STORE SEPARATION TRAJECTORY PREDICTIONS AT LOW SPEEDS

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Abstract

Store separation techniques for military aircraft using Computational Fluid Dynamics (CFD), modelling and simulation, wind tunnel and flight testing are well established. This paper describes how this methodology could be applied to the civilian airworthiness regulatory environment for Search and Rescue stores from the Challenger 604 aircraft for the Australian Maritime Safety Authority.

1.0 Introduction

Over the past quarter of a century, the US Air Force, Army and Navy, Royal Australian Air Force, and Royal Canadian Air Force, have cooperated to accelerate the validation and verification necessary to enable the insertion of the latest scientific and engineering methods into the aircraft stores compatibility modelling and simulation, experimentation, test & evaluation and certification methods [1]. The Australian Maritime Safety Authority (AMSA) is replacing Dornier 328 turboprops with Bombardier Challenger 604 special mission jets modified for Search and Rescue (SAR) stores. Similarly configured CL-604 Multi-Mission Aircraft are in service with the Royal Danish Air Force.

There were several aircraft stores compatibility challenges posed by replacing a turboprop aircraft with a turbojet covering spectrum of carriage and especially employment of the SAR stores. For the Dornier 328 the rear cargo door used for store separation is well clear of the engine, Figure 1. For the Challenger 604 it's just underneath the nacelle, Figure 2. In addition, the minimum airspeed at which the 604 can release stores is higher.

Figure 1. AMSA Dornier 328

Figure 2. AMSA Challenger 604.

Unlike military aircraft, the company undertaking the certification of the Challenger 604 Search and Rescue aircraft for AMSA did not plan to use wind tunnel testing, CFD nor Six Degree-of-Freedom (SDOF) trajectory simulations for assessing the stores separation prior to design of the delivery system and flight testing. This might have been since the released stores were relatively light weight, the airspeeds low, and incidental contact with the aircraft unlikely to cause significant damage at low airspeeds. Furthermore, the company decided not to procure previous certification artefacts and aerodynamic data to establish provenance.

In Australia the Civil Aviation Safety Authority (CASA) is responsible for civilian airworthiness standards and type certification for all Australian civil registered aircraft. CASA confirmed that the certification basis of the Challenger 604 under US FAR 25 was suitable but requested that the company undertaking the type certification for AMSA and CASA receive technical advice on the proposed test planning and execution for the SAR stores carriage and employment by the authors.

1.1 AIM

The aim of this paper is to discuss the application of the military aircraft stores compatibility modelling and simulation, experimentation, test & evaluation (T&E) and certification methodology in the Australian civil airworthiness regulatory environment using the Bombardier Challenger 604 special mission jets modified for Search and Rescue (SAR) as a case study.

1.2 Predicting safe and acceptable aircraft stores separation trajectories

As noted in references [2, 3, 4] predicting accurate store separation trajectories on high speed aircraft under the varying conditions of altitude, Mach number, flight path angle, load factor, and other factors related to delivery techniques (particularly where multiple carriage of stores is involved), is a complex task, requiring a skilled and experienced analyst. Several techniques are available for store separation analysis, and these are documented throughout the scientific literature. Well proven wind tunnel and CFD have supported advanced weapon development and integration. Most nations use a variety of unique CFD codes to augment wind tunnel testing. These techniques have been extensively validated for external store separation. During the past decade, various American Institute of Aeronautics and Astronautics (AIAA) challenges have seen great progress and the US, under the auspices of the DoD High Performance Computing (HPC) Modernization Program Office have combined each of the Services' initiatives to establish an Institute for HPC Applications to Air Armament (IHAAA) which has included key NATO and Five Eyes nations. Some are purely analytical in nature, utilizing theoretical aerodynamics and complex mathematical manipulation and analyst interpretation. Others utilize wind tunnel testing of small scale models of the store and aircraft, while still others involve a combination of theoretical and wind tunnel data, utilizing a high speed digital computer for data reduction. Wind tunnel test data for store separation may be obtained from one, or a combination of, the following:

1.2.1 Captive trajectory. This test uses a strain gauge balance within the separating store to continually measure the forces and moments acting on the store. An on-line computer simulation determines successive positions of the store through its trajectory.

