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QUANTITATIVE GRADING OF STORE SEPARATION TRAJECTORIES

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ABSTRACT

When a new store is integrated with an aircraft, it is necessary to verify that it separates safely for all possible release and emergency jettison scenarios. A large number of store separation analyses are required to comply with this requirement. This paper describes the development of an automated analysis process and software that can run a multitude of separation scenarios. A key enabler for this software is the development of a quantitative grading algorithm that scores the outcome of each release against clearly defined criteria. The separation grading algorithm eliminates the need for the analyst to assess each separate store separation scenario manually and subjectively by assigning scores based on a number of specific and measurable criteria. The scores obtained over a range of separation scenarios form a robust and quantitative basis for defining safe release envelopes for an aircraft/store combination and for motivating applicable pilot limitations.

The application of this approach to the release/jettison dynamics of a typical aircraft/store configuration is described.

INTRODUCTION

When a store is integrated with an aircraft, it introduces significant changes to the aircraft's mass, inertia, aerodynamics and structure. As the store is released, it must traverse an aerodynamic flowfield that is perturbed by the presence of the aircraft and it experiences different dynamics to what is found in free flight. These changes in the store dynamics can result in collisions between the aircraft and the store. The safety implications mean that store separation analyses are required by airworthiness regulations governing store integration with aircraft, e.g. MIL-HDBK-244 and MIL-HDBK-1763.

The separation dynamics of any new aircraft/store combination must be evaluated over the full release/jettison envelope, requiring a large number of simulations. The simulation task grows when compliance is required with the MIL-HDBK-244A §5.1.1.2.3.1(g) requirement that all reasonable perturbations of store mass and physical properties, ejector rack

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performance and aircraft flight conditions, etc. be considered. Those factors plus the number of configurations to be considered often results in a requirement for a very large number of store separation analyses. In response to this challenge, the separation analysis process is usually automated where the separation analysis tools are integrated into a single code system that can automatically run a multitude of separation scenarios. A typical process flow for store separation analyses is presented in Figure 1.

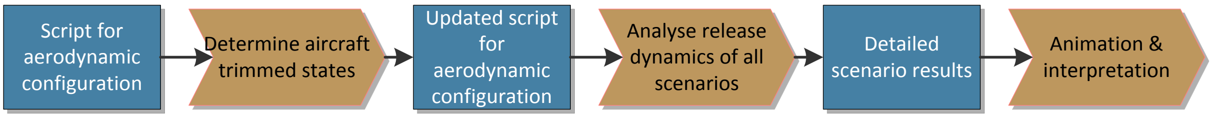

Figure 1: A typical store separation analysis process

The focus of this paper is on the last step of the process: interpreting whether the predicted trajectory is acceptable. The starting points for determining what trajectories are acceptable are the airworthiness regulations for store integration. MIL-HDBK-1763 presents separation acceptance criteria that differ depending on whether the store separation is for employment or for jettison. In this context, employment is defined as when the store is operated in its normal mode to accomplish an operational objective [MIL-HDBK-1763 §270]. Jettison is the safe release of stores from the aircraft and is done simply to separate the stores from the aircraft for safety or performance reasons [MIL-HDBK-1763 §270].

In [MIL-HDBK-1763 §271.4] the acceptance criteria for employment separation are described as follows:

1. Positive movement away from aircraft: Any store being separated from an aircraft must have positive movement away from the aircraft such that no part of the store will strike the aircraft or adjacent stores.
2. No portion of the store may penetrate a predetermined interference boundary of the aircraft including remaining suspension equipment and stores. The interference boundary is defined by a six (6) inch encapsulation of the aircraft (in the immediate area where separation is occurring), the pylon, the ejection rack and any adjacent stores.
3. Portions of the store being inside the encapsulation boundary are prohibited from further encroachment. Once outside the boundary no part of the store may re-enter the boundary.
4. In the vicinity of the aircraft empennage, the encapsulation boundary is expanded to ten (10) feet minimum.

Likewise in [MIL-HDBK-1763 §280.4] the acceptance criteria for jettison separation are described as follows:

1. Separation should be safe, but need not be satisfactory.
2. For non-emergency jettison store-to-aircraft contact is unacceptable.
3. In emergency cases, minor store-to-store or store-to-aircraft contact may be acceptable.
4. Items jettisoned may break up or otherwise fail after release as long as such break-up does not threaten the aircraft.

The criteria are significantly different and specifications for proposed separation envelopes must clearly distinguish between employment envelopes and jettison envelopes.

PROBLEMS IN ASSESSING ACCEPTABLE SEPARATION DYNAMICS

Traditionally the interpretation of the acceptability of a store separation trajectory was performed qualitatively by analysts examining animations and graphs from the store separation analysis results. There are two objections to this approach, firstly the subjective and qualitative approach is naturally inconsistent and will lead to different outcomes from different analysts. Secondly, when separation analyses are automated, the volume of results is often too much for analysts to assess each trajectory individually. There is thus a need for an automated tool that can quantitatively grade each store separation trajectory according to criteria that are traceable to regulatory and client requirements. Problematic store separation scenarios can then be flagged for further investigation by the analyst.

