Defence Science Journal, Vol. 72, No. 2, March 2022, pp. 165-171, DOI : 10.14429/dsj.72.17608

Unsteady CFD Studies for Gust Modeling in Store Separation

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ABSTRACT

Aircraft and different store configurations must be certified before a flight. There is a small but finite probability of aircraft being hit by gust wind at the time of separation. Most store separation analyses from airborne platforms do not consider the gust phenomena because of the complexity and inadequate knowledge of its behavior. A dedicated task group was recently created to understand the gust-related phenomena in aircraft safety. Of the various gust cases, vertical gust is most severe and can cause instability leading to store collision. The situation is compounded in a long and heavy store due to its large projected area. No test procedures exist for simulation or practical tests of gust. A study was conducted to identify a test procedure for gust simulation using MIL standard data and Indian conditions. The current paper studies the emergency release condition where a vertical gust is hitting the aircraft to ascertain safe separation. A discrete gust with a 1-cosine shape and specified length and amplitude is imposed at the inflow boundary. The gust is allowed to sweep the computational domain containing the airborne platform and the store. The computed trajectory of the store, the miss distance, and its angular rates in the presence of gust are analysed in this work to study the safe separation of a store from an airborne platform. Simulations are also carried out to determine the effect of gust at the highest dynamic pressure in the flight envelope.

Keywords: Gust; CFD+6DOF; Miss distance; Safe separation

NOMENCLATURE

H	=	Enthalpy
M	=	Mach number
P	=	Pressure
Q	=	Heat flux
p,q,r	=	Angular rates
R	=	RPM of roll of rocket
S	=	Fin span
WAF	=	Wrap around fin
Y^+	=	Non-dimensional thickness of turbulent boundary layer
ρ	=	Density
θ	=	Pitch angle
ϕ	=	Roll angle
ψ	=	Yaw angle

1. INTRODUCTION

Safe separation of the store from an airborne platform is mission-critical. In early years, the certification of the safe separation was carried out through flight and wind tunnel tests (Captive Trajectory System (CTS), grid test, or drop test). The advent of powerful computer, robust numerical methods has enabled the Computational Fluid Dynamic (CFD) methods to play an essential role in the certification process worldwide. The details of the developments of experimental and numerical procedures are explained in Refs. 1 and 2. In India, the certification agency (CEMILAC) also depends heavily on CFD methods for approving the flight worthiness of any store from any airborne platforms. CFD calculations[3-4] of store separation in practical configurations form the basis of the certification.

Different weather conditions such as atmospheric gusts and turbulence have a catastrophic influence on aircraft safety. Gust phenomena also affect the safe separation and dynamical stability of the store in the vicinity of the mother aircraft. Several review articles and research report[5-8] published in the last few decades have enriched our knowledge significantly. A dedicated task group (NATO AVT-282) was recently created to study the flight-relevant gusts, urban wind fields, and air wakes pertaining to large-amplitude gusts encountering the rigid wing. The details of the proceedings are available in Refs. 9-11. Atmospheric turbulence depends on temperature lapse rate λ = dt/dh in the atmosphere. The rate of decrease in temperature mostly depends on the net content of water vapour present in the air. When an air mass rises, it may cool lesser than the surrounding air causing it to rise faster due to buoyancy depending on the water vapour. Another cause of turbulence is wind shear. Wind shear causes friction between adjacent

Received : 21 October 2021, Revised : 01 January 2022
Accepted : 20 January 2022, Online published : 11 May 2022

layers of air, which in turn causes secondary shear layers and hence increases turbulence. Both discrete gusts (sharp-edge, linear-ramp, and one-minus-cosine) and continuous gusts (Von Kármán and Dryden models[12-13]) have been used to study their effect on aircraft load. It is reported that larger gusts often exist as discrete and are more suitable for predicting gust load effects[14]. Both flight testing[15] and wind tunnel experiments[16] are used to collect data for mathematical modeling of gust. In analytical modeling[17], gust is assumed to have a 'one-minus-cosine' function shape with a fixed wavelength and variable amplitude. This approach, although simple, has worked well and has been adopted by the aircraft industry and certification agencies. The interaction of vertical gust with the aircraft and store is shown schematically in Fig. 1. The interaction of gust with the store during the separation stage from aircraft may produce adverse forces and moments on the store. This interaction may cause a collision of the store with the aircraft, which is far more critical than the aircraft flying in quiescent air. There has been no precedence in flight test procedure(s) or computer simulation(s) for predicting separation trajectory under gusts. Therefore it is essential to use a methodology to execute computer simulations. The methodology must provide:

- Parametric definition of gust,
- Methodology of using the defined gust in the simulation,
- Methodology of calculating aerodynamic forces on the store as it moves along its trajectory, and
- The procedure of calculating position and orientation of store knowing the aerodynamic forces.

