight condition with wing-fin and thrust misalignments. It is observed that the missile separation is safe. Sensitivity of launching conditions on the trajectory parameters are also studied to obtain the influence of these conditions on the resultant trajectory. As a post flight analysis, CFD simulations are also carried out at exact flight condition with the tip-off parameters obtained from the flight data. The predicted trajectory parameters using CFD simulations compare well with the flight measured data. This analysis forms the basis for the flight clearance by the certifying agencies and creates a lot of confidence to the test pilots and designers to go ahead for further flight trials at different launch conditions.

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