1.2.2 Grid data. An instrumented store is used to measure the forces and moments acting on the store in the flowfield through which the store must separate. Trajectories are calculated off-line using this information as inputs to a trajectory program.

1.2.3 Dynamic drop. The dynamic drop tests use dynamically scaled models that are physically separated in the wind tunnel. Data can either be photographical or telemetry. This method is generally limited to simulated level flight releases only.

1.2.4 Carriage loads. In this test, forces and moments are measured on the store, with the store or weapon attached to the aircraft in its correct carriage position. These data are used as inputs to trajectory computation programs.

No single technique will suffice for all cases. Rather, the analyst must examine the particular and select the technique that, in his opinion, offers the most advantages for his particular situation. Most purely theoretical techniques available today suffer severe degradation when applied to transonic store separation, or where multiple stores carriage is involved.

2.0 Search and Rescue (SAR) Store Separation from Turbojet Aircraft.

2.1 Civilian Case Study

The AMSA CL-604 aircraft has a large selection of Search and Rescue (SAR) stores (figure 3) that can be released from the Air Operable Door (AOD). These range from freefall items of less than 1kg all the way up to parachute delivered 74kg fuel containers. It would be expensive and time consuming to flight test every single item that can be released and so a means to reduce testing is required for the stores and possibly eliminate the requirement for separation tests for variations of these stores in future. Using the military approach this is ideally accomplished using modelling and simulation with only limited selective flight tests to validate the models and/or to provide sufficient test evidence for clearance by analogy where possible.

Any separation event is driven by the initial conditions, in this case the velocity and orientation that the store enters the air flow, and the physical properties of the store such as mass properties, and external shape. The latter determines the free stream aerodynamic loading that is applied by the air flow and so subsequent motion. Stores near an aircraft experience an aerodynamic interference effect between the store and aircraft flowfields that can dominate the separation trajectory and drive the store into a violent collision with the aircraft, particularly for high speed aircraft at transonic conditions.

Figure 3. Challenger 604 SAR Stores

However, in the case of door launch from a SAR aircraft it was considered that any interference is likely to be small due to the compactness of the stores, lack of store lifting surfaces, and very low airspeed of the aircraft at release [5]. Any aerodynamic effect is also transitory as the store is launched from within the cabin, rather than starting in a location with such interference. Consideration of the free stream aerodynamics alone was believed to be satisfactory for a useful separation model, with some treatment for the progressive transition from relatively still cabin air to the external flow.

The use of CFD to determine interference effects was also a consideration but thought too time consuming for even simple Euler methods given the variety of stores and launch conditions. However, the application of older panel methods may have some merit in this scenario [6].

CFD has been used to produce the store freestream aerodynamics databases.

For a SAR aircraft, where stores are effectively hand launched or slide down a ramp out of the door or pivot on the door step, the major impediment to the use of the MIL-HDBK-1763 stores clearance process is the large variability in the launch conditions. This lack of repeatability in launch also brings into question the validity of the traditional flight test-based approach in this situation, where all possible launch conditions could not have been tested with even the most comprehensive test program. In contrast, a modern separation simulation tool can be used to assess thousands of launches using Monte Carlo or batch runs. An example of such a separation model has been generated with the ASTERIX [5] (Aircraft Store Trajectory Estimation Realized In Xcos) store separation modeling system, with an indicative output shown in figure 4.