[Akroyd, 1998] describes one such tool, the CRASH 3D collision and minimum distance monitoring program. This program processes the geometries of the aircraft and the store for each time step and determines the closest approach point, giving an output indicating the minimum distance between the bodies, the time it occurs and the geometries involved. A plot file presenting the time history of the minimum distance is also created.

A problem with such a tool is that it focuses solely on the separation distance between the store and the aircraft. The criterion for positive movement away from the aircraft is not evaluated. Another issue is that there is no graduation in the criteria so the analyst receives no indication of which separation scenarios are presenting better or worse outcomes.

DETERMINING QUANTITATIVE SEPARATION CRITERIA

A literature survey on this topic does not reveal any recent papers on this topic. Older papers do address this issue, for example [Schoch, 1969] and [Covert, 1971]. These criteria related the acceptability of separation trajectories to the initial velocities and accelerations of the store predicted immediately after ejection. These criteria were developed based on analytical considerations that were supported by the available test data. These criteria are no longer used to judge an entire trajectory as modern computational technology makes routine computation of entire trajectories feasible.

Based on experience, a set of separation rating codes are proposed in Table 1 to provide a graduated scale for ranking different separation trajectories. These codes are based on the typical dynamics of ejector released stores and a different scale using the same philosophy may be developed for rail-launched stores.

Table 1: Separation rating codes for assessing trajectories

Code	Definition
0	Store strikes some part of the aircraft
1	Store misses the aircraft marginally
2	Store moves towards the aircraft
3	Store “hovers” near the aircraft
4	Store separates cleanly from the aircraft

Converting the rating codes into appropriate quantitative analytical criteria is essential for meaningful application and correlation with regulatory acceptance criteria. Developing the criteria required a number of iterations over a period of time. The criterion for code zero (0) is simple: some portion of the store penetrates the surface of the aircraft or any non-store appendage on the aircraft. The code 1 is more complex. When the store has just been ejected it is by definition very close to the aircraft. A dual-stage separation criterion is used to manage this situation. [Covert, 1971] postulated that any store that fails to move one radius away from the nearest point on the aircraft in 0.25 s is assumed to be unsafe. This criterion is adopted for the near-miss code. However, stores rotating rapidly in the vicinity of the aircraft can cause near-misses in less than 0.25 s and an additional criterion tests for a miss distance of 20 mm after 0.07 s (typically the end of an ejection stroke). Another factor is store movement towards the aircraft during the ejection stroke (negative relative velocity before 0.06 s).

The criterion for code 2 is negative relative velocity (after 0.06 s). For code 3, the store separation velocity must be less than 30% of the ejection velocity after 0.07s. Code 4 applies when none of the other criteria are applicable. The criteria are summarized in Table 2. Note that the separation distance is defined as the smallest separation between any part of the store from any part of the aircraft at any given time instant. Likewise, the separation velocity is defined as the minimum relative velocity between any part of the store from any part of the aircraft at any given time instant. The separation distances and velocities are not based on the motion of the store's centre of gravity.

Table 2: Criteria used to define the separation rating codes

Code	**Absolute Separation Distance**	**Separation Velocity**	**Separation Velocity Relative to Ejection Velocity**
0	< 0		
1	< 0.02 m after 0.07 s < store radius after 0.25 s	< 0 before 0.06 s	
2		< 0	
3			< 0.3 V_{eject} after 0.07 s
4			

These separation codes and associated criteria were scrutinized in a workshop incorporating the various role-players in aircraft store integration, including a military aircraft airworthiness specialist, a senior test pilot, engineering representatives of the store original equipment manufacturer (OEM), the CSIR's store integration technology manager and store separation analysis specialists.

Separation codes of 3 or 4 are deemed acceptable for operational release scenarios, complying with the requirement for "positive movement away from aircraft". Separation codes of 1 or better are acceptable for ordinary jettison conditions. Contact with the aircraft is only acceptable during emergency jettison if the relative velocities are very low (the exact velocities depend on the type of store). Contact with the aircraft is seldom acceptable by clients and stakeholders, even for emergency jettison.

IMPLEMENTING A SEPARATION GRADING ALGORITHM

The scoring of store separation trajectories was implemented in the CSIR's automated store release analyses code system as a separate function. As an aerodynamic model of the carriage aircraft and the store is usually created in the CSIR's ARUV panel code [van den Broek, 1984] for each store separation analysis project, it was convenient to use the paneling of the aircraft and the store to define the geometries used to calculate the miss distances. An example of an ARUV model is presented in Figure 2. This is an approximation as the wing and pylon thicknesses are not physically meshed in ARUV. However, as the wings and pylons are relatively thin the approximation is acceptable compared with the costs of developing and analyzing more complete solid models.