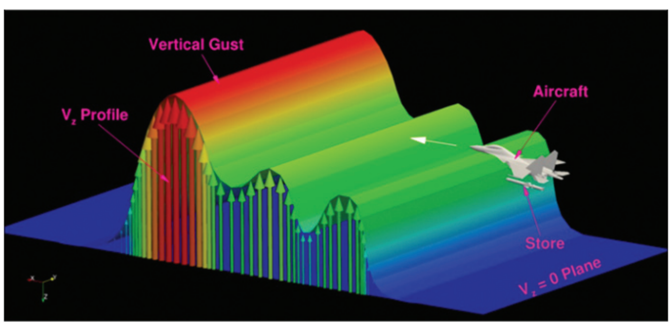

Figure 1. Vertical gust schematic.

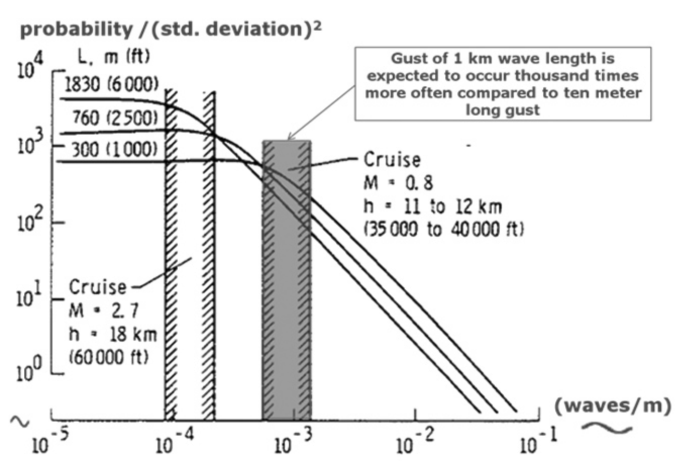

Figure 2. Von Karman atmosphere turbulence model.

MIL Standards (HDBK-1797A[12] and F8785C[13]) use von Karman and Dryden gust models. The scales and intensities used in these gust models for the discrete gust are the same. However, the standards are silent on the methodology for store separation using the gust models. In this work, a discrete gust model is used where the direction and shape of the gust (variation of gust velocity vs. distance, length of the gust, and amplitude) have been provided as inputs to simulation.

As per the suggestions of the MIL standard, a 1-cosine variation of gust shape is chosen. Each wavelength of gust has its own probability of amplitude and occurrence. As per MIL-STD-1797A[12], the probability of gust of wavelength of 10 meters is 1000 times lesser than 1 km length (Fig. 2). The smaller the wavelength, the smaller the magnitude of the gust will be. A longitudinal and lateral gust would have a less severe effect on the store physically. Hence, only vertical gust was studied.

The study uses the gust that has length resonating with the length of the store. The probability of such a gust occurring was one in one million. However, it was decided that this most severe simulation will be a superset of all store separation cases on the platform.

Similarly, the gust amplitude was taken from the standard that had a very low probability of occurring though it had the most severe effect on the separation. Owning to the highest air density at sea level and emergency jettison occurs during takeoff, all simulations were carried out at sea level. The highest Mach No. that can be achieved during sea level was used for simulation. Indigenously developed CFD package CFD Expert®[18-19] was modified to model the unsteady gust flow. The store separation from fighter aircraft was taken as the test case for validation. The computed trajectory of the store, the miss distance, and its angular rates are analysed in this work. The paper is organised as follows: Section 2 briefly describes the simulation methodology, governing equations, computational grids, and gust modeling. Simulation results are presented in section 3, and finally, conclusions are provided in section 4.