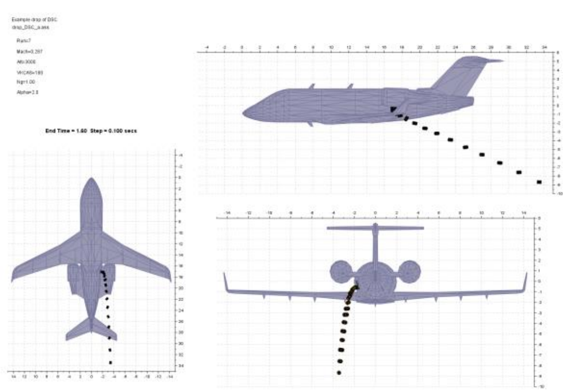


Figure 4. 604 Separation Prediction

These simulations were produced by using linear theory combined with DATCOM techniques to predict the freestream aerodynamics, as previously described [5].

Even using modeling and simulation there are still many different stores to be accommodated and so analogy should be used where possible. In this situation analogy would rely more on similarity of shape, with mass as a secondary consideration. For example, with a range of squat cylinder-shaped stores, assessing the lowest mass and highest mass would allow clearance by analogy to the remainder. To facilitate such an approach the SAR stores were grouped as follows.

2.11 Squat cylinders – e.g. Diesel pump, Droppable Stores Container

2.12 Slender cylinders – e.g. SLDMB, Marine Supply Container

2.13 Bagged stores – e.g. Life raft, Sea Anchor kit, Tropical Recue platform

2.14 Small, hand launched –e.g. EPIRB, Signal kit

2.15 Large Square stores – e.g. Petrol pump, 40L fuel container

Simulations and flight tests for samples in each group should be sufficient to allow clearance analogy for the rest. Such initial simulations were undertaken and determined that separation at the required SAR flight conditions should be safe, though there were some concerns for the very light hand launched stores due to the large variation in possible launch direction and velocity. The provision of Flight Clearance during this process served to clarify the project management and test teams approach to reconfiguring the stores operation in preparation for the ground and flight trials. Flight testing was conducted successfully and met expectations, but unfortunately no test data has been made available by the operators for direct comparison with simulations.

3.0 Freestream Aerodynamics

The preliminary trajectory simulations for the AMSA CL-604 aircraft were produced by using a linear theory panel code [6]. As may be seen in Figure 5, these predictions were in poor agreement with DES [7] predictions for a cylinder with a Length to Diameter L/D ratio of 2.0.

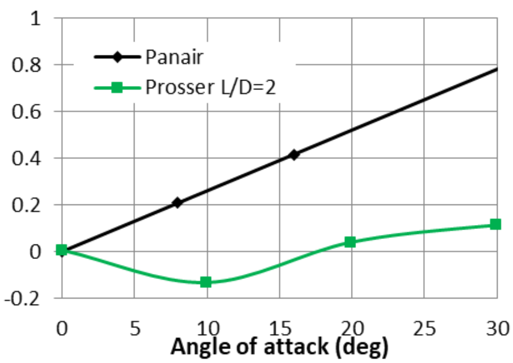
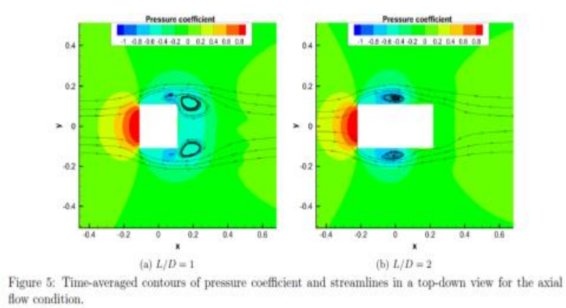


Figure 5. Cylinder Pitching Moments

Visualization of Prosser's solution at zero angle of attack is shown below (included by permission of the author).



Calculations were also made using Star-CCM+ [8] for a cylinder with and L/D ration of 3.33. As may be seen in Figure 6, there is a wide variation in the predicted forces and moments for cylinders of different L/D ratios. As the L/D ratio increases the normal force increases, and the cylinder becomes more unstable.

