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GRID-MODE TRANSONIC STORE SEPARATION ANALYSES USING MODERN DESIGN OF EXPERIMENTS

Kevin A. Jamison
Aeronautic Systems Competency,
Council of Scientific and Industrial Research, South Africa

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Abstract

The analysis of the separation of a Precision Guided Munition (PGM) from many configurations of an advanced jet trainer was performed using aerodynamic data from wind-tunnel tests characterised using the grid method. As strong aerodynamic mutual interference is present due to transonic shockwaves between the wing of the aircraft and the tail of PGM the loads on the store changes significantly for different combinations of PGM position and orientation relative to the aircraft. This means that the grid method must sample a wide range of positions and orientations. If this is done in usual manner, the grid test matrix is large and costly. There is another method for efficiently characterising phenomena with a number of mutually interacting variables known as the Modern Design of Experiments (MDOE) which can significantly reduce the number of grid samples required. The possibility of developing the grid test matrix using the MDOE method is investigated using a simple panel code model. The correct approach to implement the MDOE grid method is identified and the relative interpolation errors are characterised. The application of the MDOE method to the trainer jet/PGM separation wind-tunnel test is described.

1 Introduction

1.1 The challenges of store separation analyses

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 flow field that is perturbed by the presence of the aircraft and its flight dynamics are different to what is found in free flight. These changes in the store dynamics can result in collisions between the aircraft and the store [1]. The safety implications mean that store separation analyses are required by airworthiness regulations governing the integration of stores with aircraft, e.g. MIL-HDBK-244 [2] and MIL-HDBK-1763 [3].

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 performance and aircraft flight conditions, etc. be considered. Those factors plus the number of aircraft/store configurations to be considered results in a requirement for a large number of store separation analyses. The complexity of the analysis problem is compounded by the wide store jettison/employment envelopes of modern combat aircraft, often encompassing subsonic, transonic and supersonic flows.

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 [4] is presented in Figure 1.

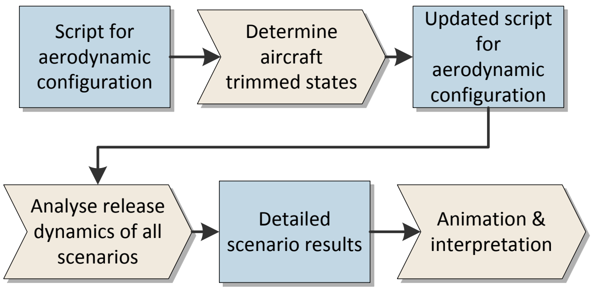

Figure 1. A typical store separation analysis process [4]

1.2 Approaches to store separation analyses

There are several options for characterising the aircraft/store aerodynamic interference for generating store separation trajectories, including the following:

- Free drop tests (usually in wind-tunnels).
- Captive trajectory simulation (CTS) in wind-tunnels.
- Time-accurate store motion integration in computational fluid dynamics (CFD) models.
- Quasi-steady or grid survey (wind-tunnel and/or CFD).

Free drop testing involves making models of the store that are scaled geometrically and in mass properties according to some variation of Froude's scaling laws [5]. The model store is released from the parent aircraft using a mechanism replicating the dynamics of the aircraft's ejection unit. The dynamics of the store during separation is usually captured using photogrammetry with high-speed cameras. Once everything is in place, free drop tests are simple to implement but are limited by the fact that only one trajectory can be acquired during each wind-tunnel run. Another consideration is that each test only reflects the condition being considered for that specific release scenario. Another concern is that the selected scaling law introduces errors that must be accounted for [5] as not all the variables involved in store separation dynamics scale equally.

The CTS technique involves mounting the store on a separate sting that can move and orientate the store independently from the parent aircraft [6]. A balance installed in the store measures its loads. When coupled to a computer computing the store and aircraft equations of motion, a store trajectory can be simulated in a measure-compute-move cycle. The CTS is a well-proven and accurate wind-tunnel technique and many trajectories can be captured efficiently in continuous-loop wind-tunnels. However with the CTS approach each trajectory and release scenario must be simulated in the wind-tunnel, making it costly for large projects. The CTS technique also has the limitation that each test only reflects the condition being considered for that specific release scenario.

Time accurate store separation analyses in CFD are much like the CTS technique except that it is applied within the CFD model. The aircraft and the store are modelled in CFD (typically Navier-Stokes or Euler, but also panel codes for subsonic releases) and the aerodynamic forces and moments on the store are determined and input to a 6-DOF rigid body dynamics program that determines where the store will be positioned relative to the aircraft at the next time step. The mesh of the CFD model is adjusted for the new store/aircraft geometry using one of a range of different techniques, for example, Chimera or spring analogy [5], before the loads on the store are re-computed. Time-accurate CFD can give accurate results in challenging flow fields like those encountered at transonic speeds, but require long computational times for the large number of perturbations as required by MIL-HDBK-244 [2].

The grid survey approach involves positioning the store at a predetermined array of positions and orientations beneath the aircraft and measuring the loads at each point to generate a database of store aerodynamic loads in the vicinity of the aircraft. This database can then be interpolated off-line as part of the 6 degree of freedom (DOF) rigid-body simulation to generate the store trajectories. When applied in wind-tunnels, the same independently mobile sting and store balance used for CTS testing is used for grid surveys. The grid technique can also be used in CFD where the store loads are computed at an array of positions and orientations beneath the aircraft.

The grid technique requires the measurement of a large number of data points in the wind-tunnel or the CFD model in order to survey a multi-dimensional domain under (or ahead for boosted stores) the aircraft that is detailed enough to accurately capture the aerodynamic flow conditions present [8]. However, once the grid database has been captured, a large number of separation scenarios can quickly be run using it, as long as the store external shape is unchanged or reasonably similar. This suits the analysis requirements for MIL-HDBK-244A §5.1.1.2.3.1(g). In this case, the grid survey method can be very efficient in the use of wind-tunnel or CFD time and it is currently the preferred approach for store separation testing [8].

