EVALUATING THE RELEASE OF A LARGE STORE FROM THE BAE HAWK MK120

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Keywords: *Store release, panel code, CFD*

Abstract

The analysis of the release of a large store from the outboard pylon of the BAE Hawk Mk120 is described as a case study. The process adopted to address this challenge included using both the ARUV panel code and the CFD-FASTRAN Navier-Stokes Computational Fluid Dynamics (CFD) code where applicable to calculate the carriage loads; calculating the rigid and flexible structural dynamic responses from the ejection forces and using a three-component look-up table to model the loads on the store in free-flight through the aircraft flowfield computed by ARUV.

Nomenclature

ARUV	Aeronautics Research Unit Vortex-doublet
CG	Centre of Gravity
CAD	Computer-aided Design
CFD	Computational Fluid Dynamics
Cm	Pitching moment coefficient
CN	Normal force coefficient
CSIR	Council for Scientific and Industrial Research
CTS	Captive Trajectory System
ERU	Ejector Release Unit
FEM	Finite Element Model
Mk	Mark
mm	millimetre
ms	millisecond
OEM	Original Equipment Manufacturer
PC	Personal Computer
PGM	Precision Guided Munition
SAAF	South African Air Force
SMURF	Side Mounted Unit Root Fin
3D	Three-dimensional

1 Introduction

The integration of stores with combat aircraft always requires careful investigation as the store introduces significant (and often adverse) changes to the configuration's mass, inertia, aerodynamics and structure. When the store is released from the aircraft, it has to traverse a flowfield that is perturbed by the presence of the aircraft. The changes in the flowfield can cause the store to behave very differently compared with undisturbed air. There have been accidents where stores have unexpectedly struck the host aircraft and this has resulted in the regulatory requirement for store release analyses.

The CSIR was contracted to perform the carriage and safe separation analysis for the Katleho Precision Guided Munition (PGM) integrated with the BAE Hawk Mk120 of the South African Air Force (SAAF). The Katleho is a variant of a family of PGMs being developed by Denel Dynamics (Pty) Ltd. As the Katleho is a large and long store, it interferes with the Hawk's flaps on the inboard pylon and can only be carried on the outboard pylon. For the carriage and release tests the prototype Katleho will be counterbalanced by an inert Mk82 bomb on the opposite pylon as shown in Fig. 1.

Fig. 1. Hawk Mk120 with the prototype Katleho PGM

It is the first time that a store release certification is being done on the Hawk Mk120 in South Africa and a methodical and prudent approach is required. The regulatory context for military stores carriage and release is described in MIL-HDBK-244A [1], which calls up MIL-HDBK-1763 [2]. The regulations state that carriage and separation analyses must be done but do not prescribe the tools to be used, stating the following:

> "*No one technique will suffice for all cases. Rather, the analyst must examine the particular case to be analyzed and select the technique that, in his opinion, offers the most advantages for his particular situation.*" [2], clause 4.1.4.5.1.

The range of tools available for performing store release analyses is extensive, but the predominant tools include wind-tunnel captive trajectory systems (CTS), grid-based CFD (Navier-Stokes and Euler solvers) and panel-based CFD. Within the category of CFD methods, the store itself can be modelled in a variety of ways ranging from full models (panel/Euler/Navier-Stokes) through engineering-level codes to look-up tables. It is clear that panel-type codes are still used to generate the aircraft flowfield for the bulk of store-release investigations and have acceptable accuracy even at transonic Mach numbers (see [3], [4] for examples). If the initial analyses indicate that the release could be critical (the miss distance between the store and the aircraft is small) or the flowfield is strongly non-linear then CTS and/or grid-based CFD tools are used to obtain more precise results.

2 The overall process followed for the integration of Katleho with the Hawk Mk120

The CSIR was contracted perform an engineering investigation into four aspects of the integration of the Katleho PGM with the Hawk Mk120 as shown in Fig. 2. The work followed the requirements of [2] and included:

1. Evaluating the carriage loads imposed by the Katleho on the aircraft structure over the full flight envelope.
2. Evaluating the aeroelastic characteristics of the configuration to ensure that it is free from flutter.
3. Evaluating the performance and handling of the configuration to verify that it can be flown safely throughout its envelope.
4. Evaluating the store release characteristics over the full jettison envelope.

This paper focuses on the store release evaluation.