Flowfield predictions for the 3.33 cylinder at 90 and 150 degrees are shown in Figures 7A and 7B. Wind tunnel data for cylinders at various angles would be desirable.

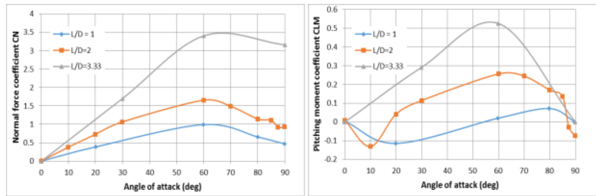


Figure 6. L/D on Effect on Freestream

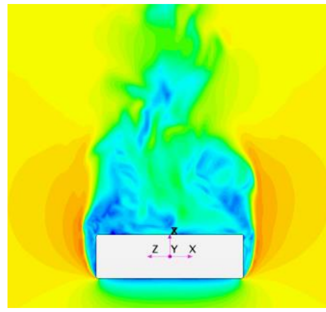


Figure 7A. L/D 3.33 Cylinder at 90º

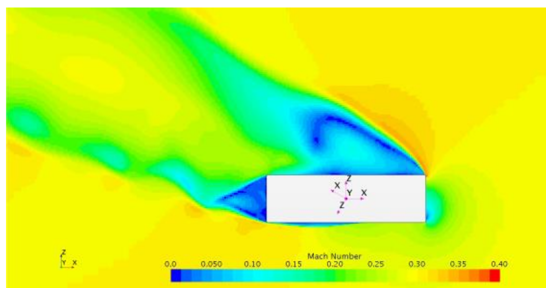


Figure 7B. L/D 3.33 Cylinder at 150º

A university course combining CFD predictions with wind tunnel pressure data might provide a great learning experience and help determine the validity of the CFD calculations. A possible low speed wind tunnel test configuration is shown in Figure 8.

A strut mounted cylinder with AOA variation could be built. No Balance would be needed since pressure taps should provide sufficient data at low Mach numbers for comparisons to CFD predictions.

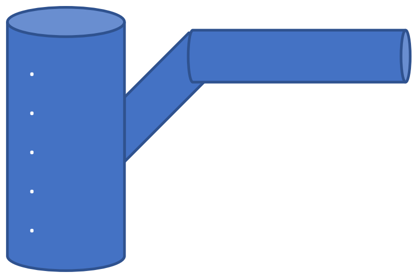


Figure 8. Cylinder Wind Tunnel Model

4.0 Flight Test Predictions

4.1 Modeling Assumptions

4.11 Aircraft

The aircraft is always assumed to be in steady-state (no acceleration) and does not change configuration (slats/flaps) before and after jettison of the store(s).

4.12 Store Inertia

The inertial properties of the store are typically provided by the manufacture, however if the case where this information is lacking, the assumption of a constant density inside the volume of the store is typically used.

4.13 Store Freestream

The freestream model computes the force and moment coefficients applied on the store in undisturbed air flow. There are multiple methods which can be used to determine these coefficients and depends on the type of store being analyzed. The simplest is a symmetric store which uses one dataset and assumes that the lateral and yawing moment has the same characteristics as the normal force and pitching moment. For an asymmetric store two different dataset are obtained with one based on the stores angle of attack and the other on the stores sideslip angle. Both methods assume that the effect of the angle of attack and the sideslip angle can be added to obtain the compound result. The final and most expensive (and most accurate) method is to use one dataset which contains sweeps of both angle of attack and side slip angle, this method works for both symmetric and asymmetric stores. The methodology chosen typically depends on the dataset available.

4.14 Aircraft Flow Field

Next to store freestream effects and initial conditions the most important impact on store trajectories is the aircraft flowfield. For military aircraft, this is of critical importance, and has caused many cases of aircraft damage, and sometimes loss of the aircraft in the early days of store separation when flight testing was conducted in a hit or miss fashion. The aircraft flowfield effects increase with the square of the release airspeed.

