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AN INTEGRATED STORE SEPARATION ANALYSIS TOOL

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ABSTRACT

When an air released store is developed or undergoes substantial updates integration to aircraft can be realized through a certification process. One of the most important steps of the certification process is to determine safe separation envelope. For this process there are several approaches: full scale flight tests, computational fluid dynamics (CFD) simulation techniques and wind tunnel captive trajectory tests. Separation tests applied with flight tests is not only very costly, but it also contains high risks for the aircraft and the pilot. CFD solutions became popular as the computational power becomes achievable in recent years, however most of the time it is not considered as accurate and fast enough to be used for entire safe separation envelope. Most popular store separation analysis method is wind tunnel tests, which may provide accurate and flexible store separation analysis with a carefully designed test plan. The aim of this study is to develop a store separation analysis tool that will allow to achieve the safe separation envelope of a store. The new tool is based on six degree of freedom (6DOF) simulation tool based on freestream flight parameters and flow parameters at the vicinity of the aircraft flow field measured at the wind tunnel. This tool is verified with the results of the wind tunnel trajectory measured by Captive Trajectory System (CTS) at the same wind tunnel. The described system allows customization of the store and motion parameters and integrates different stages of pre and post processing of the safe separation analysis.

INTRODUCTION

When a new air launched store (munitions, external fuel tanks, pods, etc.) is developed or an already existing one goes through significant variations, it needs to be certified for tactical aircraft to be used. Throughout the certification process a number of tests are performed to ensure safety of aircraft and store. One of the most essential assessments in certification process is to acquire a release envelope in which store is able to be safely employed or jettisoned from the aircraft. In order to obtain an operational launch envelope it is possible to utilize some approaches such as analogy (i.e., real flight test), captive trajectory system (CTS) and computational fluid dynamics (CFD).

Store separation certification was performed by flight tests in the distant past, before the mentioned analysis systems were developed. In this kind of test, store is released from the aircraft at different flight conditions containing different Mach numbers and altitudes to build operational envelope. However, the behavior of the store inside of the flow field at the vicinity of the aircraft is rarely known. Flow field of the aircraft sometimes results in high lift forces on the store, which a phenomenon is called flyback. This phenomenon may result in the store to gain elevation and hit to the aircraft, hence crashes. There is also a risk of losing the control of the store due to unexpected accelerations below the aircraft.

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In order to avoid risks and high costs of the analogy approach, the captive trajectory system was developed as an experimental method in the 1960s, to estimate trajectory of the store in wind tunnel tests [Davids and Cenko, 2001]. The test set-up consists of two stings located in the wind tunnel. The first sting is connected to the aircraft model. This sting often allows moving the aircraft model in two or three degrees of motion during the tests (pitch-yaw or pitch-roll-yaw). Second sting is connected to the store and allows traveling the store model in 6 degrees of freedom (6DOF). Both stings are designed to measure aerodynamic forces acting on the models.

Two sting trajectory tests can be performed in online or offline mode. In online mode, often regarded as CTS tests, position of the store is calculated by solving equation of motion of the store concurrently utilizing aerodynamic force and moment coefficients measured at the store position maintained by the sting. Separation trajectory of the store is achieved by repeating this measurement-6DOF integration-relocation procedure successively.

It should be noted that, although online mode approach allows very quick and reasonably accurate separation analysis, it is prone to geometric limitations of the tunnel and the wing tunnel data cannot be reused if integration configuration changes. Therefore, in the long run online tests can be very expensive.

On the other hand, in offline mode, aerodynamic loads are measured at various preplanned grid points and conditions under the aircraft. This grid data is collected utilizing the same two sting apparatus. Only difference is that the path of the trajectory is not calculated in-situ but is carefully determined linear paths that will cover possible separation envelopes at different flight conditions. Together with free-stream aerodynamic database, these aerodynamic loads are used to create grid a database which is then used in a 6DOF simulation model to calculate the separation trajectory of the store.

Offline method requires many CTS sweeps to build the database, therefore it requires large amount of wind tunnel time, hence cost. However; by contrast with online approach, offline approach is advantageous for investigating various separation trajectories at different test conditions by utilizing the same grid database and it is easily adjustable for configuration changes of the store during the development phase.

With the rapid development in computer technology, CFD techniques are in use to decrease certification expenses in recent years, however, it has some disadvantages such as difficulty in providing precise data in a timely manner [Panagiotopoulos and Kyparissis, 2010]. Due to the stability and precision requirements of numerical solution codes, CFD solutions of store separation is often applied on fine grids and high frequency time steps. Therefore CFD separation analyses often lead to high computational costs.

Based on the assessments above, in this study, an integrated store separation analysis tool is developed. To achieve this goal, free-stream and grid based wind tunnel tests are performed to generate a grid database. Then, this generated grid database is used to interpolate aerodynamic loads at the aircraft flowfield. 6DOF simulation model uses those interpolated loads to compute the separation trajectory of the store underneath the aircraft. Furthermore, in order to ensure that store does not collide with the aircraft until a safe range has been reached; a collision detection algorithm is also implemented. Results obtained from analysis tool are compared with that of online CTS tests for validation purposes.

OVERVIEW OF THE ANALYSIS TOOL

Analysis tool is composed of four main elements: a 6DOF equations of motion model, an aerodynamic grid database, a collision detection model and 3D animation graphical user interface (GUI). All these elements are created and combined in MATLAB & Simulink environment. Simplified structure of the tool can be seen in Figure 1. Main components of the tool is described in following sections.