2. METHODOLOGY

The flow solver is run in inviscid mode (although viscous calculations were needed to predict store pressures correctly, inviscid results were adequate for predicting the trajectories[20]). The following flow chart (Fig. 3) explains the methodology for modeling the separation of a store from an airborne platform in the presence of gust. The adopted steps are as:

- The solver is run in the steady-state mode on the platform and store configuration
- The current position of the gust (P_{gust}) is computed in the domain
- Unsteady simulation is carried out with gust until the gust travels P_{gust} distance from the inlet boundary
- The new position and orientation of the store are calculated with the computed unsteady forces and moments using the 6 Degree of Freedom (6-DOF) trajectory program
- Check whether the store collided with the platform for the new position
- Generate a new volume mesh for the new position of the

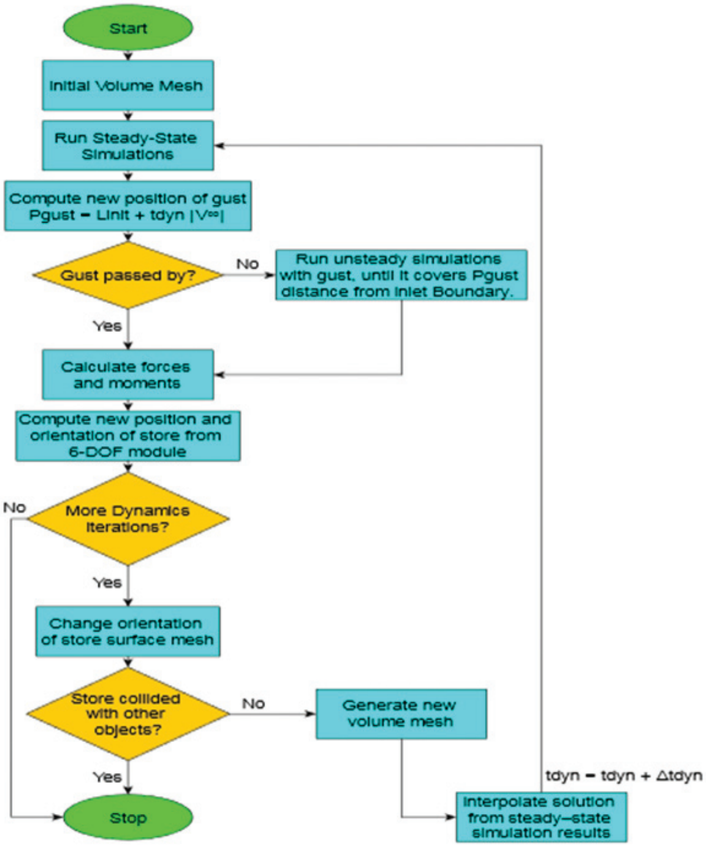

Figure 3. Flow chart for solver.

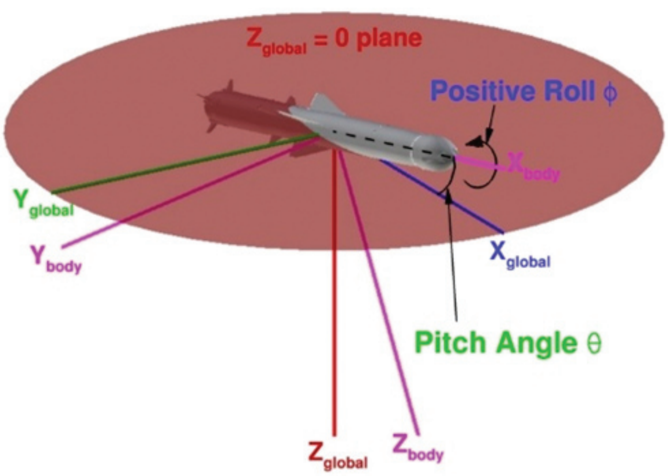

Figure 4. Coordinate axis adopted in the study.

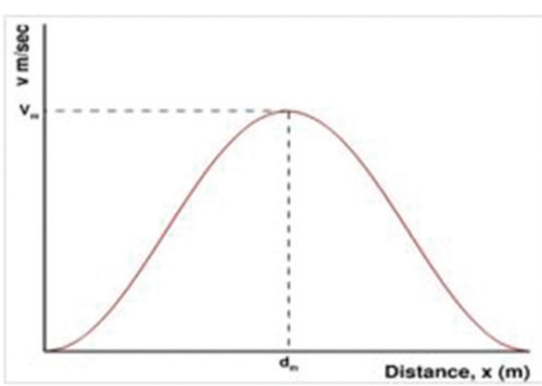

Figure 5. Graphical representation of 1-cosine discrete gust.