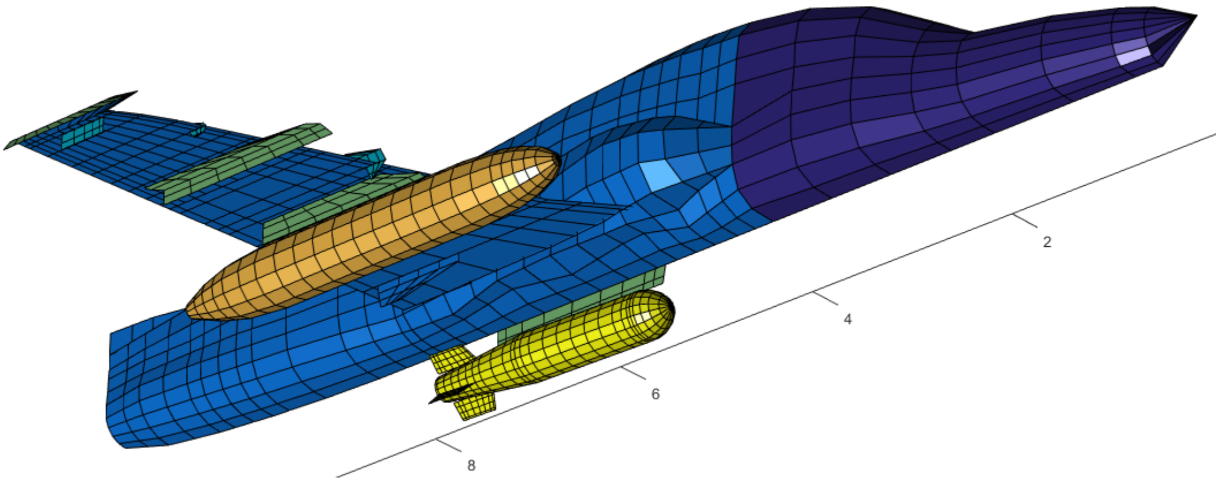

Figure 2: ARUV panel code model of the BAE Hawk Mk.120 with the Inundu electronics pod

The algorithm slices the aircraft and store trajectories into 5 millisecond intervals and at each time interval calculates the distance of every store panel corner from every aircraft panel corner. The shortest distance at each time interval is the miss distance for that interval. A typical miss distance result is shown in Figure 9. The separation velocities are obtained by differentiating the separation distance versus time data.

APPLICATION EXAMPLE

The trajectory grading algorithm is built into the CSIR's primary automated separation analysis code, MRCS. The context of the MRCS code in the overall store separation analysis process is shown in Figure 3. The overall separation analysis process begins with the compilation of a "script" of separation analysis scenarios for a given aerodynamic configuration in a spreadsheet. This script is passed to the LOTA (low-order trim analysis) code to determine the aircraft trimmed states for each aerodynamics scenario, which is added to the script. The script file is then passed to the MRCS code which automatically analyses each separation scenario in turn. If a transonic scenario is encountered, then grid data obtained from wind-tunnel tests or computational fluid dynamics (CFD) computations are used (the grid survey method is very efficient in the use of wind-tunnel or CFD time and is currently the preferred approach for store separation testing internationally [Cenko, 2010]). For subsonic scenarios the ARUV panel code inputs are used.

Each separation scenario is graded using the approach described earlier and the resulting grades are added to the analysis script as the primary output. All the related data for each scenario is compressed and saved for reference and investigation when required. If the grade code for a given scenario is a cause for concern, the analyst can animate the separation trajectory using the Pretend code for further investigation.

The trajectory grading algorithm is been applied to multiple store separation analysis projects with great success. The relief that the algorithm gives the analyst from having to study multiple trajectories allows a large increase in the number of store separation scenarios that can feasibly be investigated.