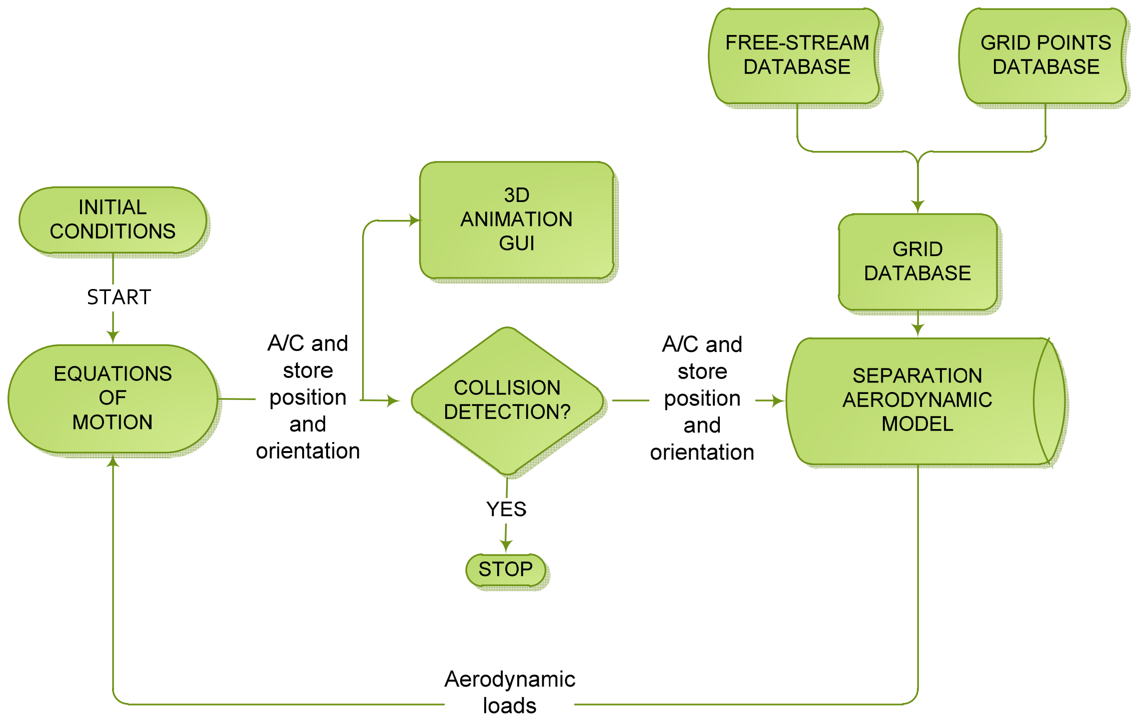

Figure 1 : Structure of the analysis tool

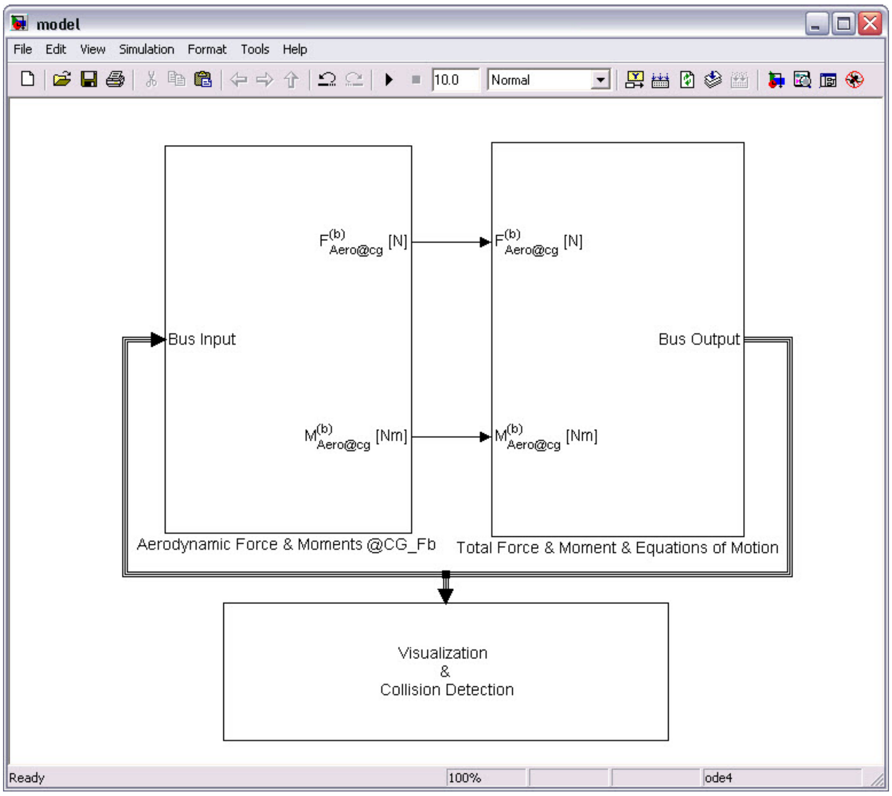

Figure 2 : Simulink model view of the analysis tool

EQUATIONS OF MOTION MODEL

In order to calculate precise separation trajectory, a high degree of freedom simulation model is vital. For this reason, the dynamic behavior of the store is modeled as 6 degrees-of-freedom. On the other hand, collision detection algorithm requires relative positions of the store and the aircraft. Therefore, in order to calculate relative positions of the store and the aircraft, the motion of the aircraft is also modeled as translational 3 degrees-of-freedom with the assumption that aircraft speed, altitude and attitudes are the same as its initial conditions, during the separation.

