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AIAC 2019 STORE SEPARATION COMPUTATIONAL FLUID DYNAMICS WORKSHOP RESULTS

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ABSTRACT

A store separation workshop that aims to determine trajectories of stores separating from cavities is proposed for AIAC 2019. This paper presents results obtained by authors using Computational Fluid Dynamics (CFD) methods and compares it with the wind tunnel data provided as part of the Workshop. Separation trajectories are calculated for two cases using wind tunnel grid test data, CFD grid test results and unsteady CFD coupled 6 Degree of Freedom (6DOF) solver. Results show that wind tunnel and CFD grid data do not match each other inside the cavity, leading to different store attitude values during separation. Application of ejector forces is important to avoid any clash between store and cavity. Shear layer between cavity and freestream leads to significant unsteadiness and store aerodynamic coefficients are fluctuating when it is inside the shear layer.

INTRODUCTION

Trajectories of stores released from aircraft need to be determined before flight testing to avoid costly and dangerous accidents. For many years, wind tunnel testing is used to calculate trajectories of stores separating from aircraft. However, it is seen from many works [Cenko 2010; Cenko, Gowanlock, Lutton and Tutty, 2010] Computational Fluid Dynamics (CFD) is applicable to estimation of these trajectory calculations for stores released from underwing stations. The Store Separation Workshop of AIAC 2019 aims to obtain aerodynamic characteristics of Mk-82 store separating from a cavity and calculate its trajectory using CFD methods.

A Mk-82 store separating from a cavity was tested previously during NICS (Navy Internal Carriage & Separation, 1989) Wind Tunnel Test campaign [Finney, 2010]. It is aimed to integrate Mk-82 stores into cavities of F-14 aircraft to provide stealth. Tests were done to obtain ejector force requirements for safe separation and grid data in x and z traverses.

This workshop also aims to compare results from available practices for store separation from cavities. Authors provided results obtained using CFD and compared them with available wind tunnel data.

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METHOD

Geometry of the Mk-82 store (Figure 1) and cavity (Figure 2) are generated using the information provided on the workshop data sheet [Cenko, 2019]. For CFD analyses, store is located inside the cavity as done in wind tunnel tests and at different vertical positions (z) and attitudes (θ) aerodynamic coefficients are calculated for grid data. In addition to that, freestream CFD analyses are done for the Mk-82 store. These aerodynamic data are combined to calculate trajectories using a trajectory estimation tool developed in-house by authors.

Figure 1: Mk-82 Store Geometry (Side and Rear View)

Note that, Mk-82 store model used in CFD analyses has no deflection on its fins (0°), whereas some sources provide a finite cant angle. Authors couldn't find a reliable source regarding fin deflections. As workshop freestream wind tunnel data for roll moment is zero for all angles of attack, it was decided to use 0° fin deflections.

Center of gravity of the Mk-82 store is at 3.48ft aft of nose. In carriage position, store center of gravity is located at x=-11.0ft, y=-0.6ft and z=0.53ft when measured with respect to the top-front-right corner of the cavity. Directions of the coordinate system used in analyses are shown in Figure 2. Gravity vector is directed towards z direction.

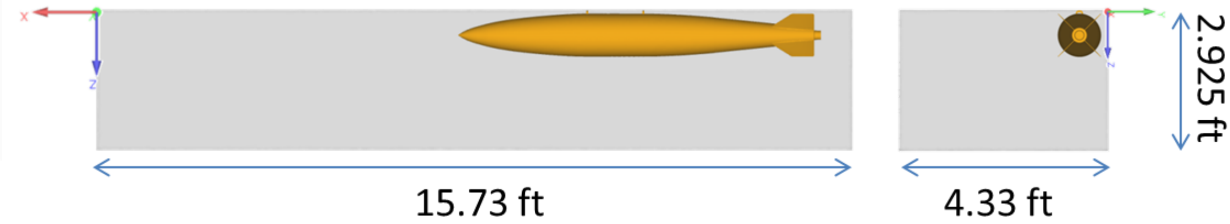

Figure 2: Cavity Geometry with Store at Carriage Position (Side and Rear View)

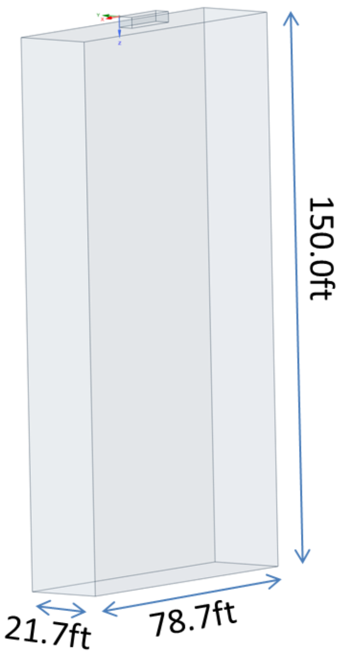

Figure 3: Size of the Computational Domain

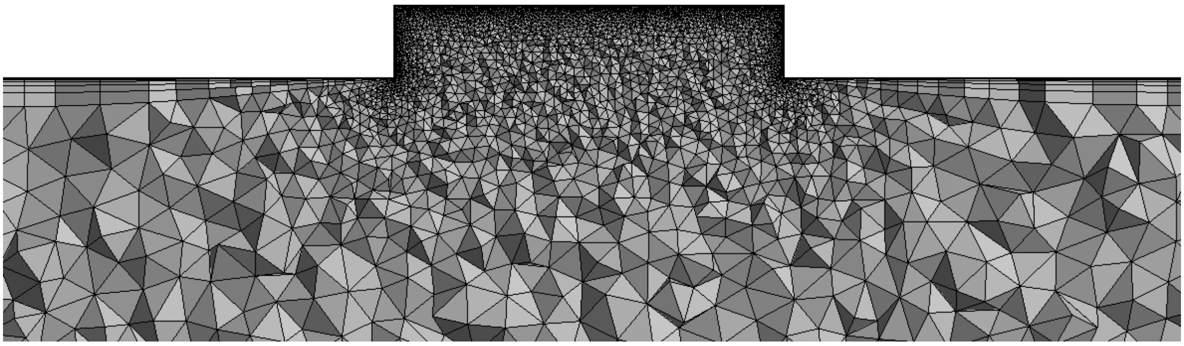

Figure 4: Computational Domain and Mesh Detail around the Cavity

For store separation trajectory calculations, grid test type analyses are used to obtain aerodynamic coefficients at distinct store position and attitudes in vicinity of the aircraft to get interference values. In this work, grid test CFD analyses are done using Chimera type mesh approach as it allows easy repositioning of the store without generating a new mesh for each position-attitude coupling. Size of the computational domain and details of the mesh around the cavity are presented in Figure 3 and Figure 4. This mesh consists of 2.5M cells approximately. Zonal mesh around the store combined with cavity mesh is shown in Figure 5 (~4.9M cells). Combined cavity and zonal meshes used for Chimera type approach are shown together at carriage position in Figure 6.

Geometry details of the exact NICS wind tunnel test model couldn't be found by authors. Therefore, upper domain face that is connected to the cavity walls is also taken as wall and dimensions of it can be seen from Figure 3.