4.2 Influence Function Method

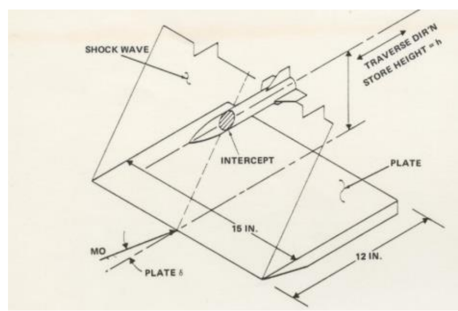


Figure 9 IFM Wind Tunnel Test

The Influence Function Method (IFM) as developed by Meyer [9], Keen [10] and Cenko [11] assumes that there is a direct relationship between the aircraft flow field along a store and the forces and moments induced by the aircraft flow field on the store. Conceptually, for a store broken into N segments, this is expressed by the relationship:

$$C_N = \Sigma\ A_i{*}\alpha_i,\ i=1,N$$
$$C_m = \Sigma\ B_i{*}\alpha_i,\ i=1,N$$
$$C_Y = \Sigma\ C_i{*}\delta_i,\ i=1,N$$
$$C_n = \Sigma\ D_i{*}\delta_i,\ i=1,N$$

The first step in the IFM process is calibration, i.e., determining the store's Influence Coefficients A_i and B_i, which determine its response to the aircraft flow field. For symmetric stores, C_i and D_i are identical to A_i and B_i. It must be emphasized that a store's Influence Coefficients are not an aerodynamic property, but rather a solution to a regression equation relating a series of store aerodynamic loads to a known aircraft flow field.

Originally, these influence coefficients were experimentally determined as shown in Figure 9. For each store position the store aerodynamic coefficients and local angle of attack α_i were known. The store influence coefficients were then determined by inverting the matrix to solve for the unknown influence coefficients.

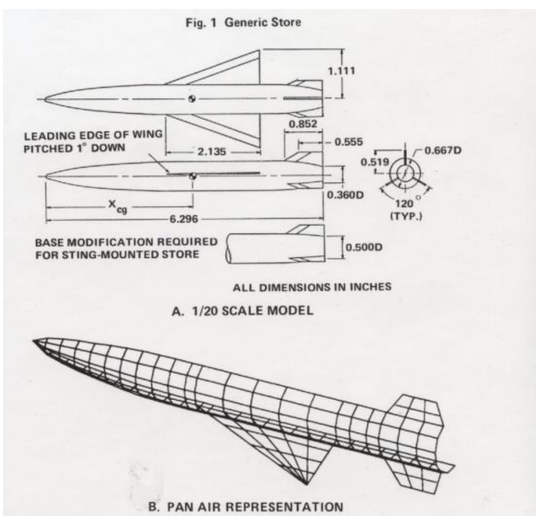


Figure 10 PanAir Representation of Wing Body Store (WBS)

It was later shown that for the Wing Body Store configuration in Figure 10 the PanAir code could accurately predict the pitching moment C_m reaction to the shock wave in the wind tunnel, Figure 11.

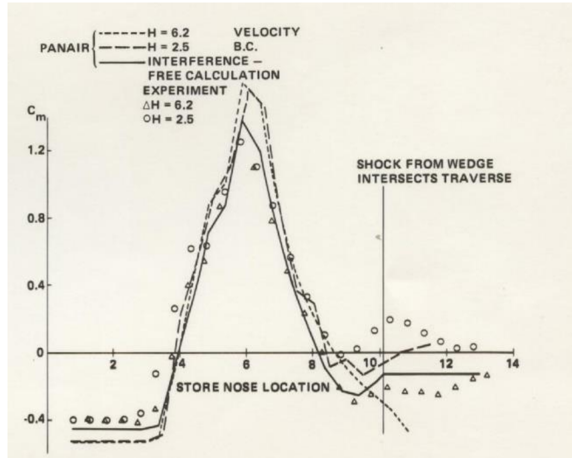


Figure 11 PanAir Predictions of WBS Moments

The second step in the IFM process is the determination of the aircraft flow field. Originally, this was done experimentally; however, with the advent of linear tools that could handle arbitrary aircraft/store geometries, aircraft flow fields were determined analytically [10].