$$\vec{F}_b = m\left(\dot{\vec{V}}_b + \vec{\omega} \times \vec{V}_b\right)$$

$$\vec{M}_b = I\dot{\vec{\omega}} + \vec{\omega} \times (I\vec{\omega})$$

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} 1 & \sin\phi\tan\theta & \cos\phi\tan\theta \\ 0 & \cos\phi & -\sin\phi \\ 0 & \dfrac{\sin\phi}{\cos\theta} & \dfrac{\cos\phi}{\cos\theta} \end{bmatrix} \begin{bmatrix} p \\ q \\ r \end{bmatrix}$$

SEPARATION AERODYNAMIC MODEL

Forces acting on an aircraft are often described in terms of static and dynamic aerodynamic force and moment coefficients defined in terms of Mach number and aircraft attitude. For a simulation of the flight of a store consist of 6DOF simulation using those coefficients found for the store. This coefficient database is called free-stream coefficients database and can be constructed from aerodynamic data obtained from different sources.

However, a store released beneath an aircraft confronts different aerodynamic forces than free stream aerodynamic forces. Therefore, measurement of the aerodynamic forces on a store beneath an aircraft is a necessity for store separation analysis.

Wind tunnel store separation analysis is often used for safe separation analysis. The most direct store separation wind tunnel test is the free drop test. Free drop test consist of dropping a carefully prepared store model from an aircraft model. The store model is prepared using similitude parameters determined by Froude modeling. This test is considered as extremely difficult an expensive, therefore is rarely practiced. Other two test methods consist of mounting aircraft and store on two independently moving test rigs, which is called two sting rig (TSR). Captive Trajectory System (CTS) is the online testing method and does not allow build-up of an aerodynamic database beneath the aircraft, rather it gives directly the trajectory of the store. Grid method that uses the same testing infrastructure allows aerodynamic data collection for desired points beneath the aircraft, which are called grid points. Grid method is an offline testing method.

Figure 3 : F-16 and store wind tunnel online CTS and grid test view

The basic drawback of the Grid and CTS methods is that, they are performed with a smaller scale test model, because of the necessity to fit also the aircraft model into the wind tunnel. Both methods also do not collect any information on the dynamic behavior of aerodynamic force since motion of the store is often constrained by the sting speed. Therefore in a simulation model these effects should be regarded. Therefore four sets of wind tunnel data is collected from the wind tunnel and a fourth calculated data is utilized. Those data is defined as:

C_{FF_full} : Full scale free stream aerodynamic data collected from wind tunnel.

C_{FF_sep} : Separation scale free stream aerodynamic data collected from wind tunnel.

C_{Grid} : Separation-time aerodynamic data collected by Grid Method and with separation scale.

C_{CTS} : Separation-time aerodynamic data and store trajectory data collected by CTS Method and with separation scale to verify the grid separation algorithm.

$C_{Dynamic}$: Dynamic derivatives obtained from analysis methods.

The reason collecting the free stream aerodynamics data is to correct scaling errors resulted due to small scale separation model and CTS data is collected to verify the accuracy of the grid method. Aerodynamic data is collected for five different linear paths, four of which constructs a pyramid and a fifth path that resides into this pyramid. For each path, three store angle of attack and store sideslip angle sweeps are performed. For each test, an aircraft Mach number and an aircraft attitude is maintained. It should be noted that aircraft attitude is an indication of flight altitude and it is used accordingly. The schematic of sweep paths used for this study is shown in Figure 4.

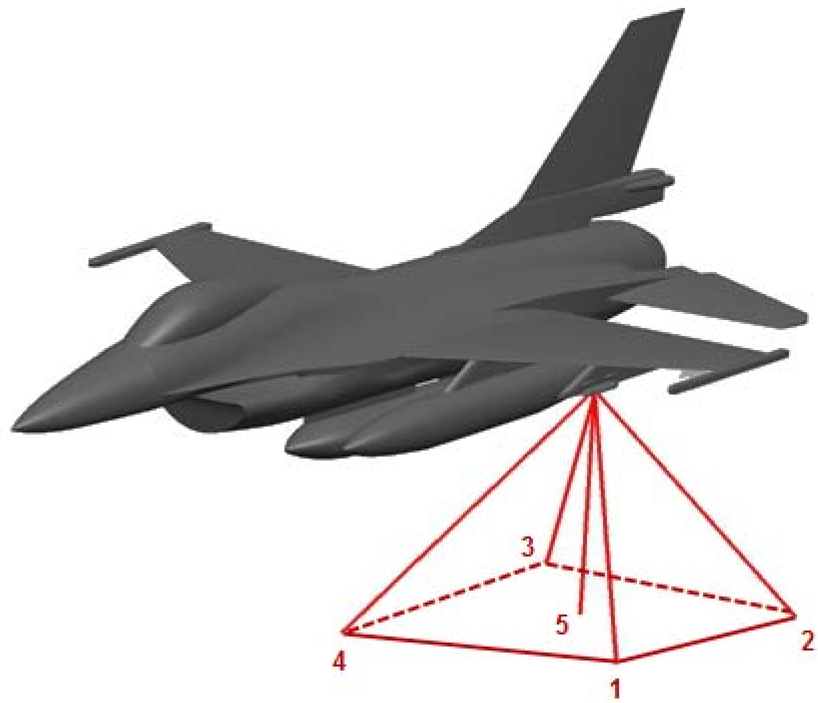

Figure 4: Schematic of grid sweep paths. Each path is swept for different pitch and yaw configurations

Aerodynamic forces on the store beneath the aircraft should be calculated for any point on the trajectory at every time steps of 6DOF simulation. Therefore, aerodynamic coefficients are calculated employing a dedicated interpolation algorithm on grid data collected from wind tunnel. This interpolated data is then corrected according to the concerns described earlier. Calculation of the beneath-aircraft aerodynamic forces is described in following sections.