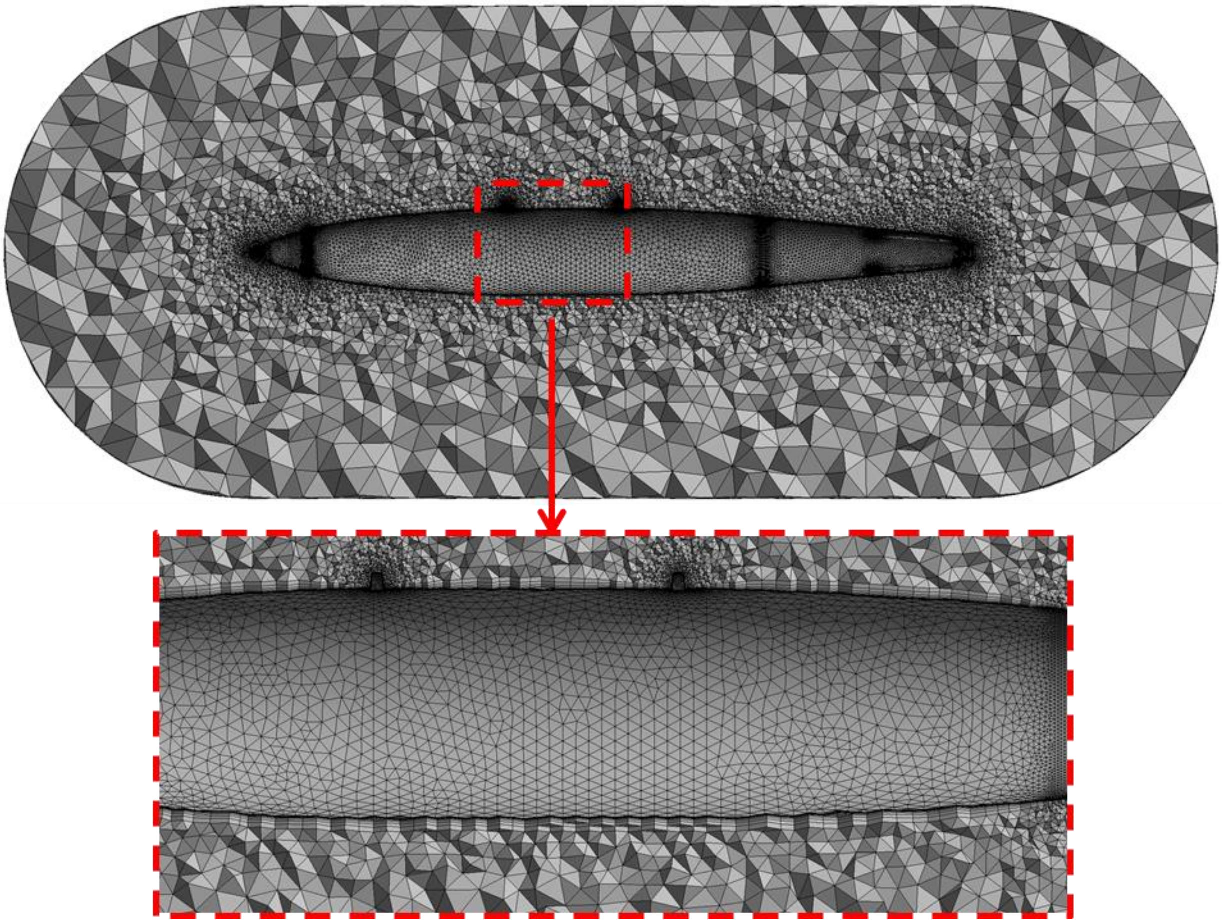

Figure 5: Solution Domain around the Store for Grid Test Analyses

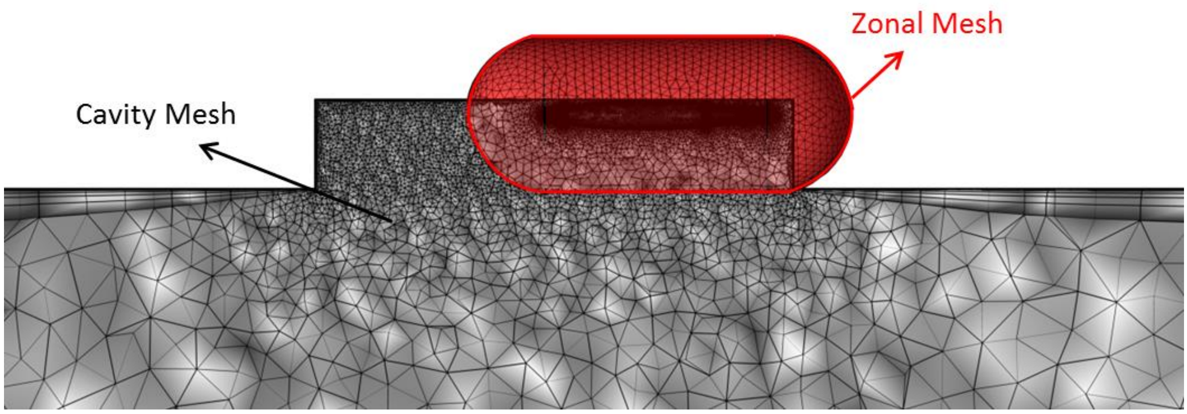

Figure 6: Combined Solution Domain for Grid Test Analyses near Cavity (Chimera Type)

Aerodynamic interference of store and cavity is calculated by combining grid test analysis results and aerodynamic coefficients of the store at freestream. Therefore, freestream analyses of the Mk-82 store without the cavity are done using another computational domain. It consists of 5M cells and shown in Figure 7.

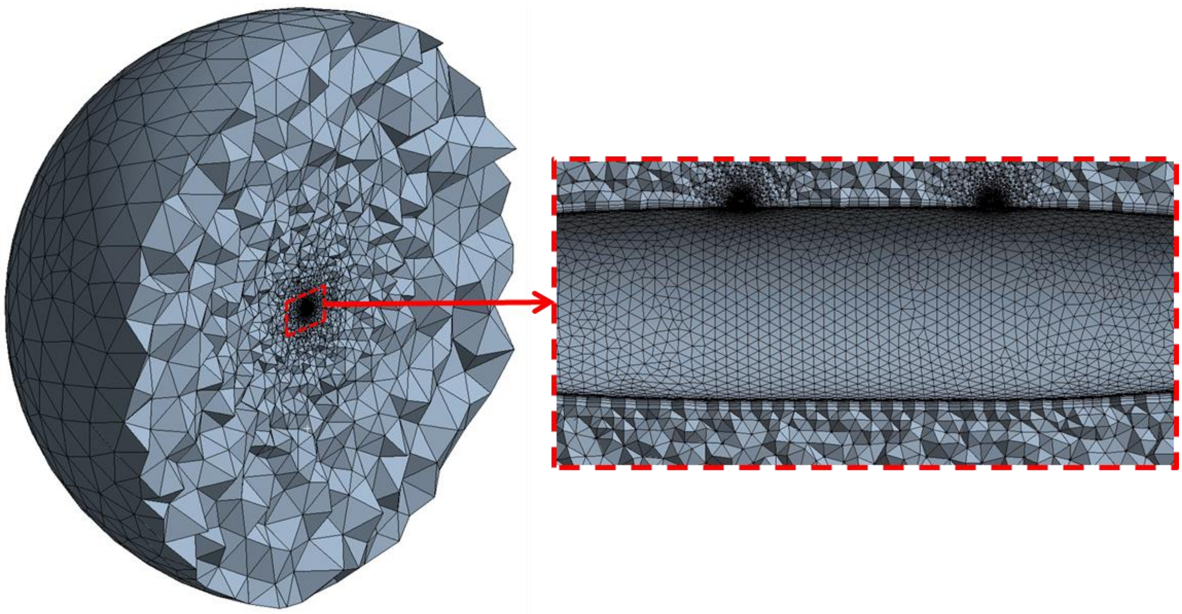

Figure 7: Computational Domain around the Store for Freestream Analyses

Aerodynamic coefficients for both grid and freestream CFD analyses are presented in results section. Moreover, using these coefficients, position and attitude of the store with respect to time are calculated using an in-house trajectory code. Both wind tunnel and CFD grid data are used for trajectory calculations. As no captive trajectory test result from wind tunnel is available to authors, store separation simulations using unsteady CFD analyses coupled with 6DOF are done. Then, trajectories are compared with results from grid data calculations. Unsteady CFD analyses carried out using Chimera mesh shown in Figure 6.

CFD++ commercial solver is used with realizable k-ε turbulence model for all CFD analyses. For unsteady analyses, time step is 0.001s and internal iterations are chosen as 35 for convergence. Flight conditions for all of the analyses are the same and given in Table 1.

Table 1: Flight Conditions for Analyses

Mach Number	0.85
Altitude	Sea Level
Angle of Attack	0° for grid, -20° to 20° for freestream
Angle of Sideslip	0°

RESULTS

Grid Test Results

Grid test results for normal force, side force, pitching moment and yawing moment coefficients are presented in Figures 8 to 11. Aerodynamic coefficients calculated using CFD by authors are compared with wind tunnel data provided as input of AIAC'19 Store Separation Workshop. Change of coefficients with respect to z position (z=0 carriage position, store moving down with increasing z) for θ (pitch attitude) values of 0°, -10° and 10° can be seen from the figures. Position change in x,y and attitudes of roll (Φ) and yaw (ψ) are equal to zero for all data points.