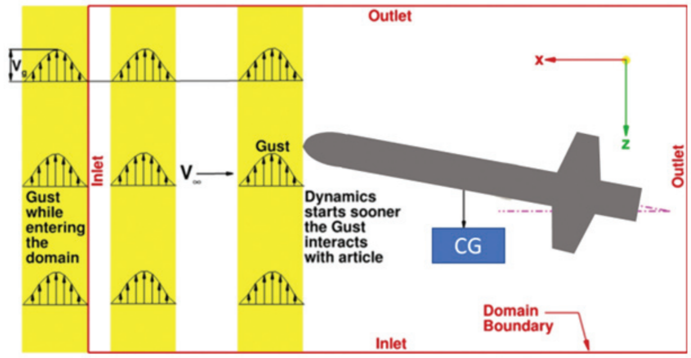

Figure 6. Boundary conditions for gust modeling.

store and repeat the solution for the next step until the store clears the platform safely.

2.1 Governing Equations

The appropriate system of equations governing for inviscid compressible gas may be written as:

Continuity equation**:**

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_k}(\rho u_k)=0$$

k = 1,2,3

Momentum equation**:**

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_k}(\rho u_i u_k)+\frac{\partial P}{\partial x_i}=0, \qquad i,\ k = 1,\ 2,\ 3$$

Energy equation**:**

$$\frac{\partial}{\partial t}(\rho H)+\frac{\partial}{\partial x_k}(\rho u_k H)-\frac{\partial q_k}{\partial x_k}=0, \qquad j,\ k = 1,\ 2,\ 3$$

Where ρ, p, u_i, H, and q_k are the density, pressure, velocity components, enthalpy, and heat flux, respectively.

2.2 Computational Details

2.2.1 Computational Grid

A steady-state simulation was first done on the platform and the store configuration to model the gust. A detailed grid independence study reveals that a 20 million mesh size is required to capture all the pertinent flow features. 99.29 per cent of cells have an aspect ratio below 5. The coordinate axis adopted in the study is presented in Fig. 4. The X-axis is taken from nose to tip along the fuselage reference line, and the y-axis and z-axis are along the spanwise and vertical upward directions, respectively. For moment sign convention, rolling moment (Mx) is considered positive anti-clockwise, pitching moment (My) and yawing moment (Mz) are considered positive in the directions of the nose up and port-side nose, respectively.

2.2.2 Gust Modeling

The importance of gust in aircraft safety and performance is already explained in the previous section. Most store separation analyses from airborne platforms do not consider the gust phenomena. To the best of the knowledge of the author, this is the first attempt to model gust in separation analysis of the store from an airborne platform

1-cosine discrete gust with $2d_m$ length and amplitude V is shown in Fig. 5. MIL-STD-1797A[12] states that the mean wind speed and turbulent wind speed have a maximum of 23.1 m/s at 20,000 ft altitude. The probability of this severe mean velocity is 10 in a million. The most probable velocity at that altitude is 5 m/s. The turbulent velocity (fluctuation above the mean velocity) has a maximum of 9 m/s. The probability of occurrence of this maximum fluctuation is 1 in a million.

2.2.3. Initial and Boundary Conditions

Boundary conditions are shown in Fig. 6. The study considers two different free-stream Mach numbers, 0.55 and 0.8, with an attack 10^0 and sideslip angle 2^0. Free stream conditions (Mach number, angle of attack, and sideslip angle) are not varied during the store separation analysis in the presence of gust. As depicted in Fig. 6, gust with 1-cosine shape with specified length and amplitude is imposed at the inflow boundary and allowed to move one sweep through the computational domain. It is ensured that the gust hits the store when it is in free-fall condition. The response of the store due to this imposed disturbance is analysed.

2.2.4. Simulation Procedure

The unsteady simulation requires the time step independence study, and it was found that 1 msec can be taken as a time step. The transient simulation used an implicit solver with multi-stage dual time stepping. A high-speed flux calculation scheme (HLLC) was used with a correction to avoid negative pressure[21]. The simulation started with the vertical gust entering the computational domain.