Interpolation Algorithm for Processing the Grid Data

<u>Interpolation in z, α, β Axes:</u>

For each line defining Grid path aerodynamic data is available in the (α,β,z) space. Let aerodynamic data is needed at $(\alpha_0,\beta_0,x_0,y_0,z_0)$ point. The projection of this point on (α,β,z) space is defined as (α_0,β_0,z_0). Let $\vec{r}=(\alpha_0,\beta_0,z_0)$.

First find eight points $\vec{V}$ that encloses this point as an hexahedron.

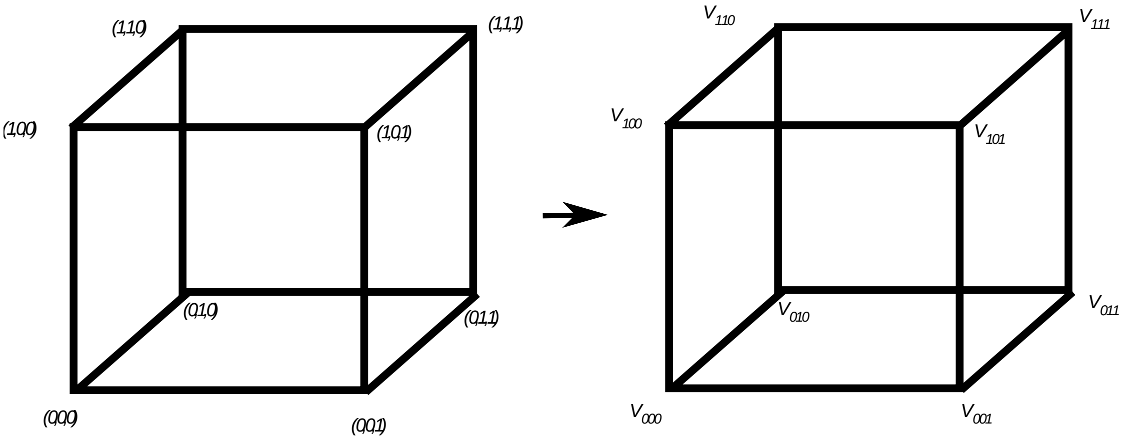

Figure 5 : Mapping to the unit cube

Then, consider these eight points are defined at eight corners of an unit cube. Then find a point v such as the value of v after bilinear mapping as r. Bilinear mapping is defined as

$$
\begin{aligned}
f(\vec{v}) \quad = \quad & \vec{V}_{000} * (1-v_x) * (1-v_y) * (1-v_z) + \cdots \\
& \vec{V}_{001} * (1-v_x) * (1-v_y) * (v_z) + \cdots \\
& \vec{V}_{010} * (1-v_x) * (v_y) * (1-v_z) + \cdots \\
& \vec{V}_{011} * (1-v_x) * (v_y) * (v_z) + \cdots \\
& \vec{V}_{100} * (v_x) * (1-v_y) * (1-v_z) + \cdots \\
& \vec{V}_{101} * (v_x) * (1-v_y) * (v_z) + \cdots \\
& \vec{V}_{110} * (v_x) * (v_y) * (1-v_z) + \cdots \\
& \vec{V}_{111} * (v_x) * (v_y) * (v_z) - \cdots \\
& \vec{r}
\end{aligned}
$$

Then find a solution of v, Indices of V denotes the upper and lower coordinates in respective directions. After finding v any aerodynamic coefficient C at r is found as:

$$
\begin{aligned}
C \quad = \quad & C_{000} * (1-v_x) * (1-v_y) * (1-v_z) + \cdots \\
& C_{001} * (1-v_x) * (1-v_y) * (v_z) + \cdots \\
& C_{010} * (1-v_x) * (v_y) * (1-v_z) + \cdots \\
& C_{011} * (1-v_x) * (v_y) * (v_z) + \cdots \\
& C_{100} * (v_x) * (1-v_y) * (1-v_z) + \cdots \\
& C_{101} * (v_x) * (1-v_y) * (v_z) + \cdots \\
& C_{110} * (v_x) * (v_y) * (1-v_z) + \cdots \\
& C_{111} * (v_x) * (v_y) * (v_z)
\end{aligned}
$$

This method is applied for each Grid path to determine the grid values at z plane. In order to verify the (α,β,z) interpolation a couple of extra sweeps on the same grid path but with different store attitude is collected from the grid tunnel. Figure 6 shows the comparison of the data collected by test run and interpolation run. It is seen that (α, β, z) interpolation algorithm shows a good approximation with the actual tests on the grid line.