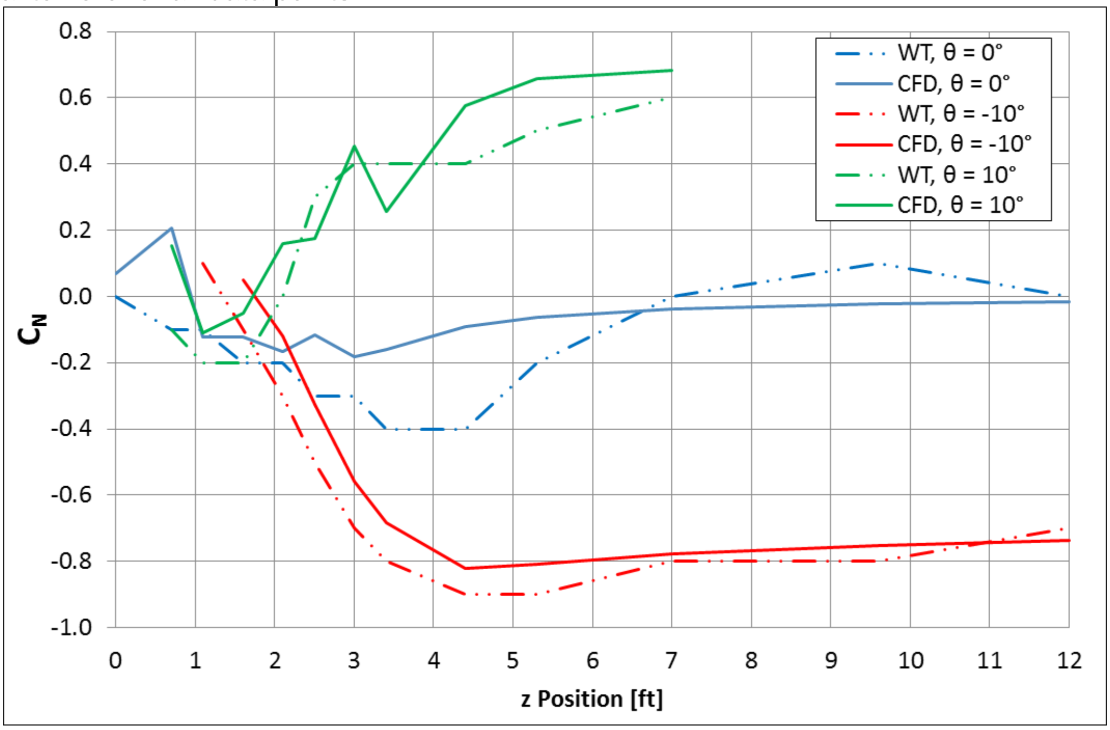

Figure 8: Wind Tunnel (WT) and CFD Results for Normal Force Coefficient (Grid)

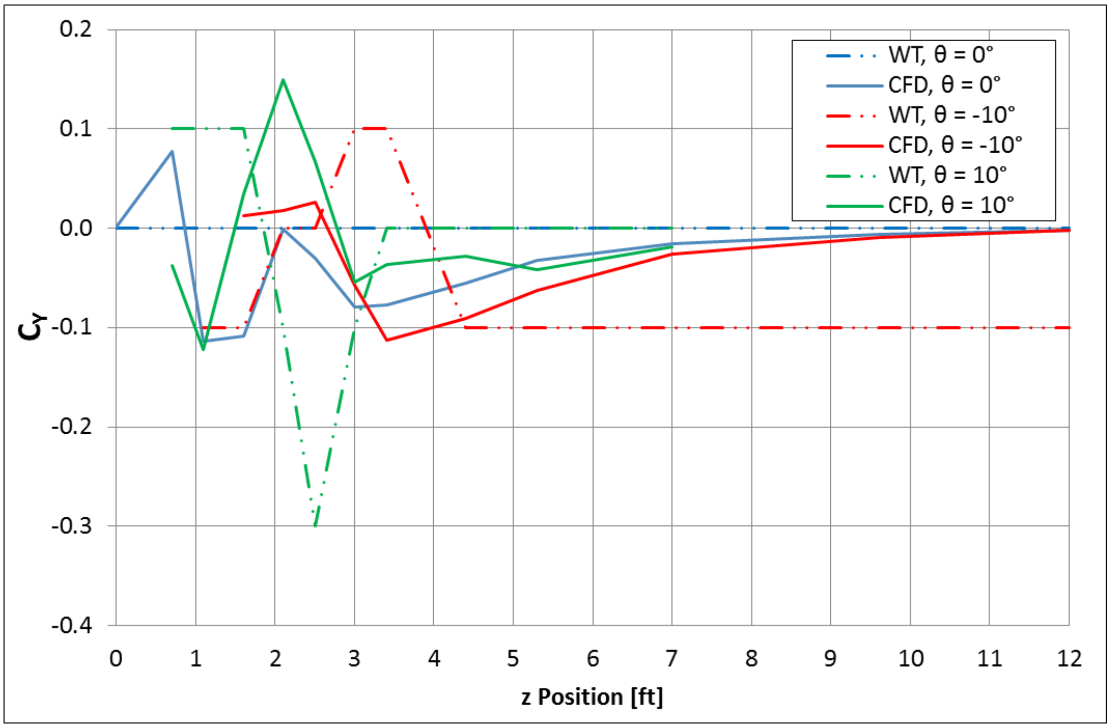

Figure 9: Wind Tunnel and CFD Results for Side Force Coefficient (Grid)

Figure 8 shows that normal force coefficient values calculated by CFD have captured the general trend of the wind tunnel (WT) data. However, there is some shift for CFD data compared to WT.

Results for side force coefficient have more disagreement compared to normal force. For small values of z position where store is inside the cavity, CFD predicts finite values of side force in contrast to WT for θ=0 case. When looked at θ=10° case, CFD and WT results are in the opposite direction. Nevertheless, coefficient values are small for C_Y as ψ=0° for all data.

Note that normal and side force coefficients almost converge to a single value after store moves 6 ft down, about 2 times depth of the cavity. Inside the cavity coefficients show zigzagging behavior, sometimes jumping from a positive value to negative one or vice versa.

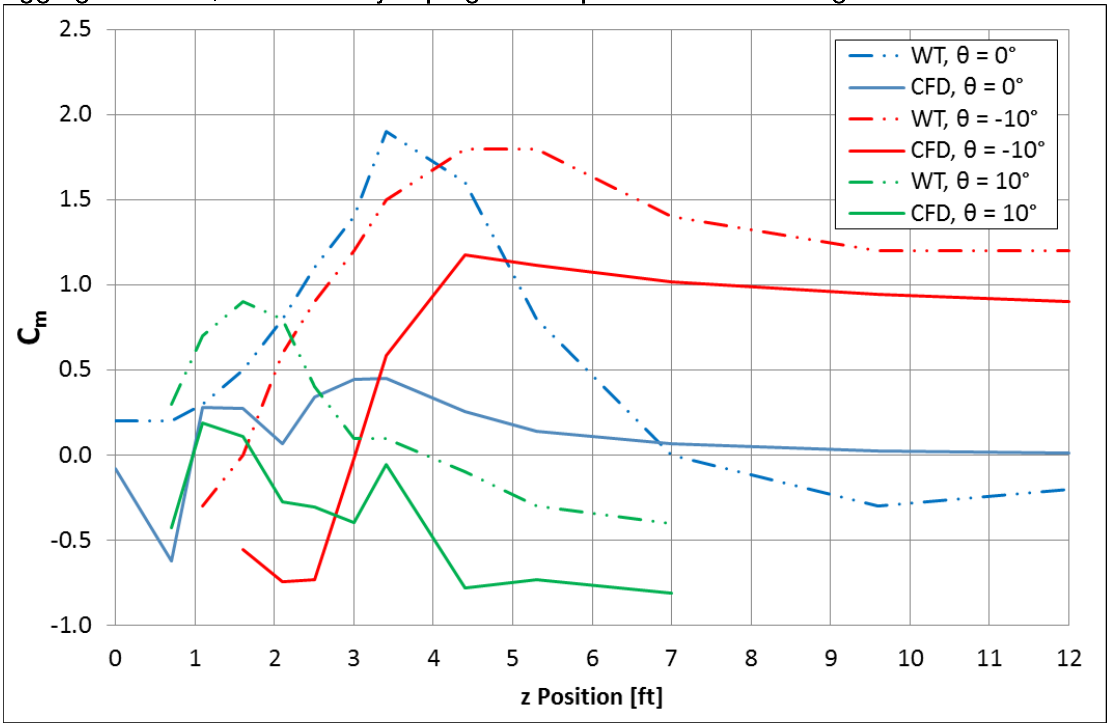

Figure 10: Wind Tunnel and CFD Results for Pitching Moment Coefficient (Grid)