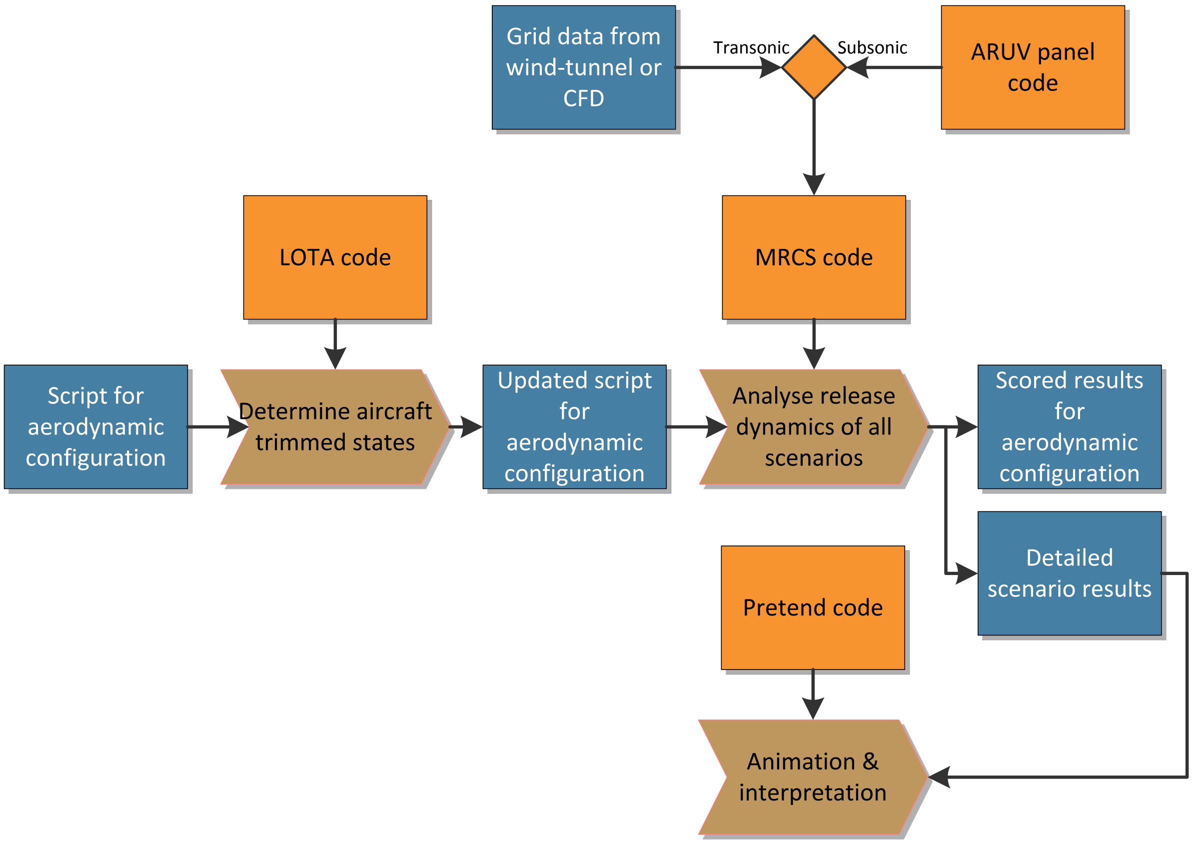

Figure 3: CSIR's automated separation analysis process

The analysis of the emergency jettison of the Inundu electronics pod from two configurations of the BAE Hawk Mk.120 is presented as an example.

The Inundu pod is an airborne electronics test, evaluation and training pod that is currently being developed by the CSIR. The current payload is capable of both mimicking the radar emission of threat aircraft/missiles and radar jamming and it is being developed to equip aggressor training aircraft. The pod is shown in Figure 4.

Figure 4: Inundu pod in the CSIR's transonic wind-tunnel for tests of its RAT

The Inundu pod airframe is based on the Hunting BL-755 cluster bomb geometry and mass properties since it is integrated on a number of aircraft, facilitating the option of integrating the Inundu pod by analogy. The pod has a radome at the front to support radar transmission and reception. The pod is designed to facilitate the exchanging of its payload without affecting its interfaces with the carriage aircraft, thus enabling the flight testing of a wide range of electronic technologies. The modular payload means that the pod is designed to accommodate a ±5% variation in mass and a range of centre of gravity locations; these have to be included in the separation analyses.

The Inundu pod is powered by an internal ram-air-turbine (RAT). The RAT delivers shaft power to an electric generator that powers the electronics inside the Inundu pod. The airflow through the RAT is controlled by varying the air inlet area and it is designed to operate over a wide variety of inlet Mach numbers and altitudes. The presence of the RAT does make the pod's aerodynamics asymmetric which has to be accounted for in the store separation analysis.

The Inundu pod is to be integrated on the centerline pylon on the Hawk aircraft in two configurations, with and without drop tanks.

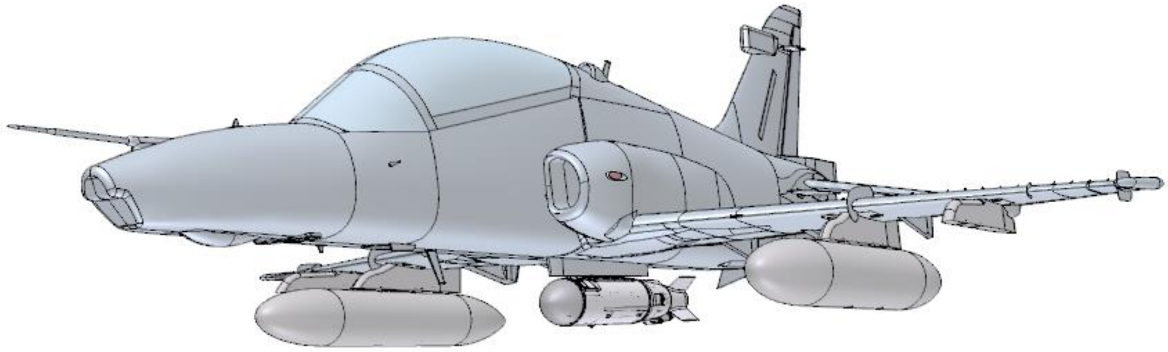

Figure 5: CAD model of the BAE Hawk Mk.120 with Inundu and drop tanks

The Inundu store is an electronics pod and is not intended to be released except in the case of an emergency. The objective of the analysis is to determine the widest emergency jettison envelope that is acceptable according to military regulations. At the same time, cost limitations dictated that the analysis be done using the fast panel code, ARUV. As ARUV is a linear potential aerodynamic code, this means that only subsonic separation scenarios could be considered.

A screening analysis was performed to investigate the emergency jettison envelope and to ensure that this envelope falls within the ARUV limitations. The screening analysis also investigates the aerodynamic loads that the store experiences in carriage due to the aerodynamic interaction between the aircraft and the store.