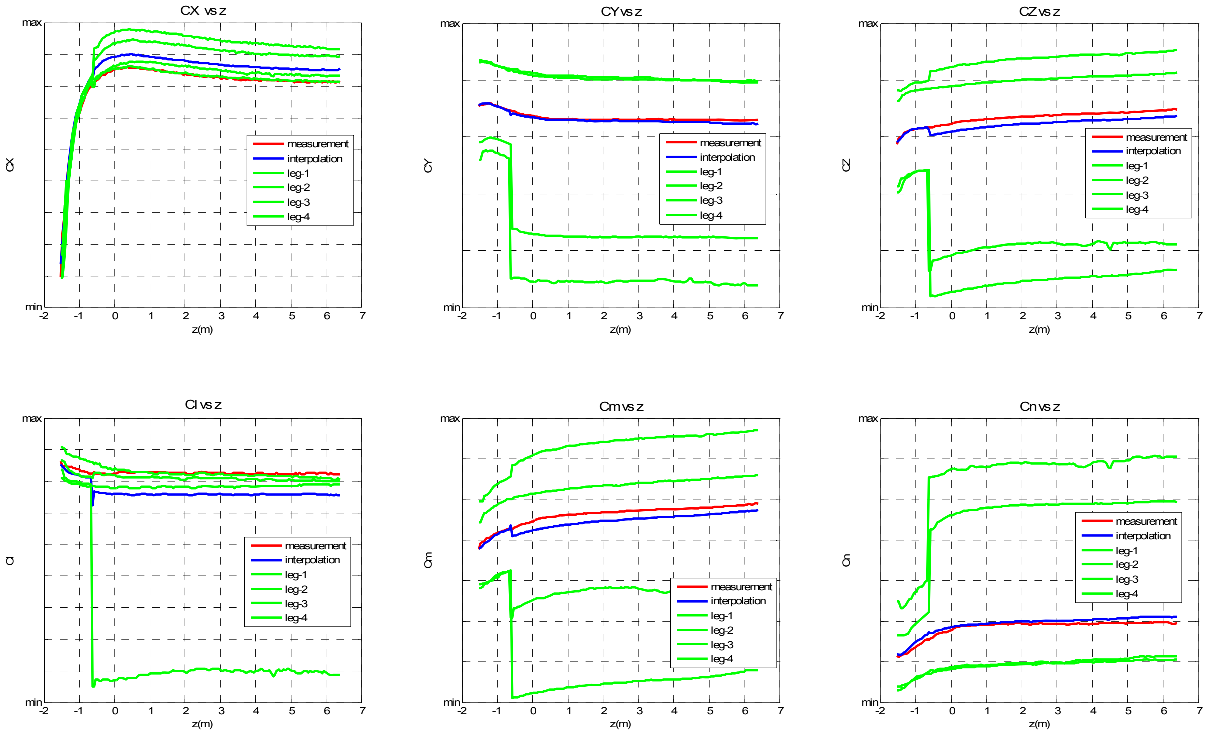

Figure 6: Verification of (α, β, z) interpolator

Interpolation at x, y plane:

After determining coefficients for five different points for all Grid paths with (α, β, z) interpolator, the next step is find the aerodynamic coefficients at the given store position and attitude. These five points forms a plane and forms four tetrahedrons as it is shown in Figure 7.

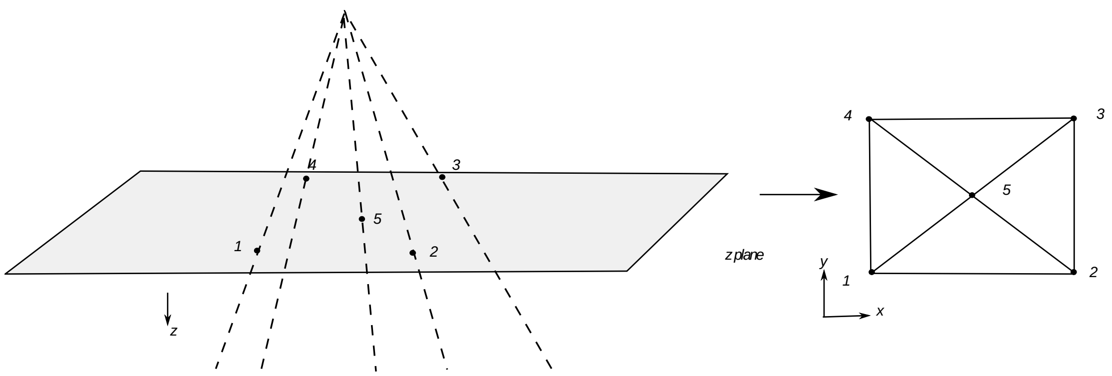

Figure 7: Definition of interpolation points in space

Three different interpolation algorithms are developed to find C coefficients at (x, y) space

1. Linear interpolation algorithm using TriScatteredInterp method of MATLAB is developed. However this interpolation does not produce valid results when the point of interest resides outside of the triangulated domain.

2. Reverse distance interpolation is employed as the second interpolation method. In this case interpolation using five points defined above is applied as:

$$C = \frac{\sum_{i=1..5} \frac{C_i}{d_i}}{\sum_{i=1..5} \frac{1}{d_i}}, \quad d_i = [[\bar{x}_i - \bar{x}]]$$

3. As a third method weighted barycentric interpolation is used. Defining d as largest value at the barycentric coordinate system the interpolation is applied as:

$$C = \frac{\sum_{i=1..4} \frac{C_i}{d_i}}{\sum_{i=1..4} \frac{1}{d_i}}, \quad d_i = \max(b_i)$$

Interpolation algorithm is run through verification CTS tests and it is seen that weighted barycentric interpolation gives the best results. Verification of the interpolation algorithm is shown in Figure 8.