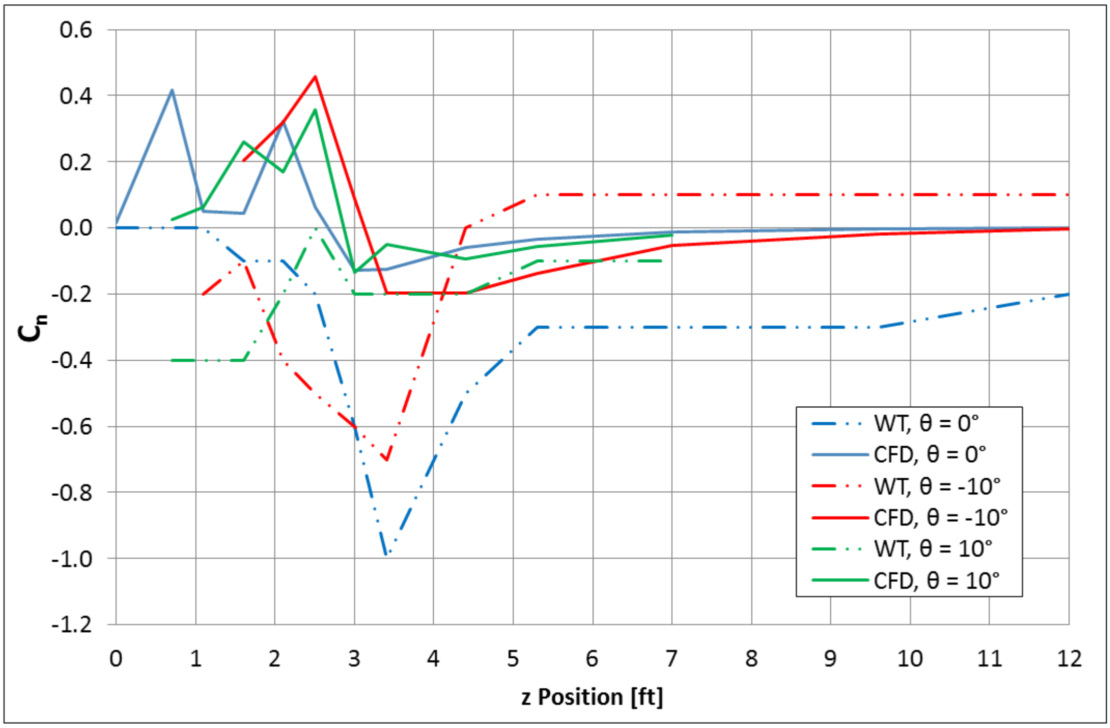

Figure 11: Wind Tunnel and CFD Results for Yawing Moment Coefficient (Grid)

Change of pitching moment coefficient with vertical position is given in Figure 10 for different θ values. As seen in normal force coefficient, general trend of WT and CFD data seem to agree with each other. However, differences are much higher when compared to normal force results of both practices.
Yawing moment coefficient results are shown in Figure 11. WT and CFD have almost no agreement for the yawing moment and they estimate the moments in opposite direction inside the cavity.
Similar to the force coefficients case, moment coefficients converge to a single value after about 6ft drop. However, the convergence values obtained from CFD and WT differ. In yawing moment coefficient case, CFD values converge to 0 as position increases, whereas in the WT finite moment coefficients are measured.
Grid results for axial force and rolling moment coefficients are not shown for clarity. In short, axial force results have no agreement and rolling moments for all WT data is zero (maybe because of WT balance used), making comparison unnecessary.
Differences between WT and CFD might arise due to the nature of both methods. WT testing requires holding the store in its position by means of stings, whereas in CFD no sting is modeled. In addition to that, NICS WT test model geometry preceding the cavity might be different than what is modeled for CFD solutions, leading to some difference in boundary layer development and behavior of the shear layer. WT model of the Mk-82 store might have different fin deflection angles than the CFD model as mentioned before.

Freestream Results

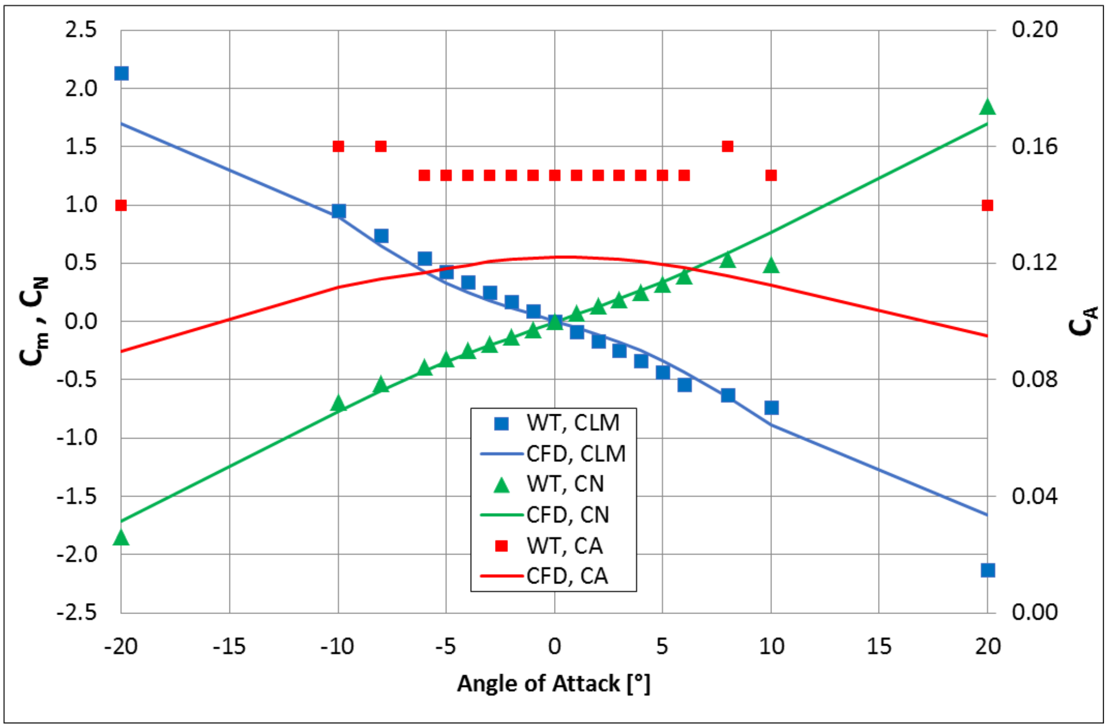

Figure 12: Wind Tunnel (WT) and CFD Results for Normal Force, Pitching Moment and Axial Force Coefficients (Freestream)

Mk-82 store freestream aerodynamic coefficients for normal force, axial force and pitching moment with respect to angle of attack are given in Figure 12. WT and CFD have similar values for normal force coefficient. In pitching moment, CFD gives slightly higher values at positive angles of attack (except 8-10°) with capturing the trend of the WT data. In contrast to them, there is a considerable difference between axial force coefficient values. Historically, it is more difficult to obtain axial force correctly with CFD methods and combined with the uncertainties mentioned in the previous section, authors could not give the exact reason for this difference. Nevertheless, it is known that axial force has less impact on trajectory calculations in store separation compared to other coefficients and no further work was done to investigate the reason for the difference.

Side force and yawing moment coefficients calculated by CFD are about 15-30 percent less than the WT. As available WT data is very limited, no conclusions drawn for them. Rolling moment coefficients are zero for all WT data points, accordingly, no comparison is made with CFD.

Trajectory Calculations

AIAC'19 Store Separation Workshop aims to obtain trajectory results for 2 different cases. In the first case, front and rear ejectors are pushing the store with 5000lbf each under given force profile [Cenko, 2019]. The second case involves no ejector forces. Results for two cases are presented in the following sections.

Case 1: 5000lbf Ejector Force

From the wind tunnel grid and freestream aerodynamic data, change of store position and attitudes with respect to carriage position are calculated under 5000lbf force acting on both front and rear ejectors. As no captive trajectory test (CTS) data is available to authors, they decided to use CFD based another method to generate data for comparison: unsteady CFD coupled with 6DOF. This method can be considered as a numerical alternative of wind tunnel CTS tests and generally have good agreement with wind tunnel and flight test data, especially for position values.

Figure 13 and Figure 14 present the calculated position and attitude values of the store with respect to time using wind tunnel grid data. As mentioned, results are compared with unsteady CFD coupled with 6DOF. There is a good agreement between y position values. Up until 0.3 seconds, z position is also in a good agreement for both methods. x position starts to deviate slightly after 0.15 seconds and results from wind tunnel grid data show increased movement in x direction. When store attitudes are considered, it can be seen that only ψ angles match for both results. Φ angle starts to deviate after 0.2 seconds with a higher roll calculation by wind tunnel grid data. Results for θ angle are quite different, unsteady CFD shows a pitch down movement for store whereas a pitch up behavior is calculated using wind tunnel grid data. Differences in x and z positions are considered to stem from the difference in θ calculations of both methods.