There are a number of key variations in how the grid technique is applied. The usual approach is to scan the store through a volume beneath the carriage position (for ejector released stores) or ahead for rail released stores and at each stop along the scan, sample a number of pitch and yaw combinations. A number of scans are typically required to account for the range of pitch and roll motions of the aircraft during the store release. A similar situation exists ahead of the launch rail for boosted stores. The result is a number of scans that resembles a pyramid with its apex at the store carriage position. This grid is then repeated at each aircraft angle of attack (and Mach number for transonic/supersonic releases). The store aerodynamic coefficients at each point are recorded and this database can be interpolated to provide inputs to the 6-DOF separation analysis program. This approach requires a large number of points to be acquired, necessitating an extensive wind-tunnel test program/CFD analysis and/or various schemes to reduce the number of grid points [9]. One approach to defining the distribution of grid points is the “Snowman” approach presented by Hetreed, et al [10]. Two types of “Snowman” grids were presented; the “Large Snowman” varying the vertical and lateral displacements and the pitch and yaw orientations for a total of 170 points. The “Central Snowman” only varied the vertical displacement (two points) as well as the pitch and yaw combinations for a total of just 18 points. The “Central Snowman” was shown to be less accurate and was used for exploratory cases and CFD analyses.

The aerodynamic coefficients in the presence of the aircraft can be used as is, especially in the case of CFD but in wind-tunnel testing, the small scale of the store model when tested together with the parent aircraft reduces the fidelity of the store aerodynamic data. Integrating a sting with the store model can also affect the results of wind-tunnel CTS tests. Those limitations are addressed using the Influence Coefficient Method (ICM). With ICM, the aircraft induced aerodynamics is deduced by subtracting the known free-stream characteristic of the store (at the same orientation relative to the overall flowfield as obtained from the qualified store aerodynamic database) from the measured loads. When computing the separation trajectory, the aircraft induced aerodynamics is added to the store loads for the current orientation to determine the current aerodynamic coefficients [11]. The aircraft induced aerodynamics identified with the ICM approach can also be used to analyse the separation of other stores with reasonably similar geometry and configuration to the original store.

1.3 The use of Modern Design of Experiments in Store Separation Grid Surveys

The number of independent factors (for example, Mach number, angle of attack (AOA), sideslip angle, aileron angle, neighbouring stores, store position and orientation relative to the aircraft, etc.) that must be investigated to generate grids for store separation analyses results is significant. To analyse all the combinations of independent factors in the traditional "one factor at a time" (OFAT) approach would require a very large number of test or analysis points, which is costly.

This problem was addressed by using the Modern Design of Experiments (MDOE) method to optimise the number of samples required by adjusting more than one factor simultaneously. MDOE is defined as a statistically driven process for planning an experiment (or a test) so that data that can be analysed by statistical methods will be collected, resulting in valid and objective conclusions [13]. MDOE obtains the most data possible out of experimentation thus making the experimental process much more efficient [14].

The basic question that tests or analyses seek to answer is how the input factors X affect the output factors Y. Some of these input factors may be controllable and others are uncontrollable. The analyst is interested in obtaining at least the following data about the system:

- Which of the input factors X are the most important influences on the system response Y?
- What are the relationships between inputs X and the response Y?

MDOE is particularly efficient at deriving black-box models of systems where the response Y of the system to inputs X known as Response Surface Models (RSM) can be predicted with a quantified error tolerance. MDOE is very effective at quantifying the interactions between the input factors.

A MDOE technique (Taguchi matrices) had previously been used for planning grid points for store separation wnd-tunnel tests [10]. Jamison [15] presented the use of RSM in store separation tests, designing a wind-tunnel test grid using the I-Optimal technique. This paper expands on the approach described in Jamison's presentation.

The RSM technique has also been used to design a CFD grid for the well-known Eglin transonic store separation test case [16], where the Uniform Latin Hypercube method was used.

2 The integration of a PGM with the BAE Hawk

2.1 The problem statement

The integration of the Al-Tariq PGM with Hawk advanced jet trainer aircraft required careful evaluation of the aerodynamic and mechanical compatibility of the combination. It is important to verify that all the aircraft and store combinations have acceptable aerodynamic, structural and dynamic characteristics under all flight and ground conditions. This evaluation is performed according to the guidelines of MIL-HDBK-244 [2] and MIL-HDBK-1763 [3] to ensure the safety of the aircraft and store combination and to minimise the risk of functional failures that can jeopardise the project.

Analysing the store separation behaviour behaviour of this combination was a significant task as the PGM has two different warhead options that are geometrically identical (shown in Figure 2) and but differ significantly in the mass properties.

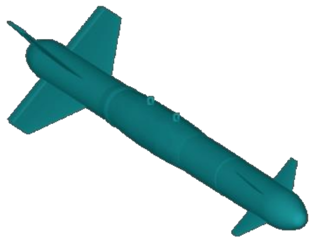

Figure 2. The geometry of the PGM without the wing-kit

A wing-kit can be attached to the PGM (Figure 3) to extend its range considerably. This results in four different versions of the PGM. The lugs are on the opposite side to the wing-kit, so the PGM is carried upside down from the orientation shown in Figure 3. The wings of the PGM deploy more than 1 s after release, so only the wings-closed geometry is considered in the separation analyses.

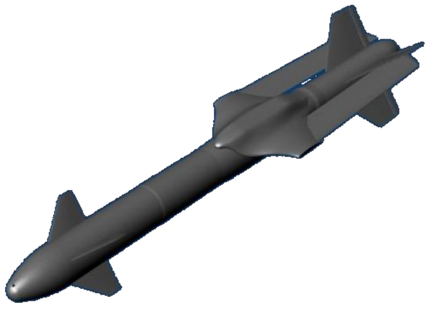

Figure 3. The geometry of the PGM with its wings closed

The Hawk only carries the PGM on the outboard wing stations. A typical Hawk configuration is shown in Figure 4. A range of other stores can be carried along with the PGM, adding up to 128 aircraft/store configurations.