Using the aircraft flow field and store influence coefficients, an estimate of store aerodynamic coefficients can be made everywhere in the flowfield in one calculation. This process was called **C**ost **R**educing **A**pplications to **P**anAir.

The store aerodynamic coefficients are then input into a six-degree-of-freedom program to simulate the store's trajectory.
The IFM technique was improved by Keen and incorporated into the AEDC Flow-Angle Trajectory Generation Program (Flow TGP) [12]. Interestingly, similar approaches were independently developed in Great Britain (NUFA) [13] and Australia (DSTORES) [14].

A key contributor to the trajectory the store will take once it is dropped from the aircraft is the local flow field characteristics near the aircraft. It is necessary to map the local flow vector and speed to determine the aerodynamic load on the store. The aircraft flow field is typically determined by means of off body points calculated by a CFD solver. The CFD calculations for this paper were made using Navier-Stokes, but Euler and panel codes have also shown decent results. The solver is then setup and run for several speeds to cover the envelope of release.

5.0 Store Separation Flight Test Result

The following are typical items that have been released from a modified CL-604 & CL-605 aircraft at low speed (250KCAS and below) and low altitude (less than 10,000ft): life raft, maritime marker, dropsone and homing buoy

For these items, minimal exit velocities, which ensure clearance of the stores from the aircraft, were determined through simulation. In this model, the IFM [9], allows for the interpolation between freestream coefficients of the stores in six degrees of freedom and the flow field surrounding the aircraft. Analysis of the flow field close to the aircraft was necessary to provide guidelines on how to safely release the dye marker. Assumptions and results focusing on the life raft analysis is presented herein.

This analysis requires the flow field near the exit door to be mapped to determine the aerodynamic loads on the store. To cover the launch envelope, CFD solutions were done at two flight conditions:

a. (stall speed x 1.15) KCAS, Mach 0.20, altitude = 200ft, Angle of Attack (AOA) = 10.5°

b. 150KCAS, Mach 0.23, altitude = 200ft, AOA = 5.8°

c. 200KCAS, Mach 0.30, altitude = 200ft, AOA = 6.1°

5.1 Life Raft

The life raft was modeled as a cylinder with filleted edges and its mass was 39kg with its inertia obtained by assuming a constant density inside the volume. Due to the dimension of the door it is also assumed that the raft bundle's longitudinal axis is horizontal and approximately perpendicular to the fuselage. It is assumed that the aircraft is travelling in a steady level flight and that the raft bundle has no initial velocity. Note that the no initial velocity condition is based on a conservative assumption that the operator would push a 39 kg object out of the baggage door with negligible horizontal speed. An illustration of the streamlines near the aft door and the initial position of the raft is shown in Figure 12.