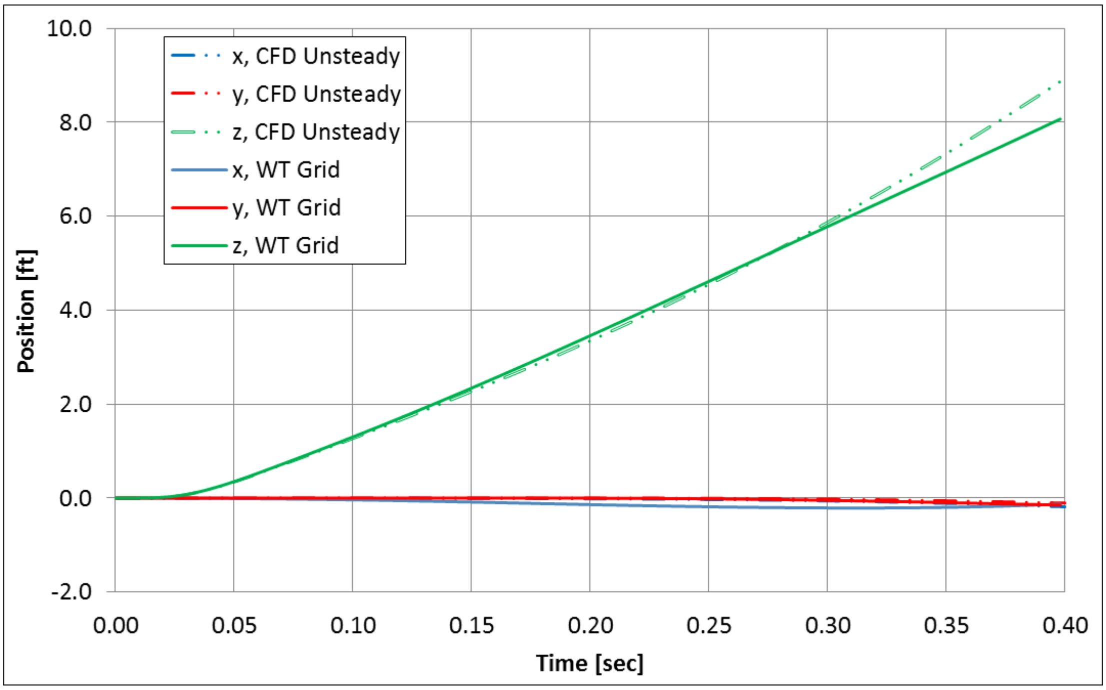

Figure 13: Case 1 Store Positions (Using Wind Tunnel Grid Data)

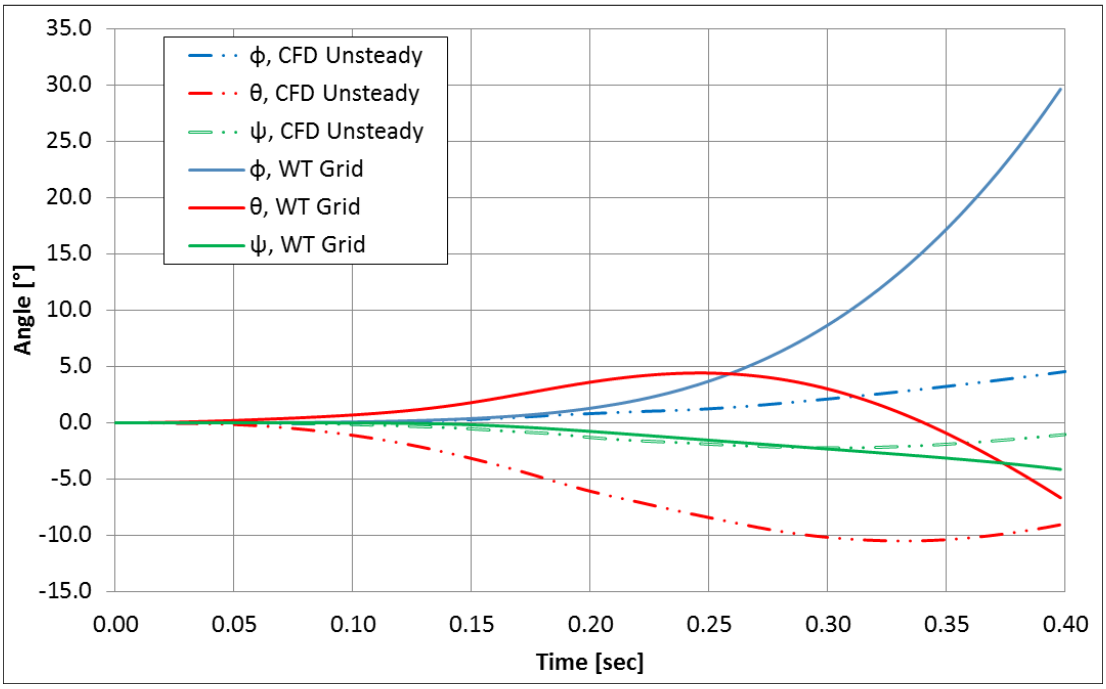

Figure 14: Case 1 Store Attitudes (Using Wind Tunnel Grid Data)

Figure 15 and Figure 16 present the calculated position and attitude values of the store using CFD grid data. x and z position calculations are similar for CFD grid data and unsteady CFD. However, for y position, a movement to the right side calculated using CFD grid data whereas unsteady CFD results in a movement to the left. Movement in y direction is very small, but considering both methods are CFD based, this shows solution approach (grid or unsteady) might affect the trajectory calculations.

As seen from Figure 16, calculated store attitudes are very different for both methods.

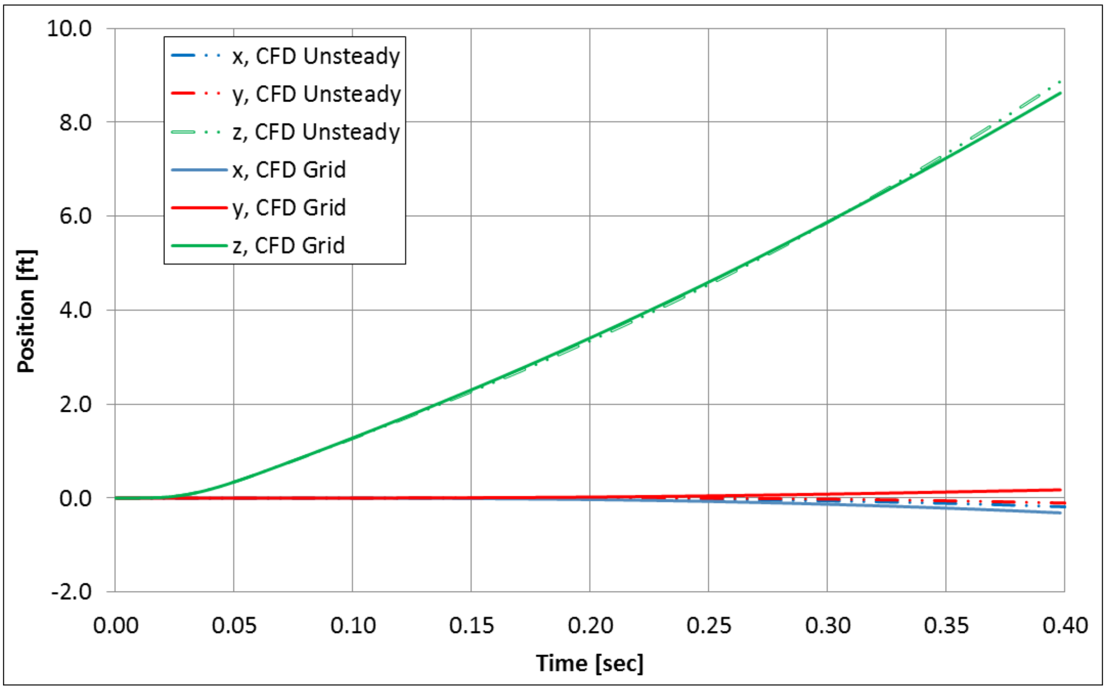

Figure 15: Case 1 Store Positions (Using CFD Grid Data)

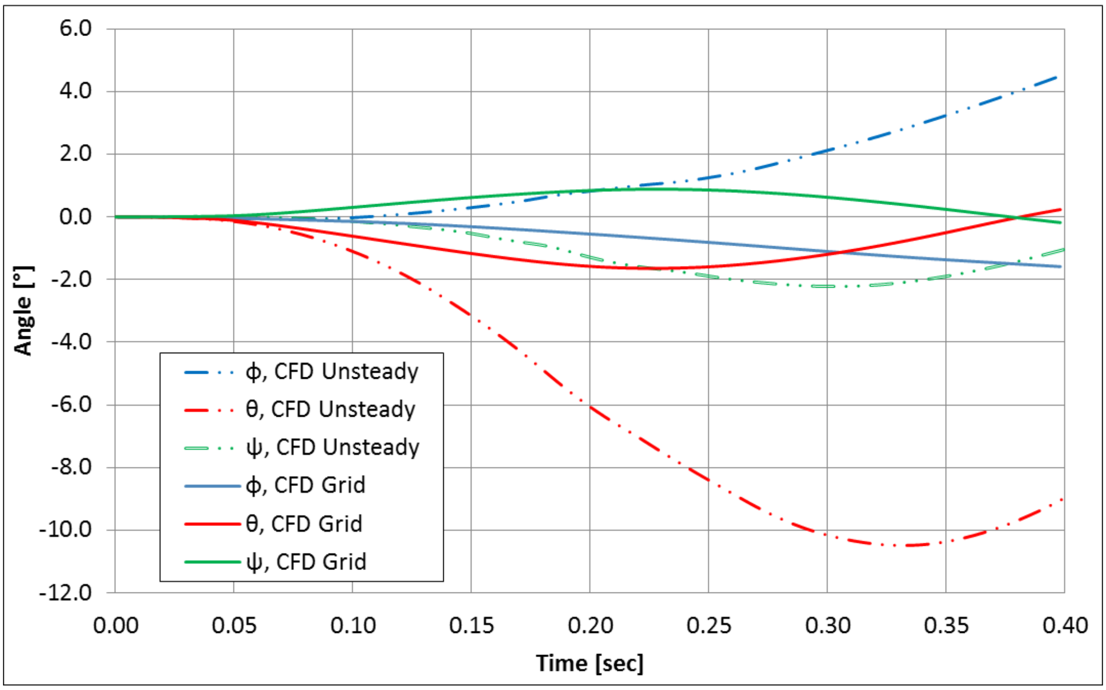

Figure 16: Case 1 Store Attitudes (Using CFD Grid Data)

When compared, WT grid and CFD grid position results are slightly different. However, due to presence of ejector forces, store moves out of the cavity after 0.2 seconds without any significant move in x and y directions. Therefore, it can be concluded that there is no contact to cavity walls when 5000lbf front and aft ejector forces are present.