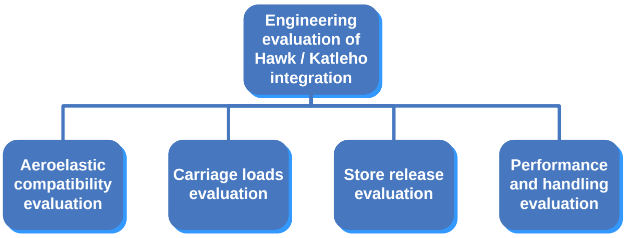

Fig. 2. The four facets of the Hawk Mk120 / Katleho integration that were evaluated

As the project was done without direct Original Equipment Manufacturer (OEM) involvement, a careful approach was followed to develop the required knowledge base for this project and future integration exercises with the Hawk. This was the CSIR's first aerodynamic analysis of the Hawk Mk120 and information regarding the Hawk's geometry and aerodynamic characteristics had to be acquired as part of the project.

The Hawk Mk120's ejection and structural dynamic characteristics were also unknown and had to be assessed. The process leading up to the store release analysis is summarised in Fig. 3. Details on each step in the process are presented in the following chapters.

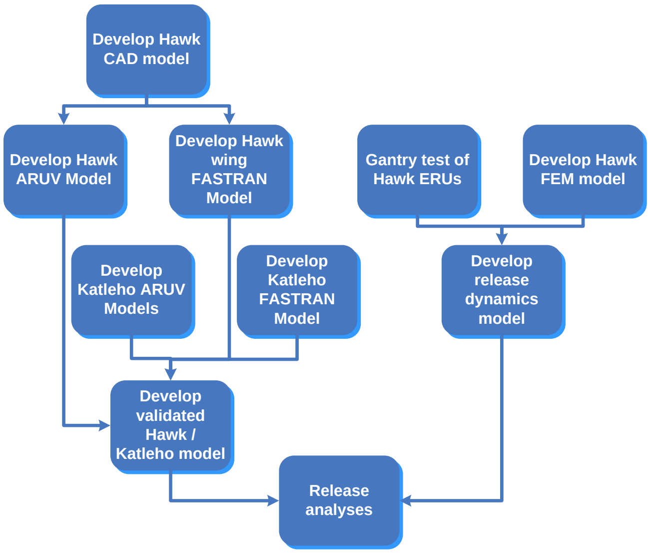

Fig. 3. The process that was followed leading up to the store release analysis

2 The release analysis requirements

The requirements for the release analysis was presented in a specification stating the desired release points for the Katleho flight tests and the carriage flight envelope. It is highly desirable from a safety perspective that the safe jettison envelope matches the carriage envelope as far as possible.

The desired normal and lateral acceleration limits and the roll rate limits for the safe jettison envelope are also specified.

3 Code selection for store carriage and release analysis

When selecting tools for a particular project, the hierarchy of store separation difficulty identified by Cenko, [5] should be considered. Cenko [5], makes it clear that CFD alone should only be used for configurations that are low-risk, even today. It is still vital to obtain experimental data to validate CFD models of the store or aircraft before proceeding with more challenging situations. Cenko's conclusions were made with reference to all CFD technologies (panel, Euler and Navier-Stokes).

No wind-tunnel model of the Hawk Mk120 was available to perform wind-tunnel CTS tests in a timely manner for this project. CFD tools were by default the only means available while much of the required confidence building measures would have to come from the overall process adopted.

The project required the following from the store release analysis tool:

1. The analysis of a large number of carriage load and release test points to open up a safe carriage and jettison envelope.
2. The ability to handle a store with highly nonlinear aerodynamics.
3. The ability to address the close interaction between the aircraft and store aerodynamics in the carriage position.
4. The ability to produce accurate results for store releases at low transonic speeds.
5. Validated and have a good track record in application.

The CSIR has a Navier-Stokes CFD store release analysis tool, CFD-FASTRAN [6] that meets most of the requirements. CFD-FASTRAN, however, is time-consuming to run with the computational resources at CSIR's disposal. It would not be able to economically produce the number of analyses required for the project.

CSIR's other store release analysis tool is ARUV, a legacy panel code with roots dating back to the 1970's. ARUV also meets most of the requirements, but is not formulated to explicitly handle transonic flows. Experience in the CSIR and in the industry in general ([10] for example) is that panel methods can still generate good trajectories at low transonic flows. ARUV's major advantage is that it is relatively quick to set up an analysis and it is very fast (a full store release trajectory analysis runs in seconds on a desktop PC).