The jettison analysis includes the usual airspeed, altitude and Mach number combinations, the pod's mass and CG range, the tolerance on the ejector release unit's (ERU) performance and the jettison envelope parameters set out in [MIL-HDBK-244A §3.1.1.2.3.1 (h)] (normal force 0.5g to 1.5g, flight path angle ±10°, bank angle ±10°, roll rates ±10°/s). This results in a large number of separation scenarios. These scenarios are prepared in a Microsoft Excel® file as shown in Table 3 for input into the MRCS store release analysis software. Even an emergency jettison analysis can have hundreds of separation scenario combinations. The Modern Design of Experiments (MDOE) technique [Jamison, 2013] is used to optimize the scenarios to minimize the number required. In this case, a formula from the aircraft's manual was used to determine the angle of attack for each scenario instead of the LOTA code.

Table 3: Variables considered in jettison analysis

Envelope point	Mach No.	Alt	Nz	Ejector force setting	Flight Path Angle	Bank Angle	Roll rate	Store Mass	Store cg-x	Aircraft Mass
		(ft)	(x 1g)	(%)	(deg)	(deg)	(deg/s)	(kg)	(m)	(kg)

Once set up, the MRCS code computes the entire list of separation scenarios and adds the separation rating codes to the Excel file. The analyst can easily see what factors contribute to low separation scores. In this case it was found that if the aircraft's ERU was configured with dual T37 throttles, the jettison envelope would be limited. The Hawk's ERU is shown in Figure 6 and the throttles used to adjust the impulse of the front and rear ERU pistons are shown in Figure 7. Configuring the ERU with rearward biased T37-T55 throttles opened up the full jettison envelope according to the air force's preferred criterion of no scenario scoring less then 1.

Figure 6: The ERU on the Hawk's outboard pylon (the ERU on the centerline pylon is identical)

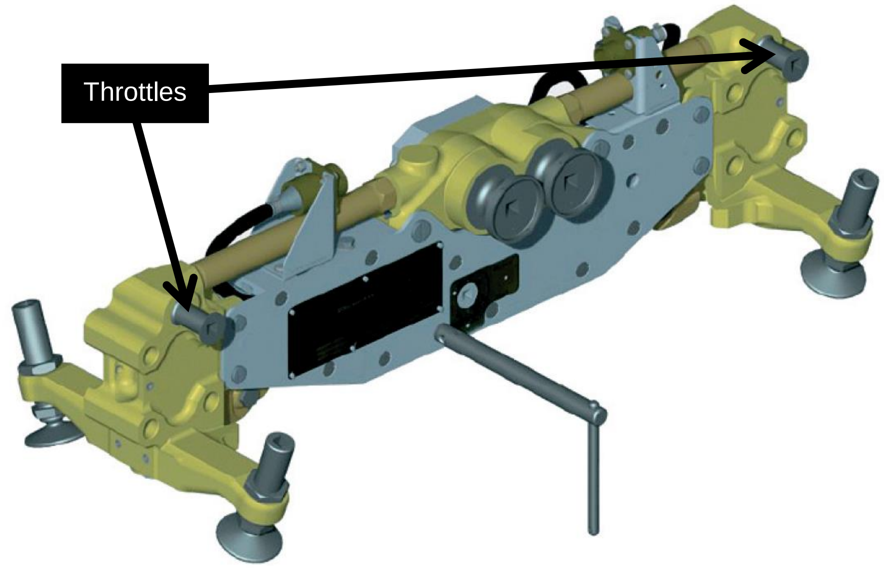

Figure 7: The Cobham ERU-119 [Cobham, 2017] showing the throttles used to separately control front and rear ejector piston impulses

Separation trajectories are presented to illustrate the outcomes. A code 4 separation trajectory is shown in Figure 8 and Figure 9. A code 0 separation trajectory (collision with the aircraft) is shown in Figure 10 and Figure 11 with the original equal T37-T37 ERU throttle setup. The same jettison scenario becomes a code 2 (moves towards the aircraft) when the biased T55-T37 ERU throttle setup is selected as shown in Figure 12 and Figure 13. While this scenario is unacceptable for operational releases, it is acceptable for an emergency jettison.