Store position and attitudes calculated using unsteady CFD at different time instants are shown in Figure 17.

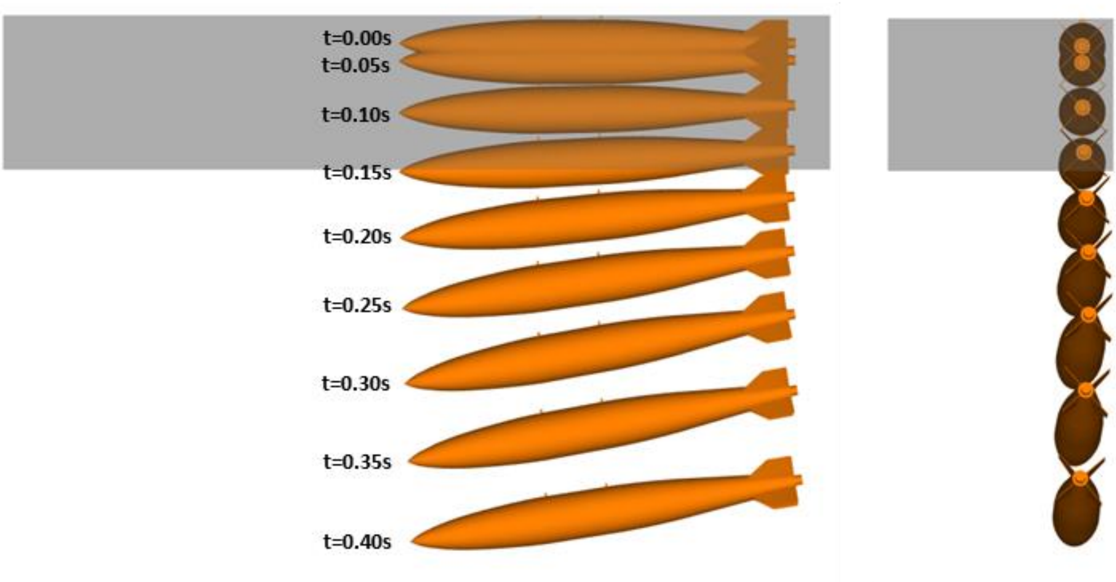

Figure 17: Store Trajectory (Unsteady CFD Solution, Side and Rear View)

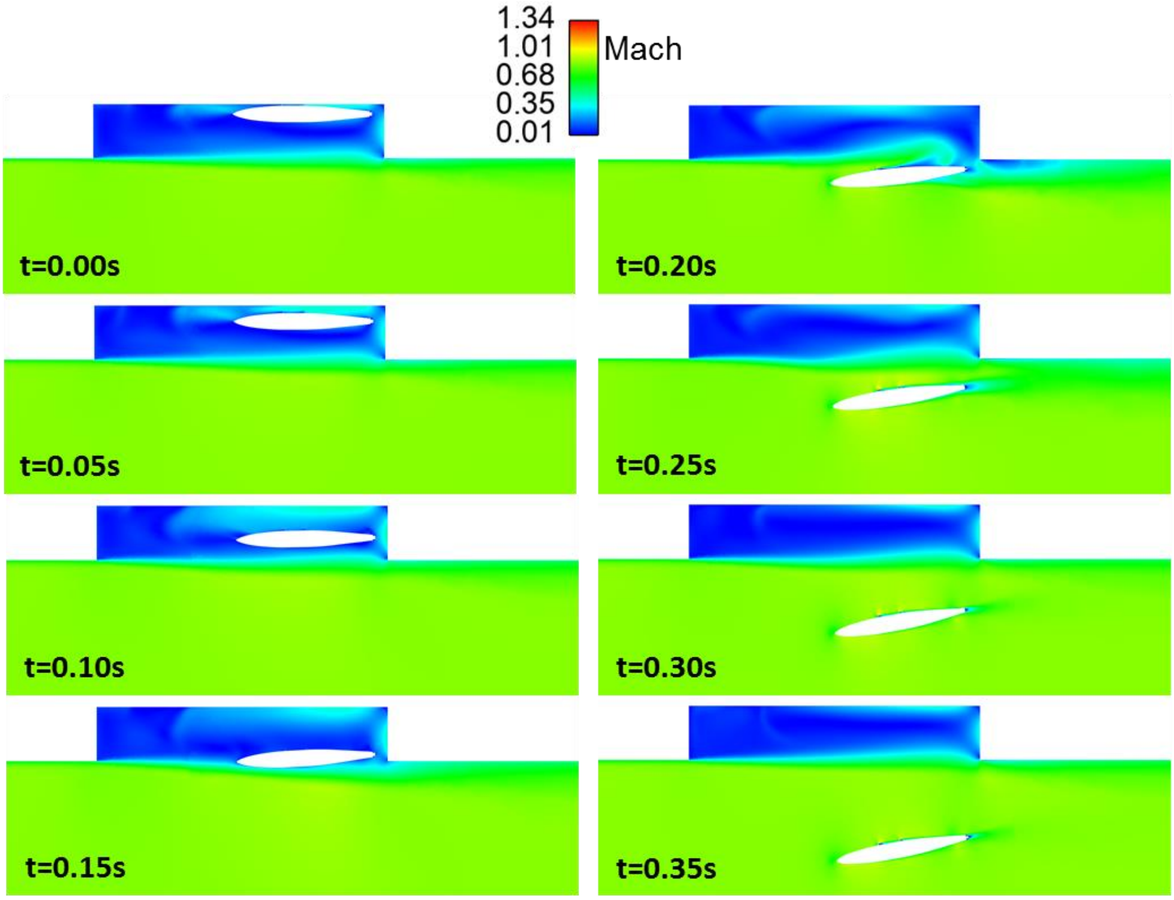

Figure 18: Mach Contours (Unsteady CFD Solution, Side View)

Mach contours during separation are shown in Figure 18. At t=0.0s, the store is at carriage position and shear layer between the cavity and freestream can be seen. As the store starts to move downwards, flow structure inside the cavity starts to change. Flow speeds up between the region of store upper side and cavity top floor until 0.15s. After that store reaches to shear layer and disturbs it (t=0.20s), leading to a complex flow field inside the cavity and around the store. As store moves away from the cavity, flow structure inside the cavity and shear layer settle back. Change of aerodynamic coefficients inside the cavity and around the shear layer is discussed in more detail after trajectory calculations.

Case 2: No Ejector Force

Ejector forces are known to be very effective in store trajectories for separation. Case 2 involves no ejector force, making it a more difficult scenario as it takes more time to clear the cavity. Figure 19 and Figure 20 shows position and attitude of the store, calculated using wind tunnel grid data and unsteady CFD. In case 2, x position calculated using WT grid data has a significant difference with the unsteady CFD. Unsteady CFD shows a small forward motion whereas WT grid gives considerable movement to backwards, making aft of the store dangerously close to the cavity rear wall. After 0.4 seconds, store moves downward about 2.3ft, meaning that it is still not fully out of the cavity. Note that in case 1, it took about 0.2 seconds to clear the cavity. As backward and side movements increase with time, it is desirable in terms of safe separation to move out of the cavity as soon as possible. Therefore, applying suitable ejector forces are crucial for separation from cavities, especially when stores are very close to the walls as we have in this workshop configuration.