Store separation methodology predicts linear and angular accelerations of the store using Newton's second law of motion written in a non-inertial frame of reference, under gravitational, aerodynamic, and propulsive forces. When accelerations are integrated with time, they give linear and angular velocities and displacements. The gravitational forces are assumed constant since the separation time is minimal. In this case, propulsive force is absent till safe separation happens.

The method used is loosely coupled CFD + 6 DOF, where the simulation runs till there is a separation of one length of the store or the store hits the platform. In the current study, no ejection mechanism is considered, and the store is constrained by two pins and released due to the gravity effect. The store will have a 1DOF (downward) motion until the separation from the pin. Once the article is free from the pin, the 6 DOF trajectory program is employed to determine the store's linear and angular position. The 6 DOF code has the following features[22].

- It uses a body-fitted coordinate system attached to the C.G. of the store
- Capable accounting for gravitational forces, ejection forces, including aerodynamic forces and moments in wind or body coordinate system
- Uses moments of inertia and products of inertia
- Calculates linear as well as rotational acceleration, velocity, and position

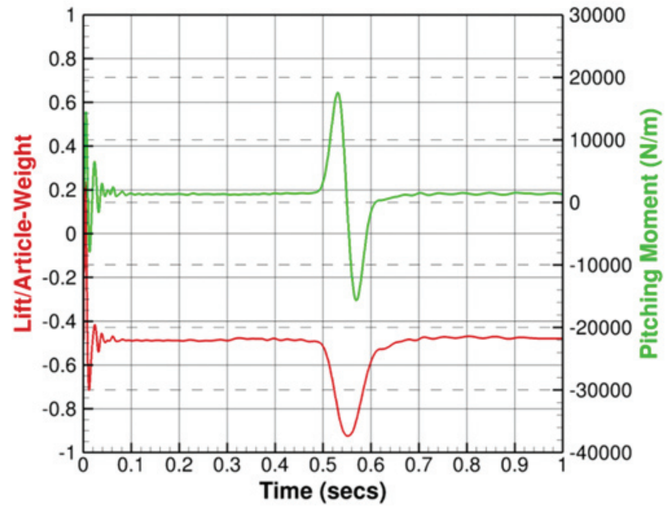

Figure 7. Time history of lift, pitching moment.

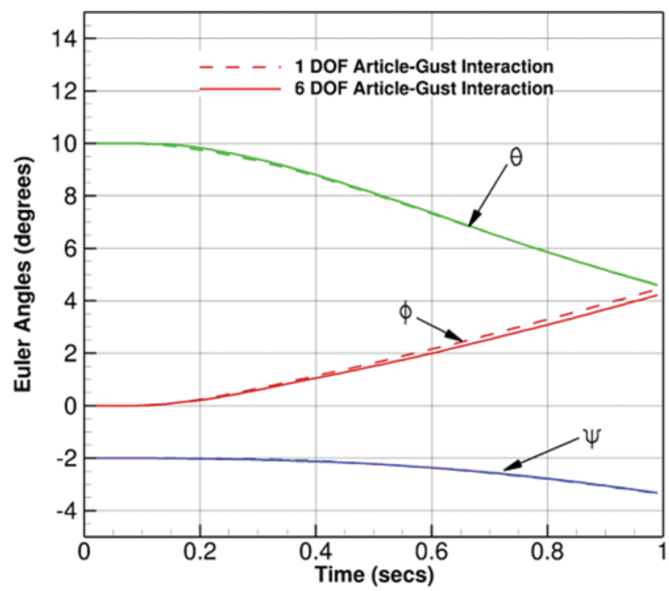

Figure 8. Time history of pitch (θ), roll (ϕ) and yaw (ψ) angles of the store.