It was decided to use both ARUV and CFD-FASTRAN for the Hawk Mk120/Katleho integration project. ARUV would be used for the subsonic analyses and to generate the wider aircraft flowfield for all the analyses and CFD-FASTRAN would be used instead of ARUV to compute the carriage loads at transonic speeds where shockwaves dominate the flowfield.

3.1 The ARUV store release panel code

ARUV is a low-order panel code with a fixed wake and an extensive array of features supporting store release analyses. It is a further development of the USTORE code developed by the CSIR during the 1970's and 1980's. The panel code shares its underlying theoretical basis with USTORE which is described in detail in [11] and is outlined briefly here.

The panel method uses the concepts introduced in Woodward's USSAERO code [12] and is based on linear potential flow theory. The surface of the aircraft and its stores are discretised into a large number of panels. The body components have constant source distributions and as a result cannot generate lift. The panels on the lifting surfaces incorporate linearly varying vortex distributions to represent lift and linearly varying source distributions to represent the thickness distribution. Both the upper and lower wing panels lie on the mean wing plane and the boundary conditions are applied in this plane. Round leading edges are treated using a special leading edge source strength that is related to the actual leading edge radius. This formulation of the panel method is both a strength as panelling is simple and the code itself is very fast and a liability when modelling aircraft with integrated lifting fuselages.

Models are divided into lifting surfaces (wings, fins, etc) and non-lifting bodies which can have an arbitrary shape. There are no special restrictions on the geometry of the store. The ARUV model of the Hawk Mk120 is shown in Fig. 4.

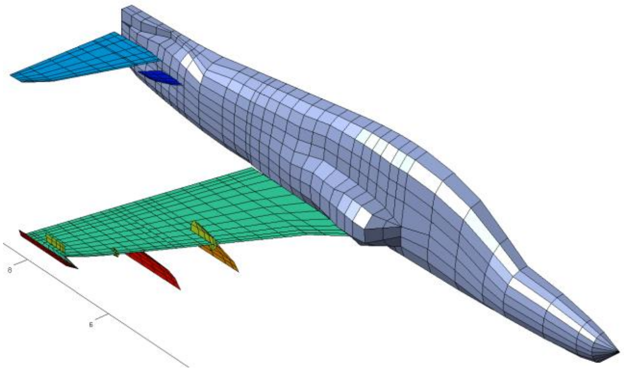

Fig. 4. ARUV model of the BAE Hawk Mk120.

Compressibility effects are taken into account using a Goethert-type rule but viscosity effects are excluded. ARUV performs well for subsonic, low angle-of-attack analyses and reasonably well for low transonic cases, depending on the configuration. The results of a validation exercise comparing the Hawk Mk120 model with flight test data is shown in Fig. 6.

ARUV has a wide range of features applicable to store release analysis (it models aircraft/store dynamics, ejectors, rail launchers, boosted stores, etc) and can either model the store as a separate panelled airframe translating within the perturbed flowfield of the parent aircraft or it can use look-up tables of the store aerodynamics derived from other sources. Multi-component look-up tables can be used to address the fact that the flowfield can change significantly along the length of the store.

The aircraft flowfield can be recalculated at every time step or a flow grid can be generated through which the store is translated. External data sources (wind-tunnels or CFD) can be used to provide the flow grid data.

3.2 The CFD-FASTRAN Navier-Stokes CFD code

CFD-FASTRAN version 2007 was used for the CFD analyses to validate ARUV and to generate the carriage loads at transonic speeds. This Navier-Stokes code uses overset structured grids and is described in [6]. CFD-FASTRAN has been used in a number of projects at the CSIR ([7] for example) with very good results.

3.3 The AnalyseEjection ejection dynamics model

The AnalyseEjection program was developed in Matlab^{TM} for this project to translate the store from its carriage position to the point where it leaves the ejector release unit (ERU) pistons. A block diagram of the model showing the factors accounted for in the model and the outputs is presented in Fig. 5.