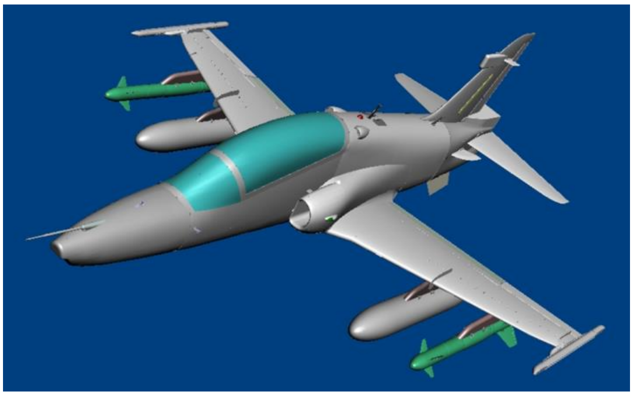

Figure 4. A typical Hawk configuration with the PGM

A wide release/jettison envelope was specified for the Hawk/PGM combination, extending into transonic Mach numbers and covering a range of aircraft dynamics during release. The sensitivity of the separation dynamics to the following parameters was also to be assessed:

- Variation in ejector release unit (ERU) performance.
- Fin misalignments on the store

The following parameters were also investigated with significant tolerances to allow for variants in the PGM family:

- Variation in store mass.
- Variation in the store centre of gravity (CG).

2.2 Preliminary analyses of the PGM separation from the Hawk

Exploratory work on the combination of a Hawk carrying the PGM found that, in the carriage position, there is strong mutual aerodynamic interference between the PGM and the aircraft. There is a significant acceleration of the air flow in the vicinity of the rear fins of the PGM due to its close proximity to the wing. This flow acceleration causes a strong suction effect, resulting in a rapid nose-down pitch rotation of the PGM when it is released. As the Hawk flies at transonic speeds, the accelerated air flow generates a strong shock wave when it decelerates (see Figure 5). The shockwave causes additional loads on the PGM that are not accounted for by subsonic aerodynamic analysis tools. The shockwave makes the store loads very sensitive to orientation during the initial portion of the release trajectory.

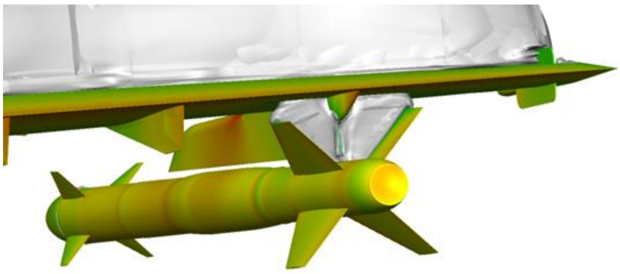

Figure 5. CFD image of the PGM in carriage at a transonic Mach number. The grey surfaces are the shockwaves.

For the initial exploratory PGM release analyses, computational fluid dynamics (CFD) was used to compute the transonic flow field but it was computationally intensive. Another issue that came to the fore is the impact of the release of a heavy store far from the centreline of the Hawk on the aircraft's dynamics. The aircraft can roll significantly during the release and this must be accounted for.

2.3 Selecting the store separation analysis approach for full integration

In selecting the analysis approach it is necessary on one hand to address the non-linear aerodynamic characteristics found in transonic flows while on the other hand, an efficient approach is required to address the 128 configurations and other parameters required to be analysed.

After careful consideration of the merits of using the wind-tunnel versus CFD to characterise the PGM's loads in the immediate vicinity presence of the aircraft at transonic flight conditions, the wind-tunnel was selected due to its productivity for large sets of data. At subsonic flight conditions the CSIR's panel code ARUV is used to calculate the aircraft influence on the store. ARUV is a low-order panel code with a fixed wake and an extensive array of features supporting store separation analyses. It is a further development of the USTORE code developed by the CSIR and which is described in detail in [12].

2.4 The approach for transonic separation analyses

In the grid survey approach the size of the grid can be extensive as the distance of the store below the aircraft increases, since the range of possible store positions and orientations escalates rapidly. This results in a large increase in the wind-tunnel testing effort. Experience has shown that the panel code ARUV provides accurate flowfield inputs for predicting store loads at transonic speeds as long as the store is outside the region of interacting transonic flows. As those flow regions are located quite close to the wing, there is a reasonable expectation that ARUV could be used to predict the store trajectories from 0.5 m below the carriage position onwards. The wind-tunnel is therefore required to measure data for the first 0.5 m of the store's translation below the carriage position. This approach dramatically reduces the amount of wind-tunnel testing required. For convenience the region close to the wing where interacting transonic flow fields could be encountered is labelled the near-field and the region beyond that is labelled the far-field. The near-field and far-field is illustrated in Figure 6.

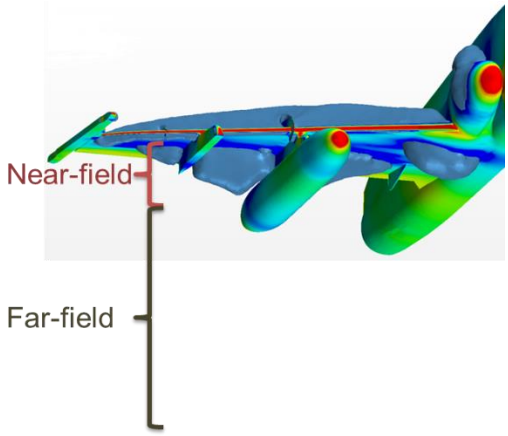

Figure 6. Illustration of the concepts of near and far fields. The gray bubbles indicate regions of supersonic flow

The ARUV panel code was used as a first approximation to perform preliminary analyses of all the release scenarios and configurations (see Figure 7). These screening analyses addressed the following factors:

- The Hawk configurations that should be tested in the wind-tunnel
- The range of parent aircraft AOA, sideslip and aileron angles that should be tested
- The extent of the release "corridor" and the possible range of orientations adopted by the store relative to the aircraft.