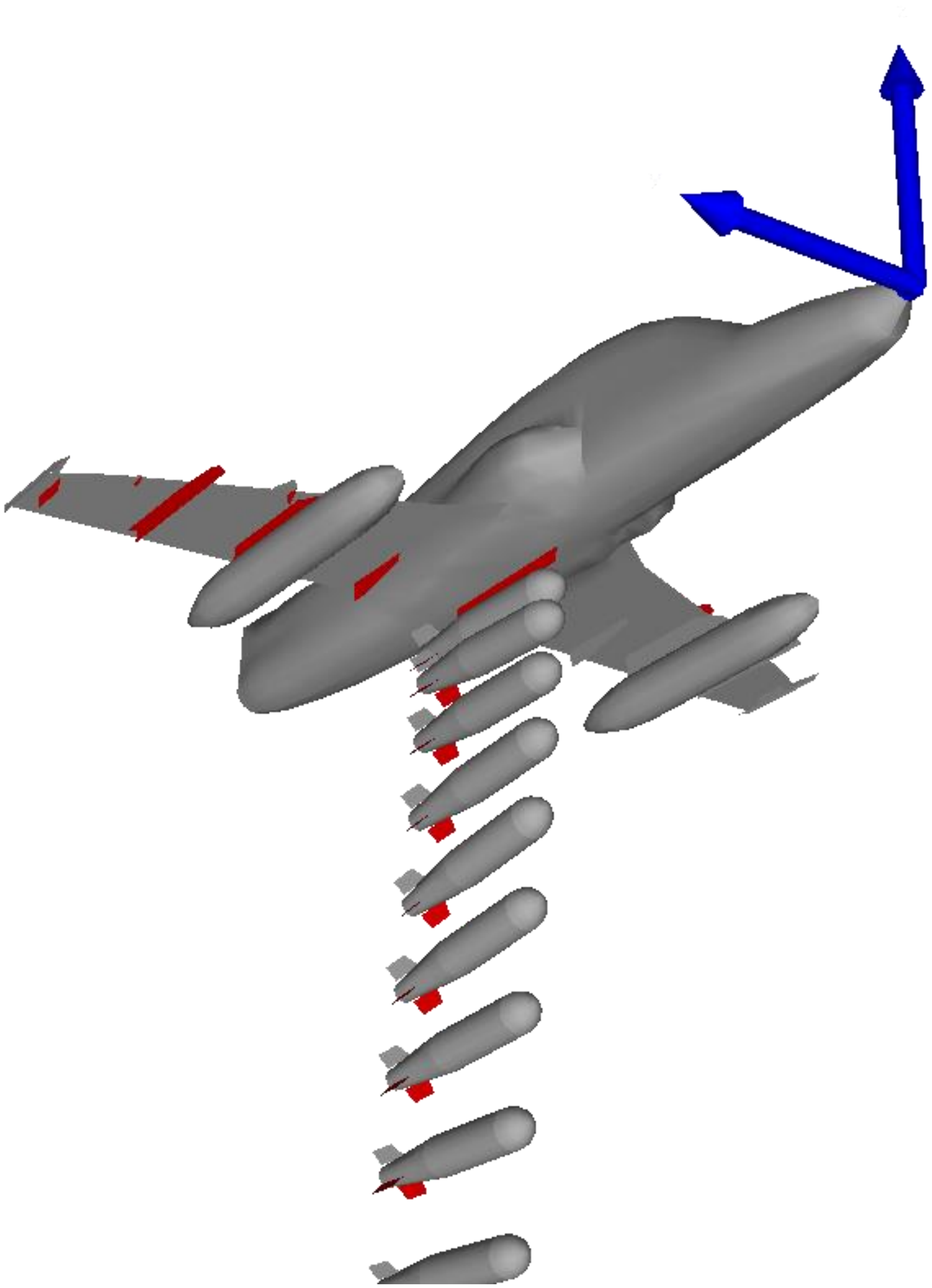

Figure 8: Separation trajectory relative to aircraft: Code 4: biased T55-T37 ejector throttles, Mach 0.665, sea-level, Nz = 1.5g, ERU = maximum, flight path = -10º, bank angle = -10º, roll rate = 10º/s, store mass = minimum, store CG = front limit, aircraft 80% fuel

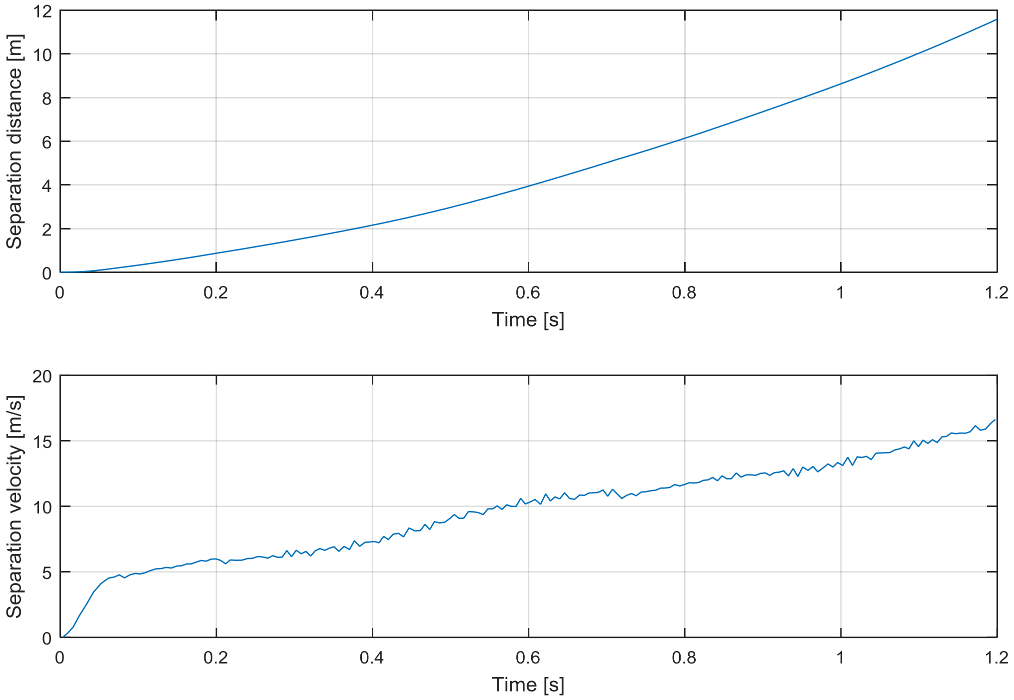

Figure 9: Separation distance and velocity versus time: Code 4: biased T55-T37 ejector throttles, Mach 0.665, sea-level, Nz = 1.5g, ERU = maximum, flight path = -10º, bank angle = -10º, roll rate = 10º/s, store mass = minimum, store CG = front limit, aircraft 80% fuel