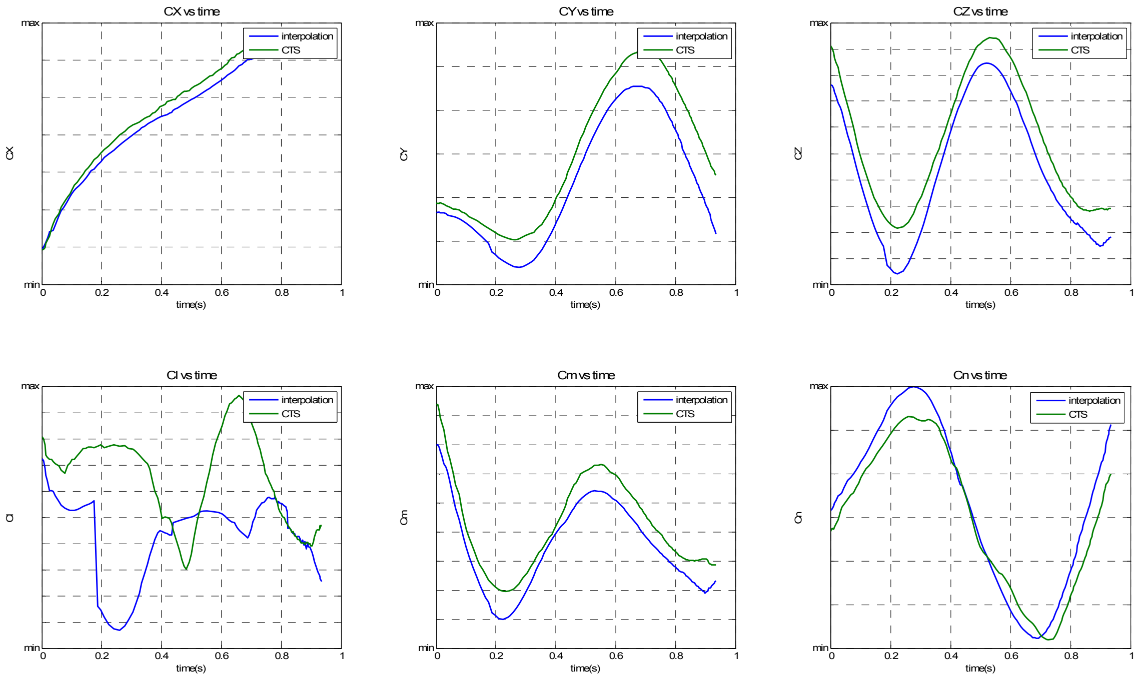

Figure 8 : Comparison of CTS tests coefficients and interpolation algorithm

Calculation of aerodynamic data

After setting up the interpolation algorithm, aerodynamic data can be prepared for the separation zone after applying some corrections. Let C_{Grid} is the interpolated grid data obtained by interpolation algorithm. It should be noted that, this data are collected from a small scale wind tunnel model. Therefore deviation from the free stream aerodynamic data for the separation zone is defined as:

$$\Delta C = C_{Grid} - C_{FF\_sep}$$

Then, scale effect corrected aerodynamic data can be defined as adding separation zone deviation to the free stream data:

$$C_{static} = \Delta C + C_{FF\_full}$$

This data represents the static values only. Adding dynamic effects on the static aerodynamic forces gives the total aerodynamic forces

$$C = C_{static} + C_{dynamic}$$

This methodology for the calculation of the aerodynamic parameters are applied for all non-dimensional force and moment parameters and calculated parameters are supplied for 6DOF integrator at all simulation steps.

COLLISION DETECTION MODEL

To ensure the safe separation, collision of the store with the aircraft must be checked, at each simulation time step. Moreover, in order to consider the separation as safe, instead of a complete collision check, minimum distance between any points of store and aircraft should be larger than a predetermined tolerance. For this reason, both aircraft and store CAD models are created and converted into standard tessellation language (STL) format consisting of thousands of triangles (Figure 9). To calculate the minimum distance between the store and the aircraft an algorithm is developed. Hence, distance between all these pair of triangles are calculated then, minimum of these distances is considered as the closest distance between the store and aircraft. Since this procedure is repeated at each simulation time step, it brings a huge computational cost. Miss distance result validation with CTS test can be seen in Figure 10.