The preliminary analyses showed that the store on the inboard pylon has a significant impact on the release dynamics of the PGM, while the presence of a wingtip AAM has a much smaller impact. Due to its close proximity to the large rear fins of the PGM, the angle of the aircraft's aileron also has a notable impact on the separation dynamics and had to be included as a parameter.

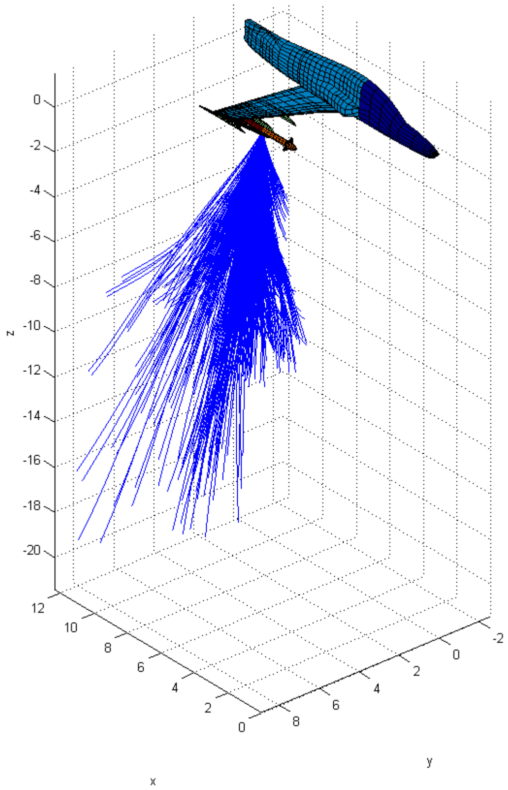

Figure 7. Preliminary investigation of the possible separation "corridor" for one PGM variant in all possible scenarios

2.5 Using MDOE to design and analyse the grid survey

It was decided to use the MDOE software package called Design-Expert version 8.0.7.1 from Stat-Ease Inc. to develop and analyse the grid survey points. There are many different MDOE RSM design options to choose from with differing implications. Other authors discussed in §1.3 have used Taguchi and Uniform Latin Hypercube matrices to generate grid points.

The D-optimal RSM design type was selected as they are sufficiently flexible to accommodate multiple real-world constraints relating to the pyramidal shape of the grid volume and are very efficient (they minimise the number of samples required) compared with other experimental designs. There are different types of D-optimal algorithms available, but the IV-optimal criteria (also known as the I-optimal) were selected for designing the grids. This criterion seeks to minimise the prediction variance of the RSM across the entire design space. A good motivation for the use of I-optimal designs over other D-optimal designs is provided in [17].

The grid survey store positions take the form of truncated pyramids due to the nature of the store separation "corridors" (see Figure 7), which complicates the MDOE test planning. However, Design-Expert has powerful tools for generating constrained matrices which was utilized to generate the grid survey points.

4 Validating the use of MDOE for grid experiments in store separation analyses

4.1 The MDOE grid test case

It is not immediately clear how best to design grids using MDOE and how accurately the grids capture rapidly changing nonlinear flow features. To efficiently investigate this, a generic test case was generated and analysed using the ARUV panel code which is very fast and well validated for subsonic analyses.

The test case is the N_1B_2W wing-body with a 45° swept wing and a single underwing pylon and the finned ogive-cylinder large force model described in [18]. In order to intensify the aerodynamic interference between the aircraft and the store to levels approaching that of the Hawk/PGM, the tip of the store was moved forward to 16.5" model scale (or 8.382 m full-scale). The depth of the pylon was reduced by 50 mm (0.098" model scale) and the carriage position of the store axis was located 0.657 m (1.29" model scale) below the wing mean chord. The ARUV model is shown in Figure 8.

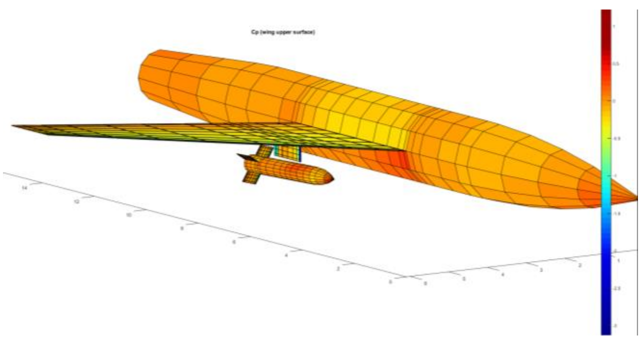

Figure 8. The ARUV model of the MDOE test case with the store in an arbitrary post-release position

A preliminary analysis similar to what is done for formal projects was done to identify the range of store release scenarios for a typical ejector released store. A typical separation trajectory is shown in Figure 9.

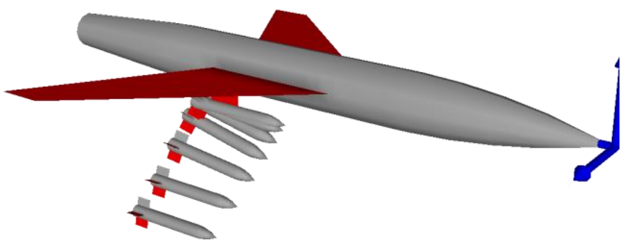

Figure 9. A typical separation trajectory from the screening analyses

This preliminary analysis identified the range of trimmed aircraft release states and the combinations of positions and orientations that the store typically attains. Typically when transonic scenarios are considered, the preliminary analyses are performed using the ARUV panel code and then a tolerance is added to the results used to design the grid. A typical result showing the pitch motion of the store relative to the aircraft for all release scenarios is shown in Figure 10. This result shows that the store rotates significantly close to the aircraft due to the strong aerodynamic interference.