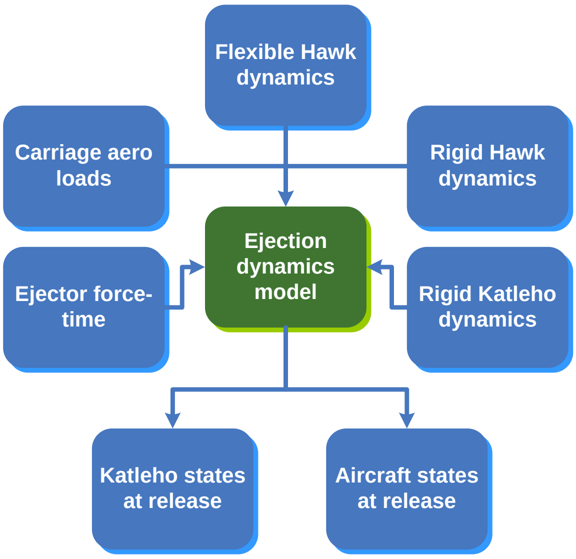

Fig. 5. Block diagram of the ejection dynamics model

The program also accounts for the release initial conditions (normal and lateral accelerations, roll rate, altitude and Mach number) and caters for the different perturbations investigated during sensitivity analysis such as changes to the store centre of gravity (CG) position and ERU forces. The aerodynamic interaction between the store and the aircraft is not modelled. The aerodynamic coefficients of the store in the carriage position determined by ARUV or CFD-FASTRAN are input and the aerodynamic loads are assumed constant for the 40 ms to 50 ms duration of the ejection.

The flexible dynamics of the aircraft structure is analysed using modal superposition in a manner similar to that described in [8]. The store is modelled as a rigid body free to move in all six degrees of freedom in response to the carriage air loads, the ejection forces and gravity. The aircraft has three rigid degrees of freedom; plunge and sideways translation and roll rotation (the store CG is close to the aircraft CG).

4 Development and validation of the models

The Hawk Mk120 and Katleho models were first developed and validated separately in ARUV. This was done to gain confidence in the models, and if necessary, apply modifications.

4.1 Hawk Mk120 Geometry

In order to perform stores release clearance work on the Hawk Mk120, a 3D computer-aided design (CAD) model of the Hawk was required. The geometry is required for both numerical and experimental aerodynamic studies. A complete CAD model of the exterior surface of the Hawk Mk120 was generated that included all relevant external geometrical features. Several sources were used for the development of the geometry; a limited CAD model, photogrammetry measurements on the full-scale aircraft, detailed measurements and 3D scans on smaller details.

4.2 The ARUV model of the Hawk Mk120

For the actual release simulations the full Hawk Mk120 geometry was generated in ARUV. This geometry was constructed with all the relevant detailed including the SMURFS, wing fences, flap hinges and pylons.

The fuselage is modelled as a non-lifting body, with the intakes faired over. The wing is built up in two parts, an inboard and an outboard section, split at the span wise position where the flaps and ailerons meet. This allows for the modelling of the control surfaces, whose hinge lines have different chord wise positions. The airfoil co-ordinates were extracted from the CAD geometry. The wing fences are simple flat plates. The pylons and flap hinges are modelled with the correct thickness distribution. The ARUV model is shown in Fig. 4.

The clean Hawk Mk120 geometry was validated by comparing the trim angle of attack and stabiliser angles against flight test data and the aircraft manual for a range of Mach numbers. Good correlations were obtained as shown in Fig. 6.

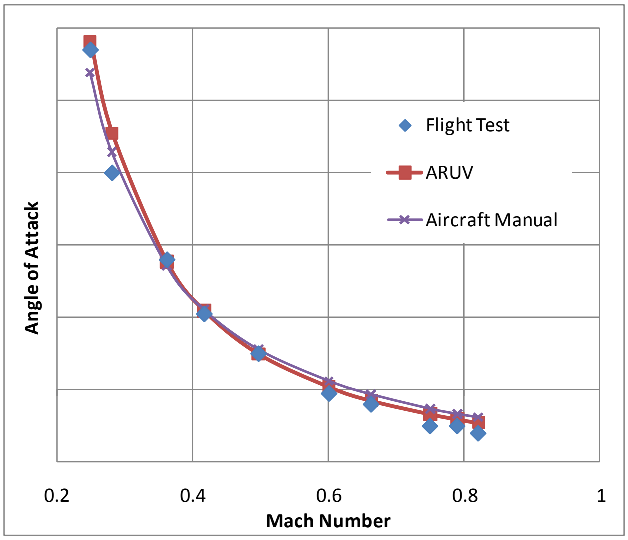

Fig. 6. Comparison of predicted trimmed angle of attack against flight test data

To validate the wing flowfields at transonic speeds, a separate ARUV model of the Hawk Mk120 wing was created to match the CFD-FASTRAN model geometrically. The wing pressure distributions at Mach 0.8 were compared with those obtained from CFD-FASTRAN. The results showed that while ARUV predicted the overall lift quite accurately there were significant differences in the pressure distributions on the upper surface of the wing due to transonic effects not modelled by ARUV. The correlations of the pressure distributions on the lower surface of the wing were good. This exercise clearly demonstrated ARUV's limitations when a shockwave is present in the flowfield.