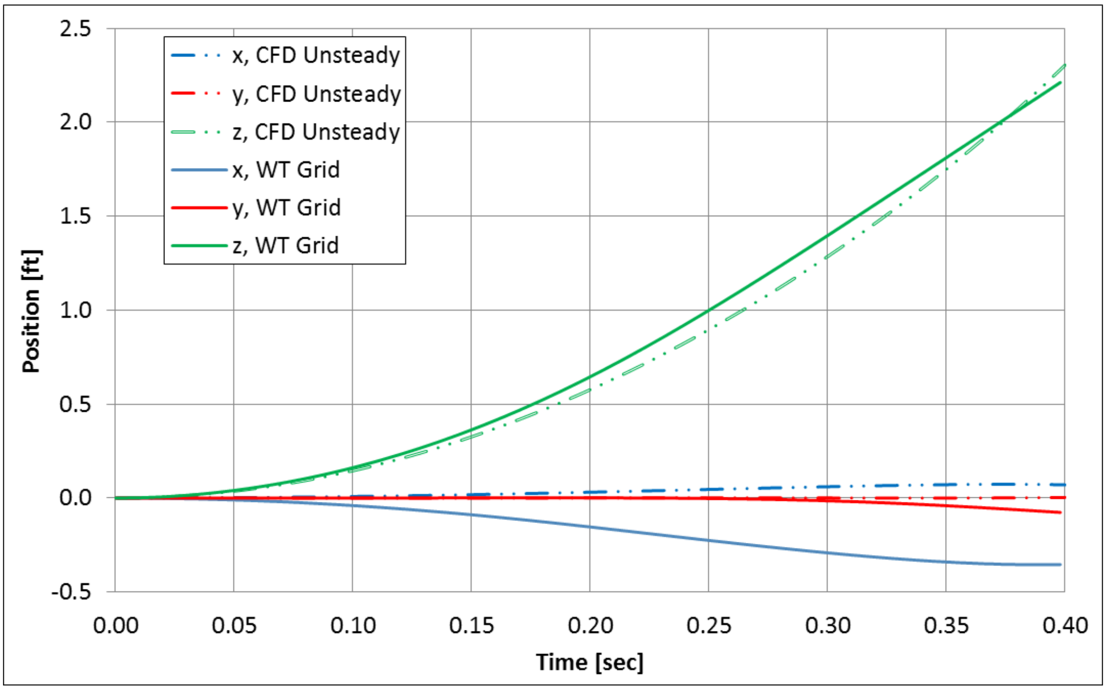

Figure 19: Case 2 Store Positions (Using Wind Tunnel Grid Data)

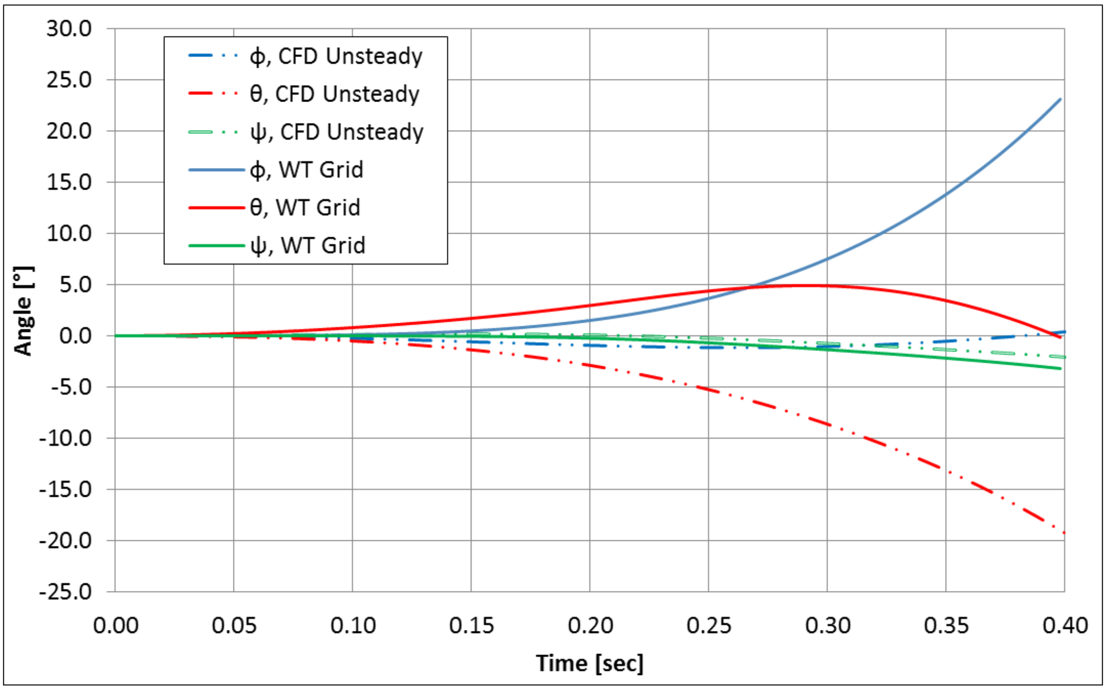

Figure 20: Case 2 Store Attitudes (Using Wind Tunnel Grid Data)

Figure 21 and Figure 22 show position and attitude of the store, calculated using CFD grid data and unsteady CFD. Compared to Case 1, agreement between the results is less. In addition to that, CFD grid shows a positive y movement as seen in Case 1. As it takes more time to clear the cavity with no ejector forces, this small movement is enough for the store to hit to sidewall of the cavity. The store could move downwards faster if ejector forces were present and hit condition can be prevented.

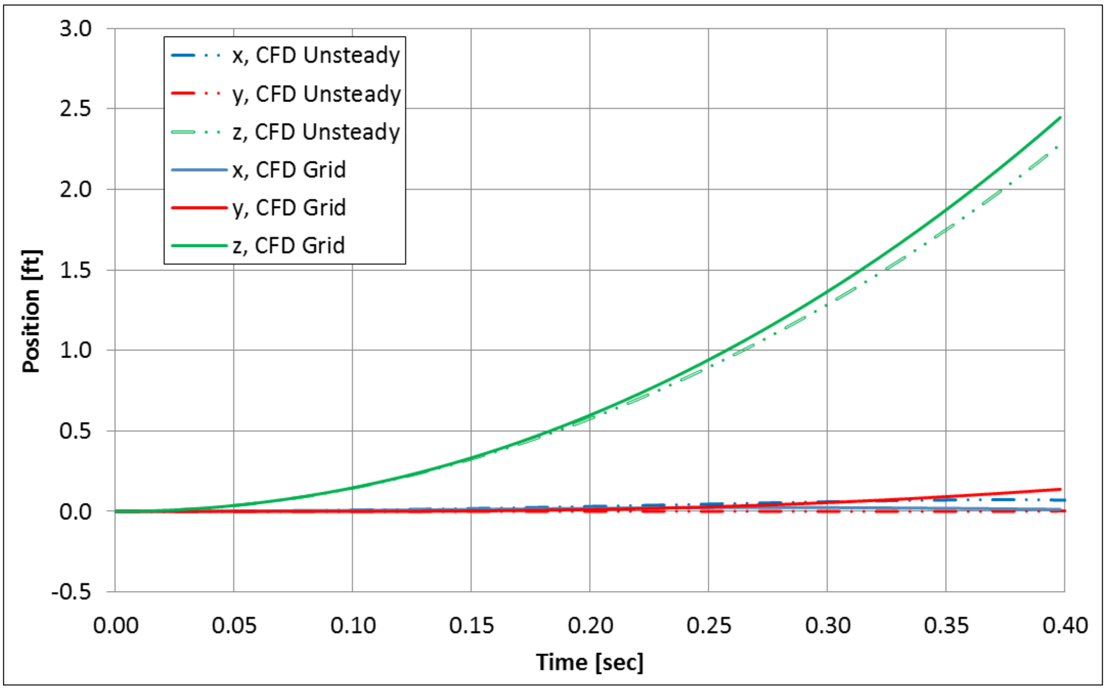

Figure 21: Case 2 Store Positions (Using CFD Grid Data)

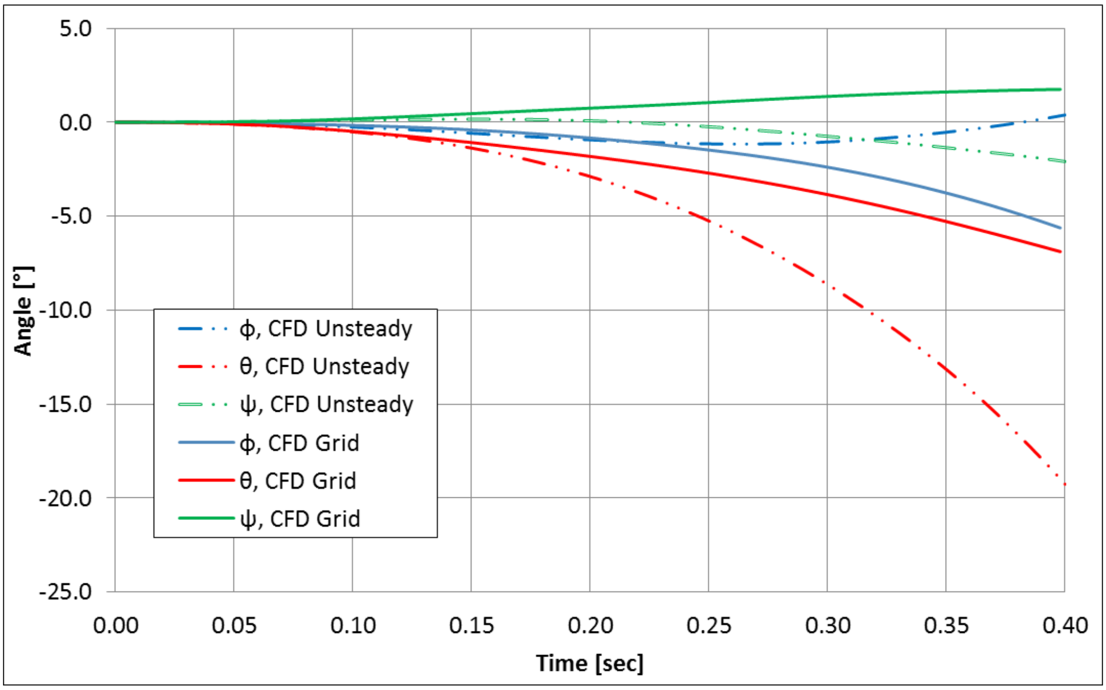

Figure 22: Case 2 Store Attitudes (Using CFD Grid Data)