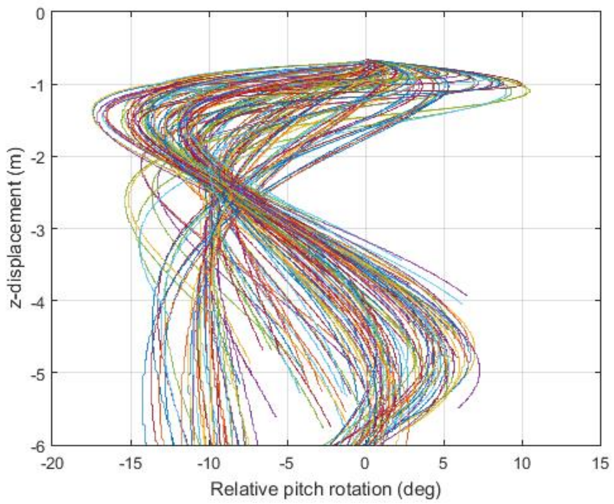

Figure 10. Store pitch rotations relative to the aircraft for all release scenarios considered in the screening analyses (positive pitch rotation is store nose-up)

4.2 Generating the MDOE grids

The aircraft parameters that will be varied for the grid are listed in Table 1. As this is a test case, only two Mach numbers are used. The range of angles of attack (AOA) includes the full range of launch profiles from tosses to dives.

Table 1. Aircraft release condition grid parameters

Mach number	0.65	0.75
Minimum AOA (deg)	0.68	0.49
Maximum AOA (deg)	6.02	5.78

The positions and orientations of the store relative to the parent aircraft are presented in Table 2. These parameters are presented as minimum and maximum values at the top and bottom of the separation "pyramid" beneath the aircraft pylon. dX and dY are x- and y-displacements from the carriage position. The x- displacement is positive towards the rear of the aircraft and y-displacement is positive to the right of the aircraft and z is positive upwards. The positive senses of the angles follow the right hand rule. A maximum z-distance of -4 m was selected as the aircraft aerodynamic influence is small at that distance below the fuselage centreline.

Table 2. Store position and orientation relative to the aircraft grid parameters

Posn./orient.	Top min	Top max	Bottom min	Bottom max
dX (m)	-0.05	0.10	-4.56	1.68
dY (m)	-0.145	0.185	-0.518	2.602
z (m)	-0.657	-0.657	-4.000	-4.000
yaw (deg)	-6.60	0.24	-6.60	6.00
pitch (deg)	-21.6	13.2	-21.6	13.2
roll (deg)	-12.0	2.4	-40.0	10.0

The parameters and their limits were entered into the Design-Expert MDOE software. Constraint equations were entered to ensure that Design-Expert only generates grid parameter combinations that lie within the pyramidal grid shape.

The next decision that the user must make is the order of the response surface model that

Design-Expert will attempt to fit to the grid. As the order of model increases, the number of grid points increases significantly. Design-Expert permits the user to fit different order models to each parameter. Table 3 presents the model order allocated to each parameter. The Mach number and AOA are linear in this case as the ARUV panel code is based on a linear aerodynamic formulation. The z-translation is quartic as the aerodynamic parameters are expected to change in a complex manner along that axis. The other parameters are cubic to force the I-Optimal algorithm to sample the space between the limits. Note that the final response surfaces only fit models that can be justified by the data so a grid generated to model a cubic parameter will not necessarily cause a cubic model to be fitted to that parameter.

To limit the number of samples in the grid, high-order interactions between more than three variables were disabled. Experience has shown that these interactions are usually insignificant.

Table 3. Response surface model order allocated to each parameter

Parameter	Model order
Mach number	Linear
AOA (deg)	Linear
dX (m)	Cubic
dY (m)	Cubic
z (m)	Quartic
yaw (deg)	Cubic
pitch (deg)	Cubic
roll (deg)	Cubic

A number of different approaches to generating the MDOE grid were explored to obtain an understanding of the relative merits.

1. I-Optimal matrix of all the parameters in Table 3. **[8-ParamD]**
2. I-Optimal matrices of Mach and AOA and the position/orientation parameters were generated separately. The position/orientation grid is repeated at each Mach/AOA combination. **[RepeatOrient]**
3. The I-Optimal matrix of all the parameters in Table 3 except the roll orientation. The effect of the store roll angle is corrected analytically. **[7-ParamD]**

Note that in all cases the grids generated by the MDOE I-Optimal algorithm are modified manually in two ways:

1. A point at the carriage position is added for each of the four limit combinations and the midpoint of Mach and AOA. This is done since the I-Optimal algorithm does not automatically place a point at the carriage position and it is important to ensure a good fit at that position.
2. For grid points at the carriage z-position (0.657 m) the values for the other position/orientation values are reduced since the motion is limited at carriage and any significant rotations causes collisions between the store and the aircraft.

4.3 Comparing the MDOE grids

A test matrix of 254 points distributed throughout the grid was generated independently of the other matrices and is used to quantify the performance of the three MDOE approaches. In each case the grid was computed using ARUV and a collision detection algorithm was used to verify that none of the grid points had the store intersecting with the aircraft. The results were imported into Design-Expert for response surfaces to be fitted to each of the store static aerodynamic coefficients. A range of tools are provided to guide the fitting of the response surface to the data and to assess the quality of each fit. An example of the resulting response surfaces is plotted in Figure 11, showing the large increase in nose-down pitching moment due to aircraft interference near the carriage position (z = -0.657 m).