4.3 The ARUV model of the Katleho

The geometry for Katleho was obtained from Denel Dynamics in the form of a CAD model and the test specification. For the release simulations of Katleho, two aerodynamic models were used, namely

1. ARUV panel method results
2. Lookup tables based on the Denel Dynamics aerodynamic model.

4.3.1 Panel method model

The ARUV model is shown in Fig. 7. Initially the control surfaces of the fins were modelled separately, as in the full-scale geometry. This however causes the model to be unnecessarily complex and takes up more of the lifting surfaces available in ARUV. By combining the fin and control surface into a single surface in the ARUV model and keeping the same airfoil thickness distribution, no changes to the resulting normal force or pitching moment coefficients were noted. Thus a single surface was used in the final model, while keeping the correct airfoil shape.

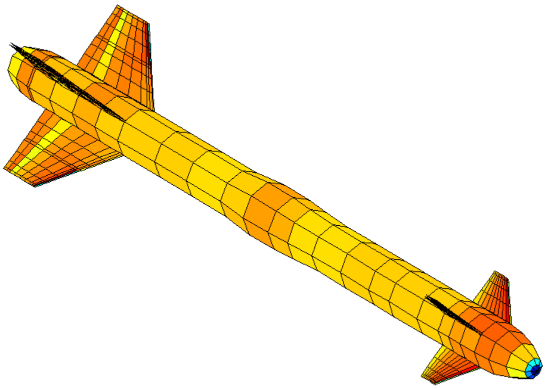

Fig. 7. ARUV model of Katleho

The original ARUV model of Katleho gave a pitching moment coefficient that was too low when compared with the aerodynamic model from Denel Dynamics. It was suggested that this was due to additional lift being generated by the nose of the bomb, which was not captured by ARUV. To improve the correlation, the chord of the canards in the ARUV model was increased by 10 mm and the leading edge was moved forwards by 10 mm. This gave good correlation of the normal force and pitching moment curves for angles of attack up to 5 degrees, as shown in Fig. 8 and Fig. 9.

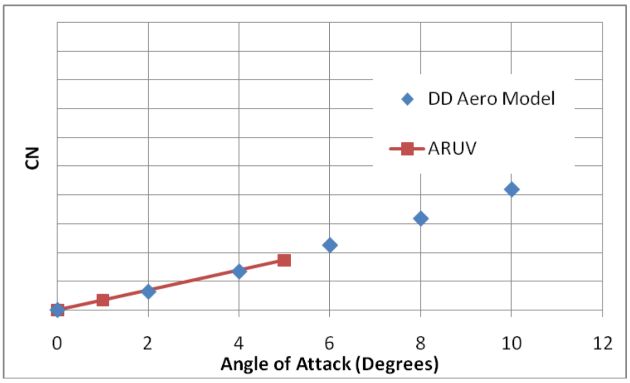

Fig. 8. Normal force coefficient curve for the modified ARUV Katleho model

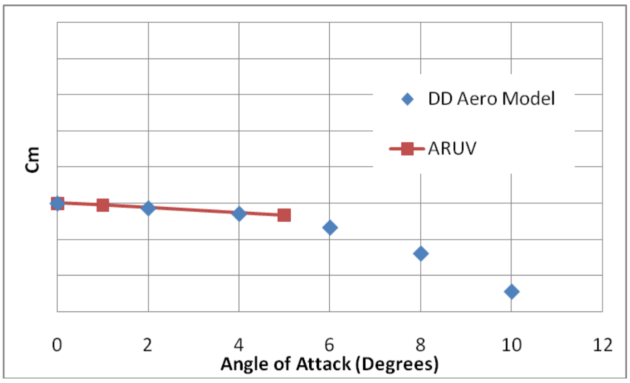

Fig. 9. Pitching moment coefficient curve for the modified ARUV Katleho model

4.3.2 Lookup table model

For angles of attack greater than 5 degrees and limited to 15 degrees, a lookup table has to be used, as the aerodynamic characteristics are non-linear. A lookup table was generated that treats the store in three parts: nose with canards, centre section and tail with fins. The three-part lookup table is required because of the significant streamline curvature near the wing, and because of the size of Katleho relative to the wing. A single point treatment would not be valid. Data for the lookup table was generated using DATCOM methods and in return checked against the aerodynamic model. Fig. 10 and Fig. 11 compare the ARUV lookup table results with the Denel Dynamics aerodynamic model.