Unsteady CFD Results for Store Positioned at Carriage and in Shear Layer

In order to understand change of aerodynamic coefficients with time, two unsteady CFD analyses are done for the store located at carriage position (z=0ft) and inside shear layer (z=2.4ft). Figure 23 and Figure 24 present Mach contours for t=0.15s.

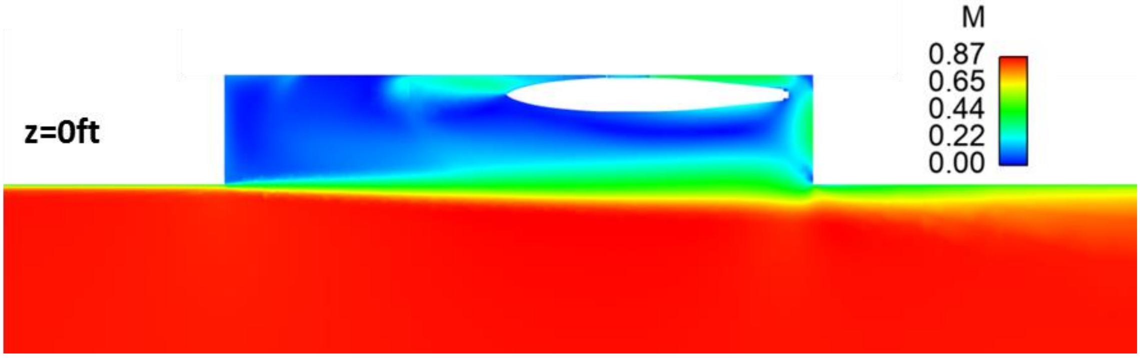

Figure 23: Mach Contours, Store at Carriage Position

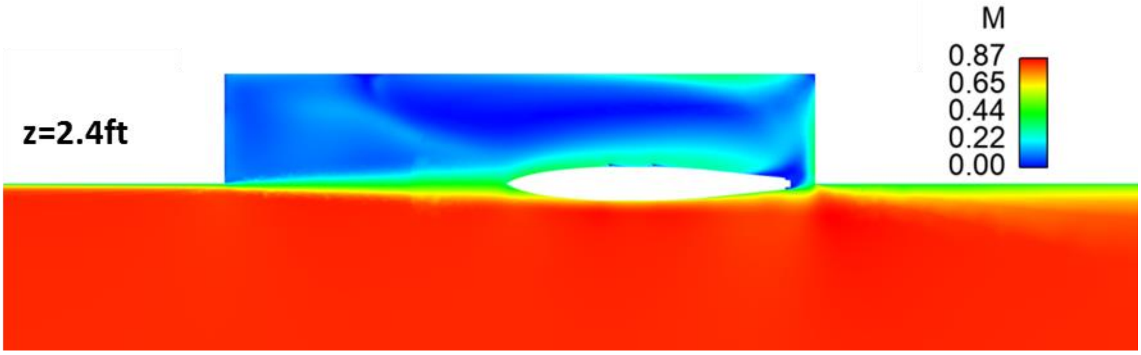

Figure 24: Mach Contours, Store Located at 2.4ft Downwards of Carriage Position

Figure 25 shows change of pitching and yawing moment coefficients with time for store located at carriage position (z=0) and in shear layer (z=2.4ft). At carriage position, fluctuations in coefficient values are relatively small. However, inside the shear layer coefficients fluctuate more, sometimes doubling the values. This indicates determining a single coefficient value for store aerodynamics near and in the shear layer might lead to errors in trajectory calculations. Traditional trajectory calculation using grid testing depends on single, time independent coefficient values at a specific store position and attitude. It is necessary to be aware of this situation when grid testing is used for cavity store separation cases.

To remedy this unsteady phenomenon, time information can be used to get exact coefficient values during simulation and for determining the store release instant, as suggested in the literature [Cenko, 2008]. However, it is difficult to match this coefficient-time relationship in flight testing and operational usage.

Ejector forces that allow the store to leave the cavity in a very short time could also be helpful for safe separation. The less time spent in the shear layer means less unsteady effects experienced by the store. As ejector forces have a considerable effect on store trajectory, increased ejector forces could make trajectory predictions easier.

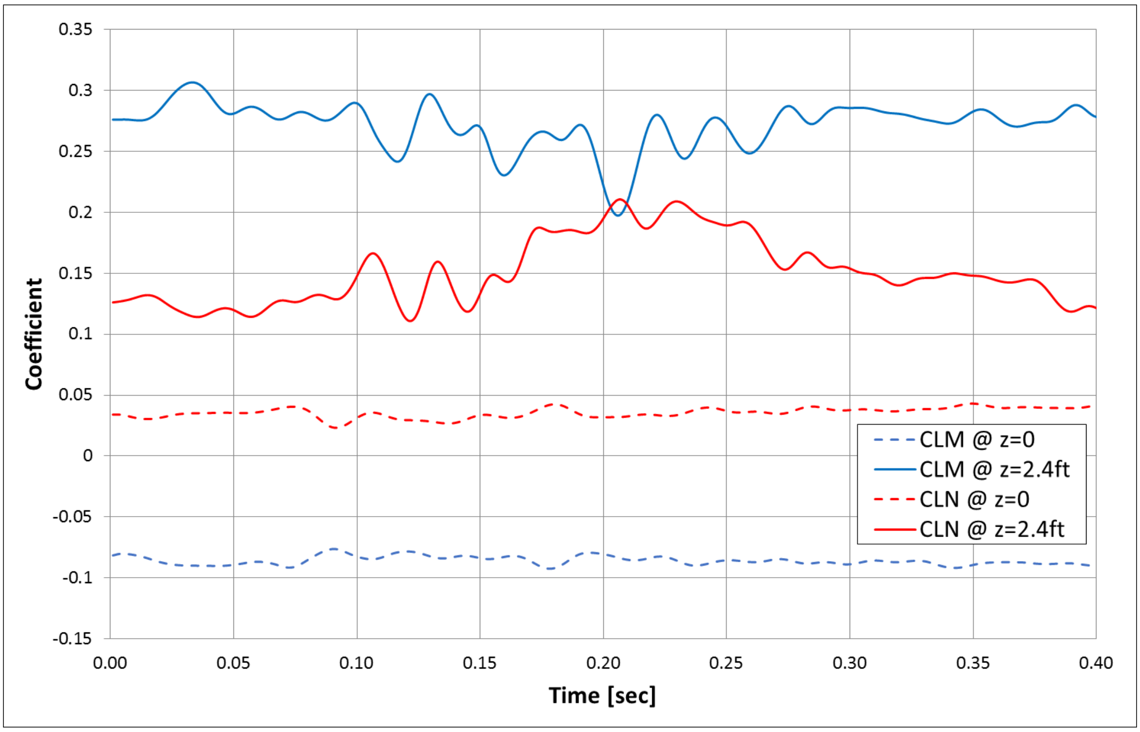

Figure 25: Change of Pitching and Yawing Moment Coefficient with Time, Store Located at Carriage (z=0ft) and in Shear Layer (z=2.4ft)

CONCLUSIONS

- Wind tunnel and CFD grid data do not match each other inside the cavity, leading to very different store attitudes during separation. This could be due to sting effects present in wind tunnel and differences in store and cavity geometries.
- Stings have a considerable effect on store aerodynamics. For cavity separation, unsteady CFD analyses with sting geometry could help to understand the effects of the sting. If results from CFD with sting could match the wind tunnel, CFD would be used with more confidence for no sting case by separation engineer.
- Application of ejector forces is important to avoid any clash between store and cavity.
- Shear layer between cavity and freestream leads to significant unsteadiness and store aerodynamic coefficients are fluctuating when it is inside the shear layer.
- Wind tunnel and CFD methods are applicable to store separation trajectory calculations with pros and cons for both. However, without any flight test result comparison, it is difficult to pick one method over the other.

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