Table 4. Results for the test matrix with different MDOE grids

Grid type	**[8-ParamD]**			**[RepeatOrient]**			**[7-ParamD]**		
Grid size (no. points)	191			200			114		
Store aero coefficient	**Average Error (%max Value)**	**Standard deviation of error (%)**	**Maxi-mum error (%)**	**Average Error (%max Value)**	**Standard deviation of error (%)**	**Maxi-mum error (%)**	**Average Error (%max Value)**	**Standard deviation of error (%)**	**Maxi-mum error (%)**
CY	0.60	0.86	4.5	1.66	2.11	6.9	0.58	0.89	6.0
CZ	0.91	1.46	10.6	7.03	8.94	25.1	0.69	1.11	10.8
CMX	3.13	6.52	57.0	3.43	6.35	63.5	2.77	6.78	67.2
CMY	2.64	4.18	36.0	6.20	8.09	35.1	1.80	2.79	15.0
CMZ	2.29	3.53	21.7	2.96	4.16	17.2	1.89	2.73	16.2

The response surfaces were used to compute results for the test matrix and the errors were calculated accordingly. The results are summarised in Table 4. The 7ParamD grid design performed the best, for the number of grid points and also the lowest average errors and standard deviation. Removing the roll parameter reduces the grid size significantly while simultaneously improving the modelling resolution of the grid. Repeating the position and orientation grid for different Mach number and AOA combinations may be attractive for wind-tunnel grid tests as this limits the number of wind-tunnel condition transitions but it does perform the worst of the three alternatives. Removing the roll parameter while maintaining the number of grid points in the RepeatOrient model may improve its accuracy.

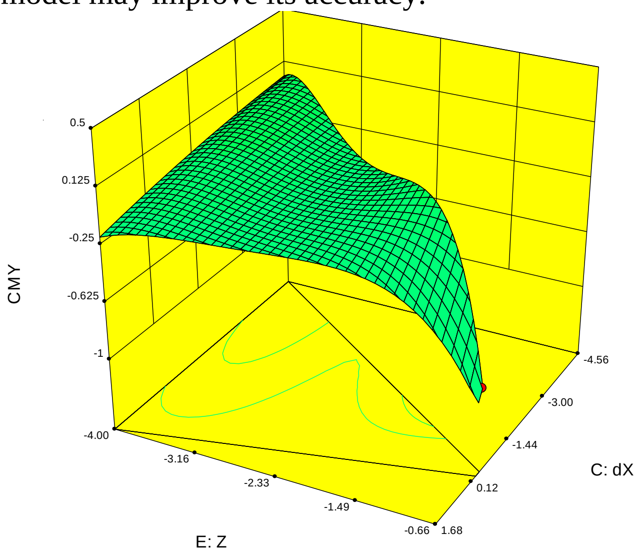

Figure 11. A typical response surface fitted to the store yawing moment (CMY) as a function of dX and z-position. All other positions and orientations are zero and Mach = 0.75, AOA = 0.49°

A comparison of the response surface model results with the exact results for a vertical z-position traverse beneath the carriage position is presented in Figure 12.

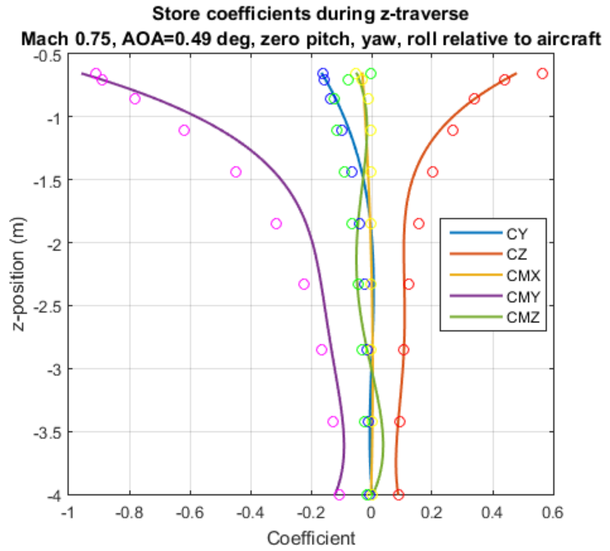

Figure 12. A comparison of the store body-axis aerodynamic coefficients during a z-axis traverse beneath the carriage position

Achieving this level of accuracy with just 114 grid points to characterise 7 parameters is a significant step forward in test efficiency. As a comparison, a traditional one-factor-at-a-time (OFAT) grid was generated with three levels for each parameter. Including the carriage points at each corner of Mach and AOA like the MDOE grids, this grid required 741 points to characterise 7 parameters. A RSM model was fitted to the OFAT results and the accuracy of this model against the test matrix is presented in Table 5. Despite the much larger grid size in samples, the accuracy of the OFAT RSM model is much worse due to the fact that only three levels were tested for each parameter which means that the maximum model order for any parameter is quadratic. Adding additional levels per parameter to increase accuracy will increase the OFAT grid size significantly.

Table 5. Results for the test matrix with the OFAT grid

Grid type	OFAT		
Grid size (no. points)	741		
Store aero coefficient	Average Error (%max Value)	Standard deviation of error (%)	Max-imum error (%)
CY	4.85	6.35	21.8
CZ	8.30	11.20	32.0
CMX	13.46	7.26	112.8
CMY	9.35	13.18	74.2
CMZ	5.22	7.67	39.3

Note that while the RSMs were fitted to the store aerodynamic coefficients in flow fields distorted by the influence of the aircraft, the same RSM procedure can be applied to characterise the aircraft induced delta coefficients in the ICM technique.

5 Applying MDOE grids to the Hawk/PGM store separation

5.1 Test design

Since the wind-tunnel takes a finite amount of time to change aircraft parameters like Mach AOA, etc, the RepeatOrient approach described in §4.2 to grid design was be adopted to minimise running time. The store roll orientation was fixed at the carriage roll orientation so the store position/orientation grid matrix addressed five degrees of freedom. The aerodynamic effect of store roll was addressed analytically in the store separation simulations.

The store position/orientation grid was repeated for each parent aircraft test point. The order of the position/orientation grid test points was randomised to minimise bias errors. MDOE was also used to plan the test points for the parent aircraft.

In order to verify the response surface models generated from the grid survey data, additional MDOE verification test points were included.

5.1 The wind-tunnel test setup

The wind-tunnel model of the Hawk's geometry was simplified with all features considered to have minimal impact on the flow field at the outboard wing station (for example the tail surfaces) being removed.