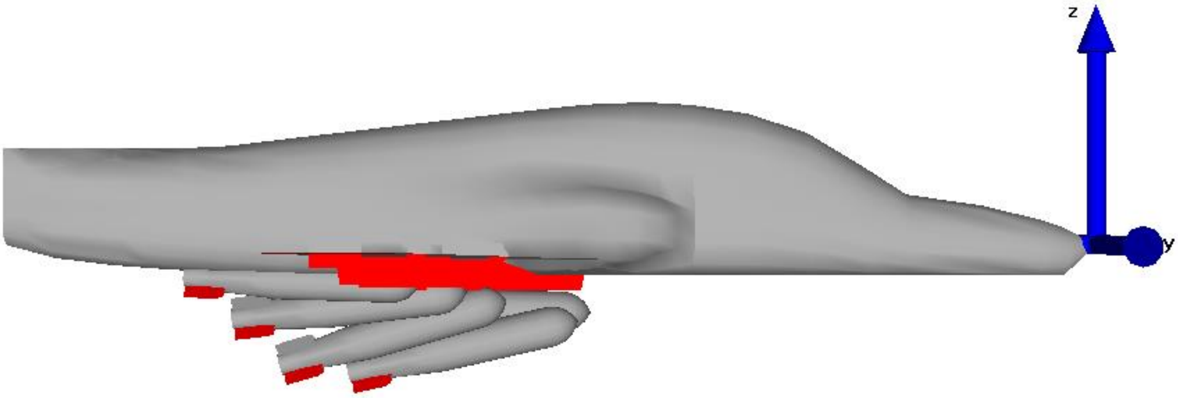

Figure 10: Separation trajectory relative to aircraft: Code 0: dual T37-T37 ejector throttles, Mach 0.665, sea-level, Nz = 0.5g, ERU = minimum, flight path = -10º, bank angle = -10º, roll rate = 10º/s, store mass = minimum, store CG = front limit, aircraft 80% fuel

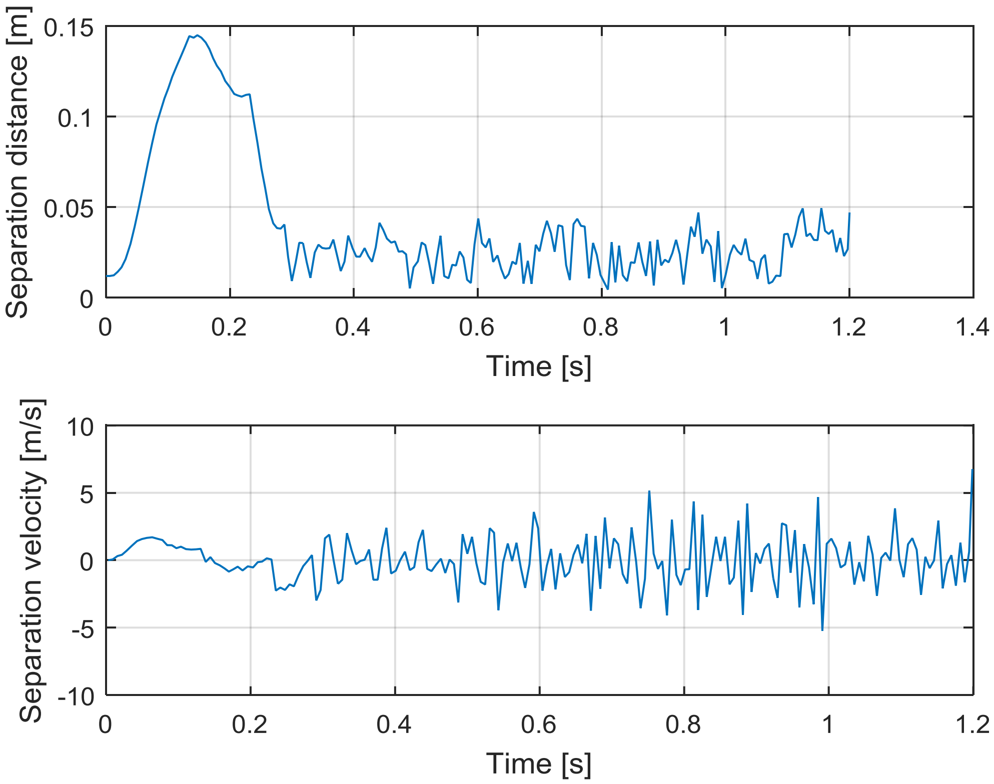

Figure 11: Separation distance and velocity versus time: Code 0: dual T37-T37 ejector throttles, Mach 0.665, sea-level, Nz = 0.5g, ERU = minimum, flight path = -10º, bank angle = -10º, roll rate = 10º/s, store mass = minimum, store CG = front limit, aircraft 80% fuel