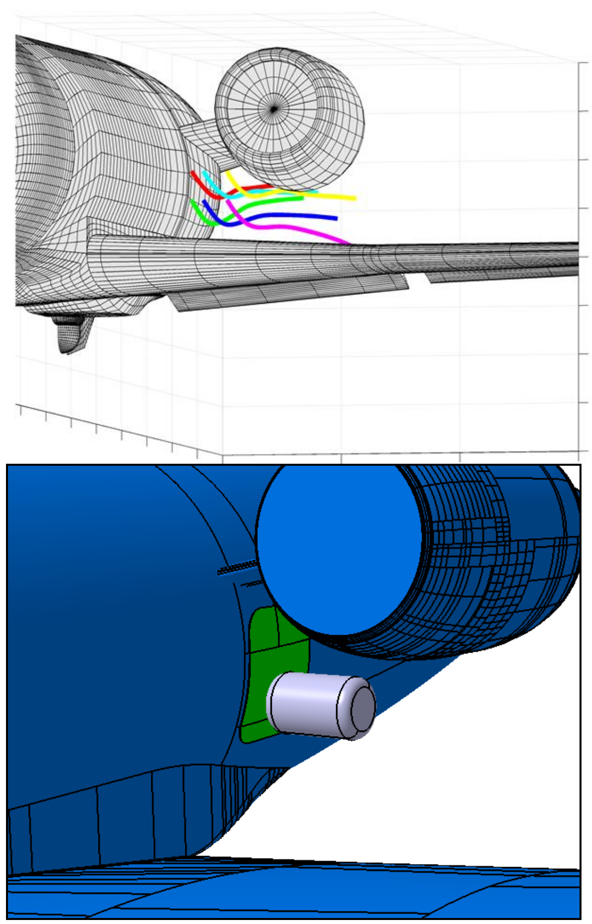


Figure 12: Streamlines and Initial Raft Position

The lateral (y axis) and vertical (z axis) trajectories of the raft were calculated, and the trajectories traced in Figure 13, with the stop at the end of the four-meter-long static line. For this analysis it was assumed that the raft had no initial lateral velocity (conservative).

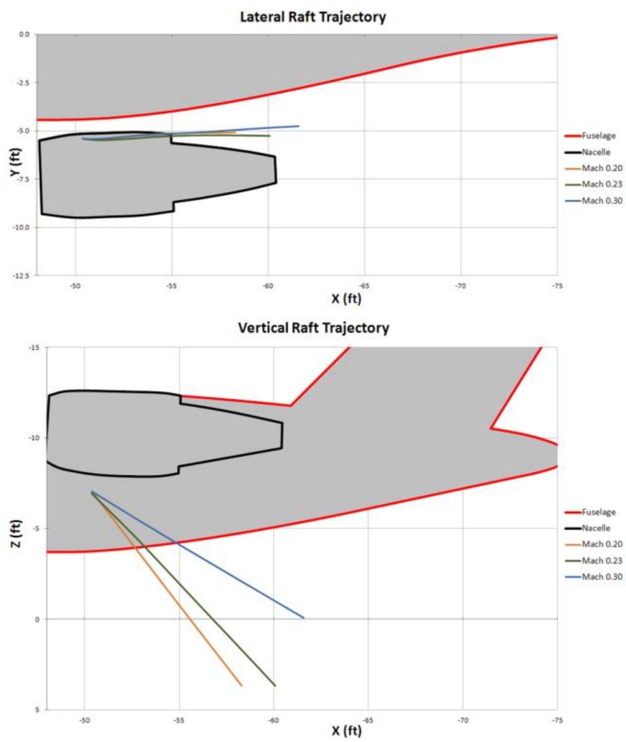


Figure 13: Lateral and Vertical Trajectory of the Life Raft

Since the starting position of the raft is assumed to be perpendicular to the flow, no visible tumbling motion is detected near the aircraft. The path is therefore relatively straight in the first four meters of travel.

The nature of the flow close to the fuselage however creates a small lateral force which moves the raft slightly inboard as it descends. In this analysis, the raft was originally positioned three inches away from the fuselage OML surface. No contact was visually observed between the raft and the fuselage.

To avoid a rubbing between the raft and the aft fuselage, the operator could ensure that the bundle has some lateral speed as it is dropped from the aircraft. To do so, it may be advantageous for the operator to sit on the floor of the aircraft and push the raft bundle with his feet. This will give better separation of the raft from the aft fuselage since the operator can apply more force in this manner.

Conclusion

This paper describes how conventional store separation prediction methodology could be applied to the civilian airworthiness regulatory environment for Search and Rescue stores.

Additional work in developing freestream aerodynamics for cylinders at low Mach numbers is recommended.

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