An optical system was built into the left outboard pylon to measure the store position and orientation relative to the parent aircraft so as to provide a zero reference for the store position and orientation at relative to the aircraft at each aircraft test condition.

The wind-tunnel models of the store were installed on a 14 mm 6-component balance and fitted to the CTS system in the CSIR's Medium Speed Wind-Tunnel (MSWT). This is a closed circuit, variable density, transonic wind tunnel [19]. Its Mach number ranges 0.25 to 1.5 with stagnation pressures varying from 20 kPa to 250 kPa. The Reynolds number can be changed by modifying the pressure. The test section has a 1.5 m x 1.5 m square cross section and is 4.5 m long. All four walls are longitudinally slotted with a total porosity of 5%. The MSWT has a CTS rig. This is a six degree of freedom system used for store separation tests. It can be used in conjunction with either of the other support systems in the wind-tunnel. The aerodynamic loads on the store are measured using five- or six-component strain gauge balance mounted in the store model on the CTS rig.

Disc-type boundary layer transition treatment was applied to all the aerodynamic surfaces to ensure that the boundary layers were turbulent at the wind-tunnel test conditions.

5.2 The five-hole probe test

The flow field in a single plane beneath the pylon was investigated using a five-hole probe to verify two key assumptions in the test design:

- That the ARUV panel code predicts the far field accurately
- That a boundary between the near and far fields can be set at 0.5 m

The results showed that ARUV has average errors less than 2% when the store is

0.5 m or more below the carriage position, validating the approach described in §2.4.

5.3 The grid wind-tunnel test

All the wind-tunnel test points were successfully acquired. Some challenges were encountered with ensuring conservative clearances between the parent and store models resulting in the modification of some store positions/orientations compared with what was planned.

As the test points were randomised, it was difficult to monitor trends in the data as it was being acquired. The results were monitored by comparing them with results from ARUV for the same test condition. The data analysis tools in the MDOE software Design-Expert were also used to check for outliers. A typical test configuration is shown in Figure 13.

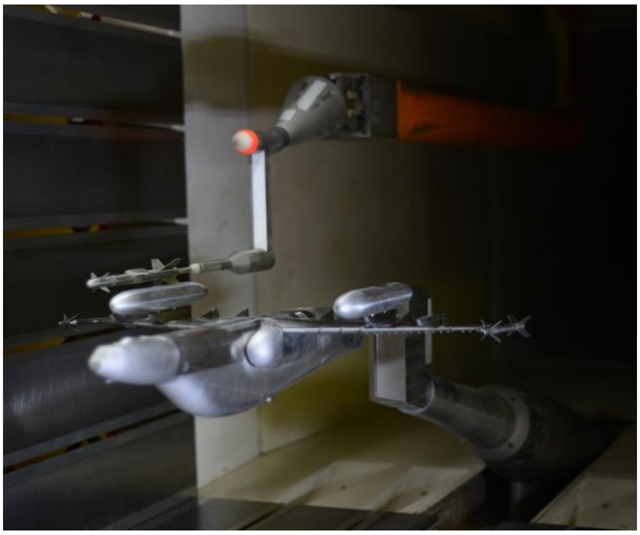

Figure 13. Wind-tunnel test of the PGM with the Hawk aircraft fitted with drop tanks

6 Wind-tunnel test results

The wind-tunnel data was imported into the Design-Expert software and the RSM polynomial models were fitted. It was noted that there are many significant interactions between the test factors. Quantifying these interactions is one of the strengths of the DOE approach and is very important in this application.

The additional grid data points that were included for verification were used to test the validity of the response surfaces. These points were located far from the MDOE test points and approximated a possible store trajectory. The response surface does not produce a "perfect" fit of the wind-tunnel data but it does capture the main phenomena of a multi-dimensional problem with minimal test points that make the wind-tunnel test affordable.

6 Separation analyses

6.1 The automated separation analysis approach

As the separation dynamics of a large number of configurations have to be analysed for a large number of scenarios, the total number of separation analyses required is significant. Consideration of the configurations required to be analysed for separation resulted in the configurations being grouped into a smaller number of "aerodynamic" configurations by considering the direct aerodynamic impact on the store being released. The indirect aerodynamic effect of the stores on the centreline or opposite side of the aircraft manifests itself in the mass properties of the aircraft and the resulting impact on the aircraft's flight condition (angle of attack, sideslip and aileron angles) and its dynamics during the separation. With the above assumptions, the 128 aircraft configurations were reduced to 8 "aerodynamic" configurations for each PGM geometric variant.

The CSIR has an automated store separation analysis process described in [4] where scripts of separation analyses for each "aerodynamic" configuration are prepared using Excel spreadsheets. The automated separation analysis code system MRCS is used to analyse the script, presenting the results in terms of release scores, grading each separation according to clear quantitative criteria. All the data for each release in the script is retained to facilitate investigation should the analyst wish to follow up on an anomaly. The overall approach is summarized in Figure 14.

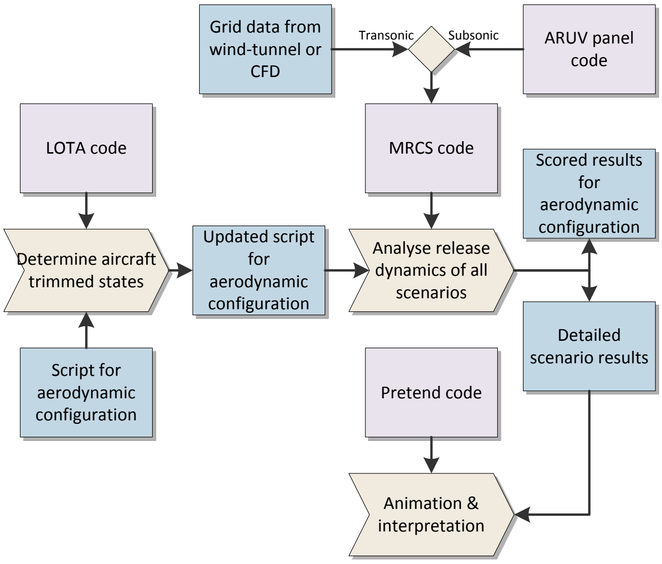

Figure 14. Summary of the automated separation analysis approach [4]

The RSMs from the wind-tunnel tests were inserted into the MRCS code as a subroutine and were used to supply the store aerodynamic coefficients while it was within the transonic near-field of the parent aircraft. The ARUV panel code was used to continue the trajectory outside the transonic interference regime using a segmented lookup table of the store aerodynamics derived from the store's qualified aerodynamic database.