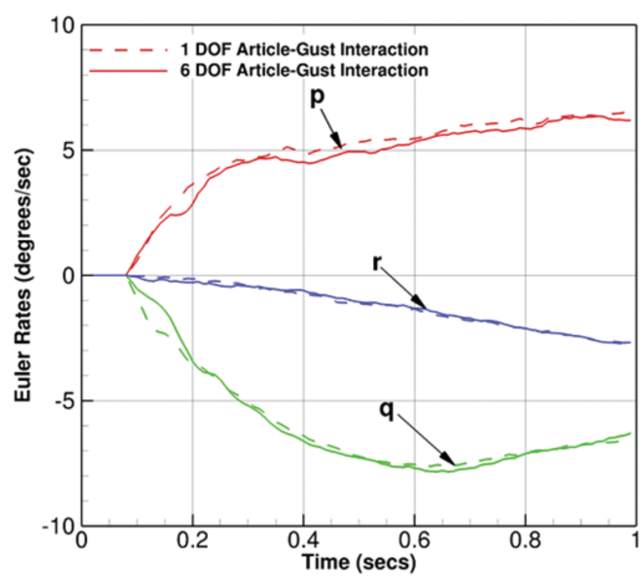

Figure 9. Time history of the angular rates of the store.

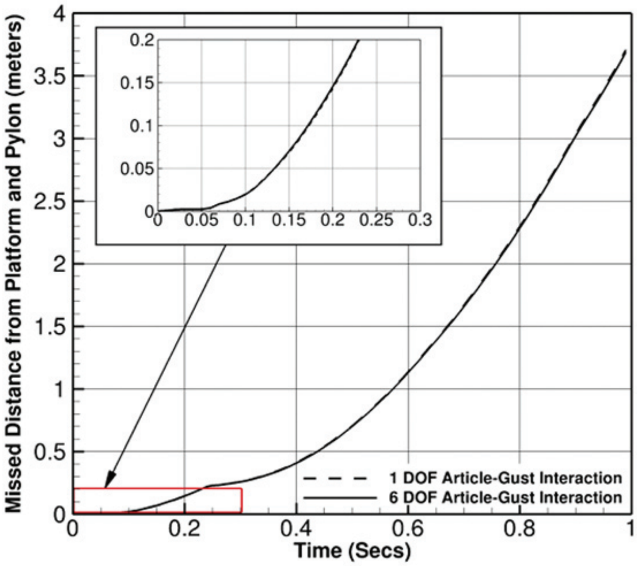

Figure 10. Miss distance history of the store.

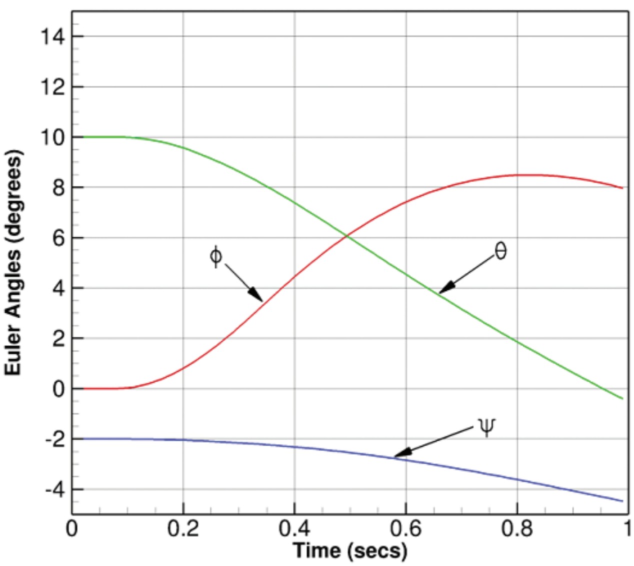

Figure 11. Angular position of store w.r.t time for Mach 0.8 case.

- Calculates the miss distance. The miss distance is the least distance from any point to aircraft to any point on the store.

3. RESULTS AND DISCUSSION

Figure 7 (*legend normalised to nearest 10K and 1*) shows the temporal variation of lift force and pitching moment. The gust reaches the nose 0.5 seconds after it has entered the computational domain. The gust would not affect the store when the separation has just started as the pins will not allow any instability in the store motion. The simulations were tuned such that the gust hits the platform when the store is clear of the pins. The store is now free, and the dynamics code transitions from 1-DOF to 6-DOF. This condition was the most severe case that would happen to the store. The time history of Pitch (θ), Roll (ϕ), and Yaw (ψ) angles and the angular rates (p,q,r) of the store are shown in Fig. 8 and Fig. 9, respectively. As seen in the figures, the Euler angles and the angular rates are very small, indicating a very benign and safe separation of the store from the platform. The results also reveal that angular motions are not very different with different trajectory models.