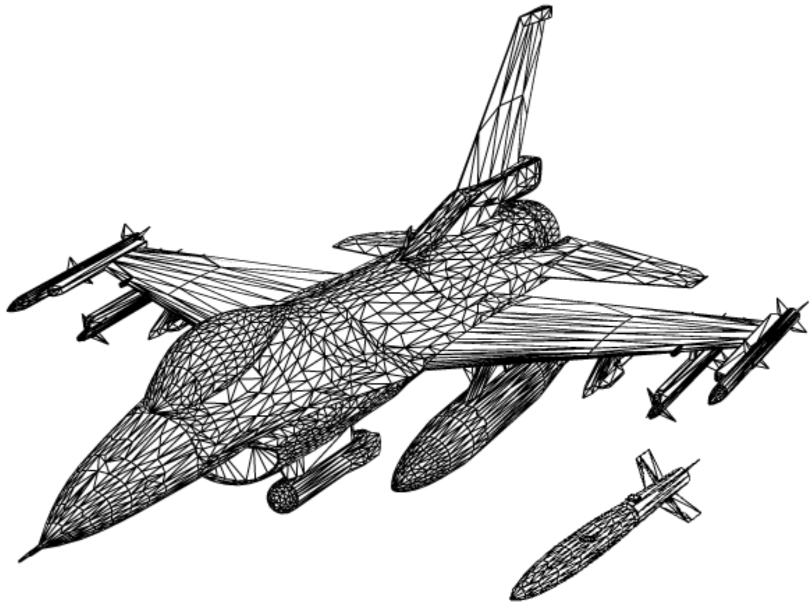

Figure 9 : Aircraft and store CAD model view in STL format

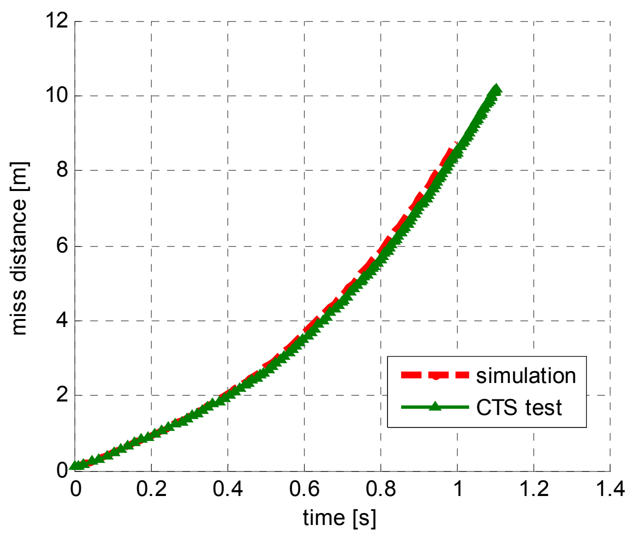

Figure 10 : Validation of miss distance between aircraft and store

Closest points of two triangles

An infinite number of equally close points between two triangles might be available. But, one can always realize T_1 and T_2, which are the closest points between two triangles, in a way that one of the points lies on the boundary of the triangles. Thus, computing the closest points between line segment and triangle for all six possible combinations of an edge from one triangle tested against the other, gives a pair of closest points between two triangles. Finding the closest pair of points between T_1 and T_2, which can be occurred either on an edge from each triangle (Figure 11.a) or as a point interior one triangle and a vertex of other triangle (Figure 11.b), is a better realization than expensive segment-triangle distance tests. In this case the problems are computing the closest point to the each vertex, which is said to be projected interior to another triangle, of each triangle on the opposite triangle and computing the closest points among all pairs of edges, one from each triangle. In other words, it is need to perform the nine edge-edge tests and six vertex-triangle tests. The global closest pair of points between triangles is the one with the overall smallest distance, among the all pairs of closest points [Ericson, 2004].

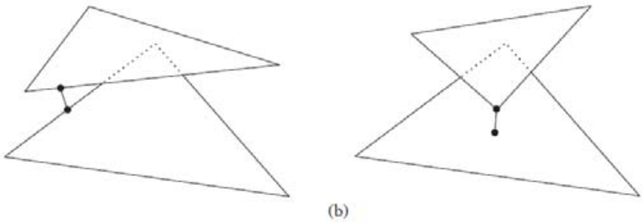

Figure 11 : The closest points between two triangles [Ericson, 2004]

3D ANIMATION GUI

Often aerospace engineer is left with the raw positions, accelerations, speeds and miss distances. However, total understanding of the separation sequence is completed with visual feedback provided for the engineer. Therefore, in such cases it is important to make the separation phenomena more understandable with animation that helps user to imagine dynamics being simulated. For this reason, a 3D animation module consisting of several different viewpoints is developed using Simulink 3D Animation Toolbox and integrated into the analysis tool (Figure 12).