6.2 The separation analysis results

A typical separation analysis result is shown in Figure 15. The consolidated results were used to define a preliminary safe release envelope for the PGM variants from all the aircraft configurations. A limited matrix of flight test releases was specified to verify the results.

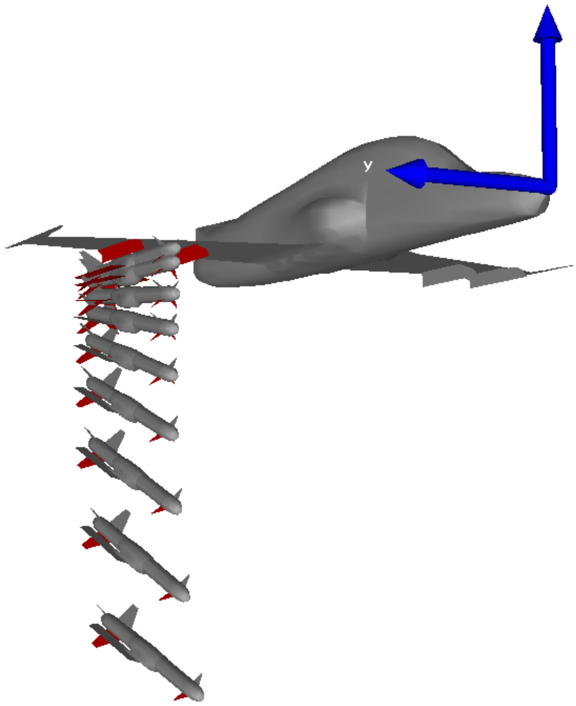

Figure 15. A typical PGM separation trajectory from the Hawk

6.3 Closing the loop with flight tests

Instrumented PGMs were released from on instrumented aircraft to verify the predicted separation dynamics. The maximum altitude release conditions was tested and assessed initially before the go-ahead was given to the highest dynamic pressure releases. A flight test release is shown in Figure 16. Once corrections were determined for the ejector release unit impulse and aircraft rigid-body and structural dynamics, the predicted separation analysis trajectories correlated very well with the flight test results as shown in Figure 17.

Figure 16. Releasing the PGM from the Hawk in the configuration without inboard or wing-tip stores

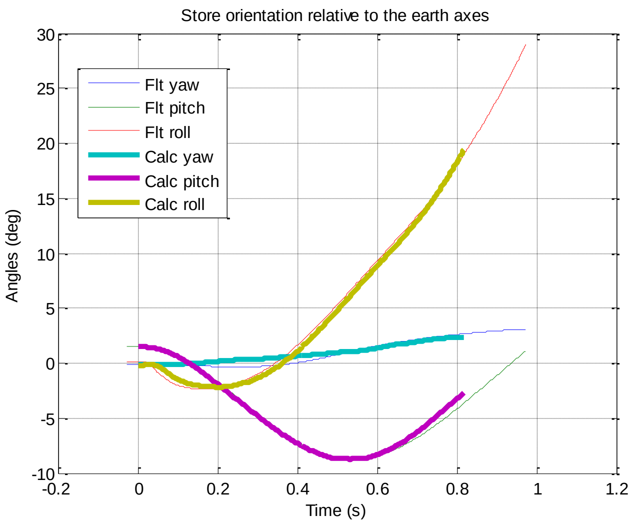

Figure 17. A typical comparison between flight test and calculated store orientations

The corrections obtained from the flight tests were incorporated into the analysis software and the separation runs were repeated, resulting in the final recommendations for the safe release envelope and the applicable limitations for each store configuration.

6 Conclusions

The challenges of a significant PGM integration project prompted new thinking on how to optimise the design of the grids used to characterise the flow fields under aircraft for store separation analyses. MDOE has been used extensively to efficiently characterise complex phenomena in a variety of fields including aerospace and it made sense to investigate its use in store separation analysis.

The use of MDOE for designing and analysing store separation grids was investigated analytically using a simple test case modelled with a panel code. This investigation showed that grids designed using the I-optimal RSM technique could characterise a very complex, nonlinear, multivariate grid with acceptable accuracy using a fraction of the samples that a traditional (OFAT) approach would have required. For most store separation cases it should not be necessary to characterise store roll orientation as an independent grid parameter as this can be corrected analytically.

It is best to generate an I-optimal grid with all the applicable parameters at once as this results in accurate models for the fewest grid samples. The efficiency of this approach makes it viable to compute grids using CFD and the CSIR has done this on subsequent store separation projects.

It is sometimes not feasible to generate an I-optimal grid with all the applicable parameters at once. This is the case for wind-tunnel tests where the finite time required to change the tunnel test condition or the model configuration is a major constraint. In that case, the store position and orientation grid and the aircraft parameters matrix can be generated using MDOE software separately. The store position/orientation grid is then repeated at each aircraft parameter test point. This hybrid MDOE approach is still more efficient and accurate than the OFAT approach. This approach was successfully utilised for the PGM/Hawk case study described in this paper.

This case study shows that MDOE is a powerful extension to the grid technique for characterising the interference flow field that the store must traverse after release that improves accuracy for a given number of samples, reduces costs and makes the use of CFD for transonic grid analyses viable.

7 Acknowledgements

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8 Contact Author Email Address

mailto: kjamison@csir.co.za

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