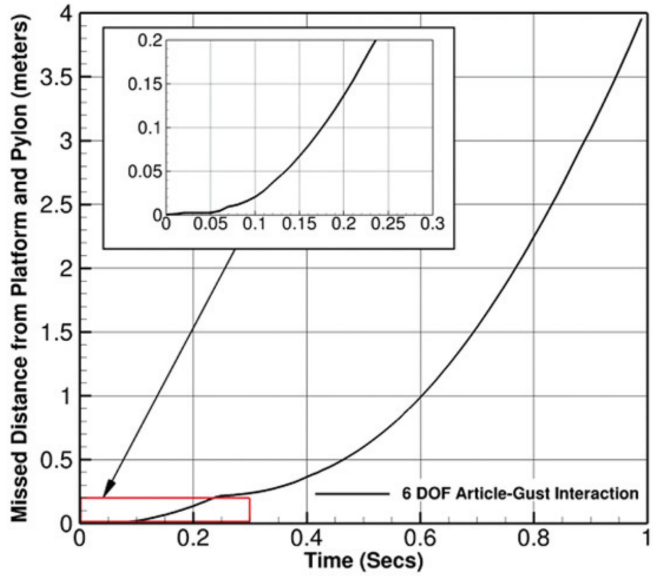

Figure 12. Miss distance history for Mach 0.8 case.

Miss distance is a critical parameter in the separation dynamics and is defined as the minimum distance between any point in the store and the platform. As specified in the MIL standards, safe separation should increase monotonically. The miss distance history is of the store for Mach no. 0.55 at an angle of attack 10^0, and sideslip angle 2^0 is shown in Fig. 10. A monotonically increasing trend is visible in the figure indicating safe separation of the article. A distinct change in slope in 2.5 sec indicates the transition of store movement is from the constrained motion in the guide pin (1 DOF) to free fall (6DOF). Simulations are also carried out for the highest dynamic pressure condition in the flight envelope for a higher Mach number of 0.8 and the same angle of attack and sideslip angle. The angular rates and the miss distance are presented in Fig. 11 and Fig. 12, respectively. Lower angular rates and monotonically increasing miss distance also indicate a safe and benign separation of the article in this highest dynamic pressure operation. It is conjectured that the wing and fuselage of the airborne platform diffuse the vertical velocity of the gust before it affects the store.

4. CONCLUSION

Atmospheric gust has adverse effects on the safe separation of the store from the airborne platform. To date, most of the separation analysis did not consider this phenomenon because of its inherent complexity and inadequate description. The methodology is established to study the effect of gust encountered in store separation from an airborne platform. An indigenously developed unsteady flow solver with coupled 6 DOF rigid body trajectory program is adopted for the analysis. As specified in the Mill standard, a 1-cosine discrete gust shape with twice the store length and 23 m/s velocity amplitude (with the probability of occurrence of 10 in a million) is taken for the study. The gust profile is applied in the inflow boundary and is allowed to sweep the computational domain containing the store and the platform. It is ensured that the gust reaches the store when it is in free-fall condition, and the store's orientation and its miss distance characteristics are examined. Grid independence and time-step independence were carried out. Simulations were carried out for two free stream Mach no 0.55 with the angle of attack 10 degree and sideslip angle 2 degree. The monotonic increase of the temporal variation of miss distance and very low Euler angles and angular rates indicates that the store's separation is very benign and safe. The effect of gust in the highest dynamic pressure in the flight envelope is considered by considering the free stream Mach number of 0.8. It is observed that the gust is having a very minimal effect in the separation event of the case investigated. It is conjectured that the wing and fuselage diffuse the vertical velocity of the gust before it affects the store. Separation of the store from the platform has been cleared for flight testing based on CFD results.

ACKNOWLEDGMENT

The authors would like to express their sincere gratitude to Sri Amit Goyal, Scientist, RCMA, NASIK, for his contributions and interest in the work, without which the work would not have seen the light of the day. The authors would like to thank Prof Gopal R Shevare (Director, Zeus Numerix) for his constant support and guidance in the study.

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Mr Sumit Kumar Jana received his MTech in Aerospace Engineering from the Indian Institute of Technology (IIT), Kharagpur. His area of interest include Aerodynamics, CFD, Dynamics, Acoustics, Inflatable structures, and Electromagnetics.
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His contribution in the present work is to provide overall guidance to the team, review the results, and prepare the final manuscript.