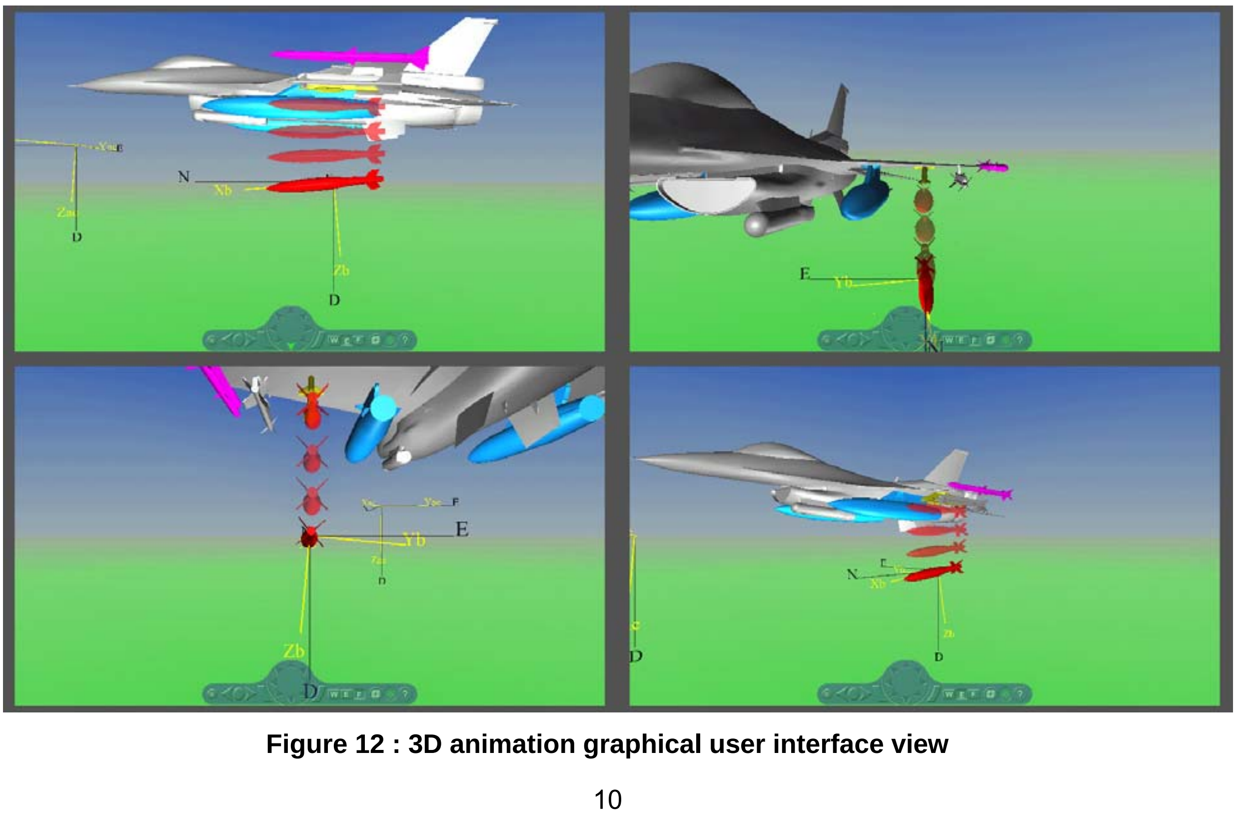

Figure 12 : 3D animation graphical user interface view

RESULTS

In this study, a numerical tool to perform safe separation analysis of a store including interpolator, 6DOF solver, visualizer and collision detection algorithm is developed and employed in real-world calculations. Figure 13 shows comparison of the simulation results for a separation case applied at 40000ft altitude and 0.95 Mach number. In this figure CTS test results are also shown.

It can be observed in this figure that CTS results and grid results are generally in good agreement. Inconsistency in roll axis results is a known phenomenon and results in the repeatability and accuracy issues measurement in such rigs in wind tunnels.

The main advantage of grid separation method is embraced during the design phase. Sensitivity to store mass property changes as well as sensitivity to release piston forces is also investigated during a real-world store design process. Therefore safe separation is ensured even in problematic release conditions and safe separation envelope is thoroughly investigated. Integrated tools such as visualizer, collision detection tool, speeds up post processing and evaluation processes significantly.

As a future work, comparison of the results with the CFD results as well as real release measurements is planned. Those comparisons will provide further awareness of the precision of the tool and they will provide an opportunity to refine our methodology to ensure the safe separation before any flight tests.

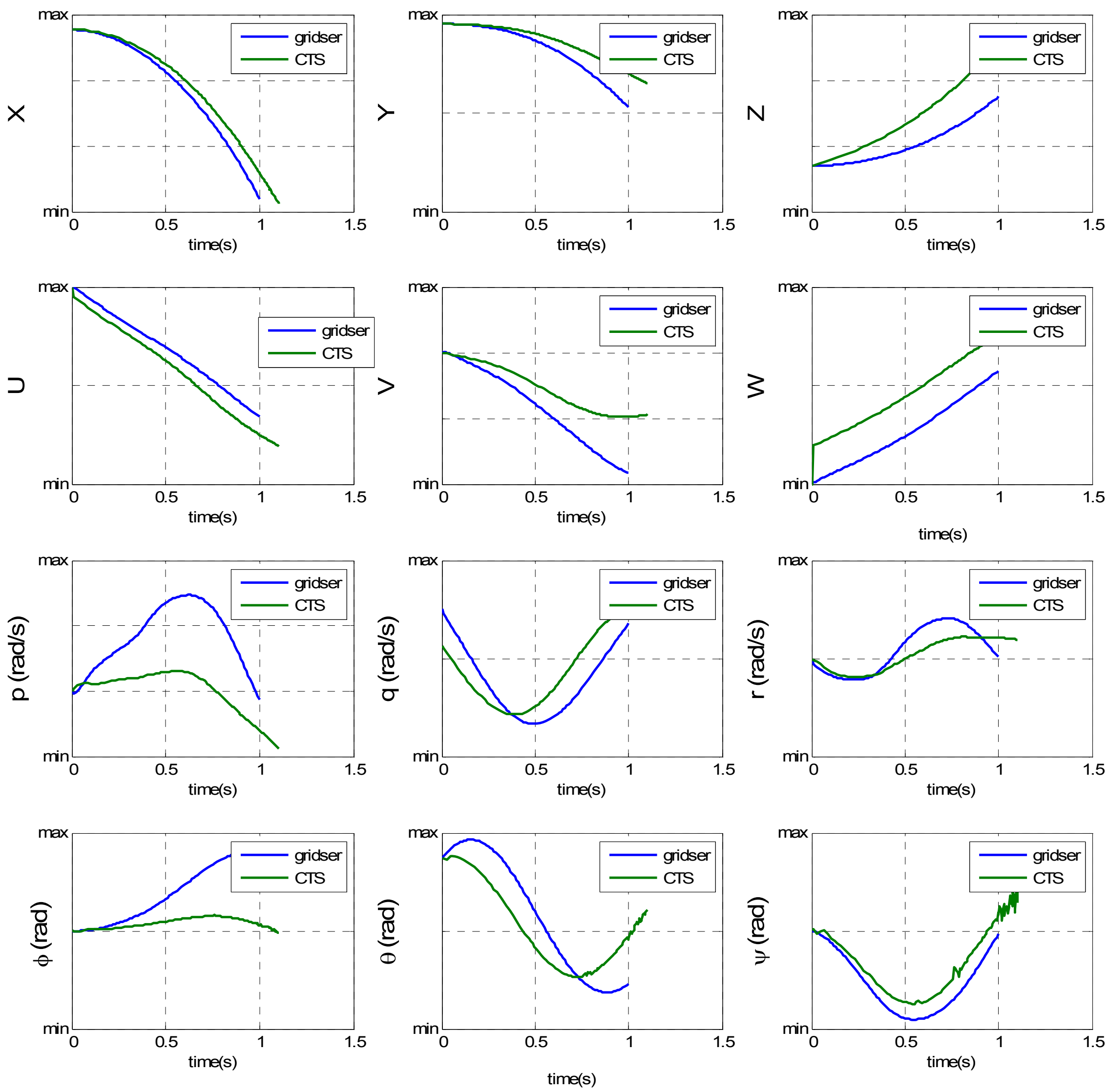

Figure 13: Results of grid separation simulations and comparison with the CTS results

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