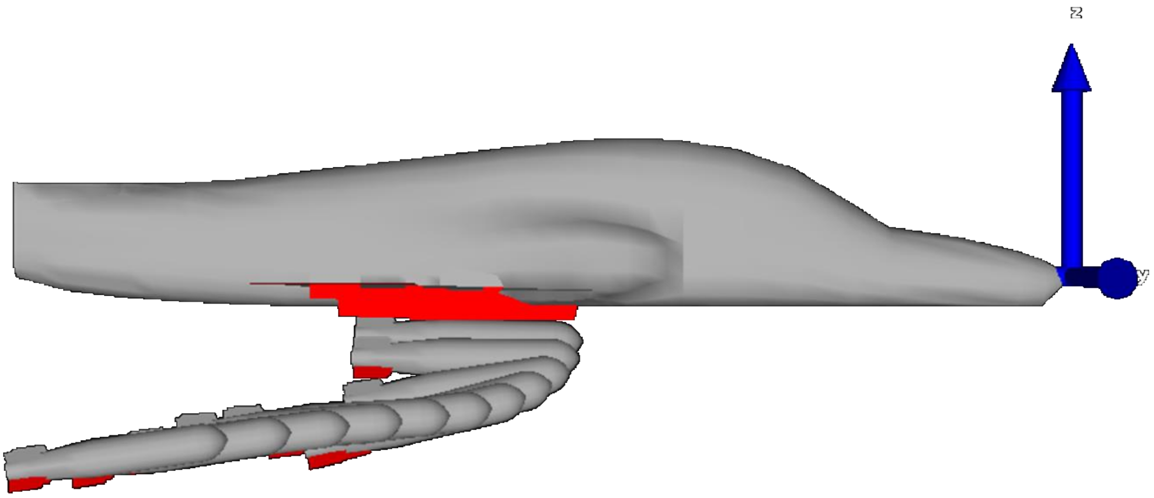

Figure 12: Separation trajectory relative to aircraft: Code 2: biased T55-T37 ejector throttles, Mach 0.665, sea-level, Nz = 0.5g, ERU = minimum, flight path = -10º, bank angle = -10º, roll rate = 10º/s, store mass = minimum, store CG = front limit, aircraft 80% fuel

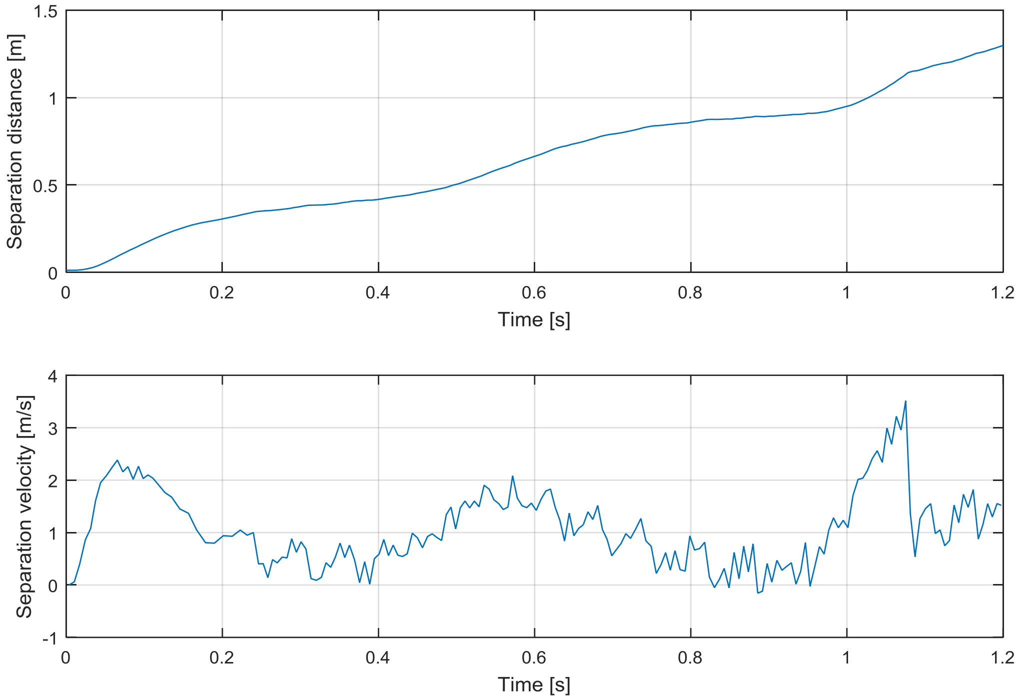

Figure 13: Separation distance and velocity versus time: Code 2: biased T55-T37 ejector throttles, Mach 0.665, sea-level, Nz = 0.5g, ERU = minimum, flight path = -10º, bank angle = -10º, roll rate = 10º/s, store mass = minimum, store CG = front limit, aircraft 80% fuel

CONCLUSIONS

A scale was introduced to grade the acceptability of a store separation trajectory. A set of quantitative criteria related to regulatory criteria are used to determine the score based on the motion of the store relative to the geometry of the parent aircraft. These criteria are based on the motion of ejector released stores and must be revised for other release techniques, although a similar philosophy can be adopted.

This store separation trajectory grading algorithm has been integrated into an automated store separation analysis code system and facilitates the analysis of large numbers of store separation scenarios, as required by the airworthiness regulations. The CSIR has successfully applied this algorithm to a number of store separation analysis projects, an example of which is presented.

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