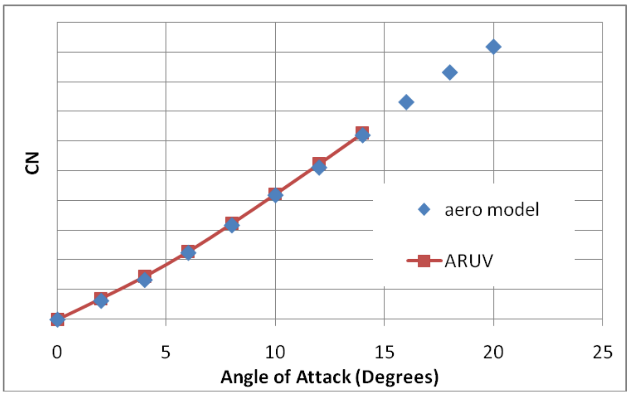

Fig. 10. Normal force coefficient curves for the ARUV lookup table results compared with the aerodynamic model

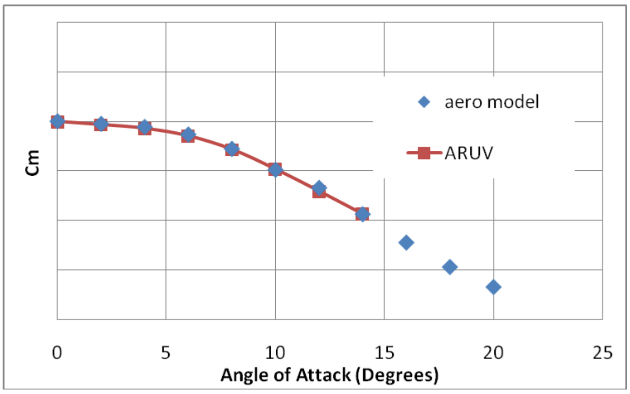

Fig. 11. Pitching moment coefficient curves for the ARUV lookup table results compared with the aerodynamic model

4.4 The combined Hawk Mk120/Katleho model

To validate the transonic results (Mach 0.8 only) with the Katleho store on the Hawk Mk120 wing, ARUV simulations were compared to CFD-FASTRAN CFD simulations to calibrate the predicted carriage loads on the store. The same simplified Hawk Mk120 wing geometry discussed in §4.2 was selected for the validation model. The Katleho store was added to this validation wing model.

The outcome of the comparison is that results from ARUV cannot be used to determine the Katleho loads in the carriage position at transonic speeds (Mach 0.8). A strong shock wave is present between the upper surfaces of the upper two rear fins of the Katleho due to interaction with the pylon and the resulting suction effect significantly increases the nosedown pitching moment of the Katleho. This effect is illustrated in Fig. 12. It was found that if the Katleho is moved 85 mm below its carriage position (approximately the position at which the store moves away from the pylon ejectors), the correlation between CFD-FASTRAN and ARUV is greatly improved.

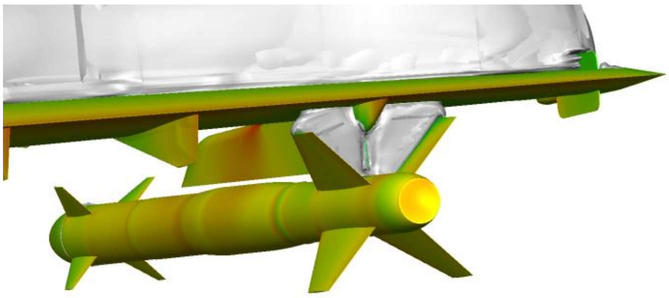

Fig. 12. CFD-FASTRAN computation of the flowfield with the Katleho in the carriage position at Mach 0.8 (the Mach 1 contour is highlighted in grey to indicate the location of the shockwaves)

ARUV has a limit of lifting surfaces that can be defined in a single geometry. Thus for the case of the Katleho simulations, the horizontal stabiliser, SMURFS and the inboard flap hinge were removed from the geometry for the Katleho carriage and release simulations. The combined model is shown in Fig. 13. The changes to the ARUV model have an insignificant impact on the flowfield at the Katleho location.

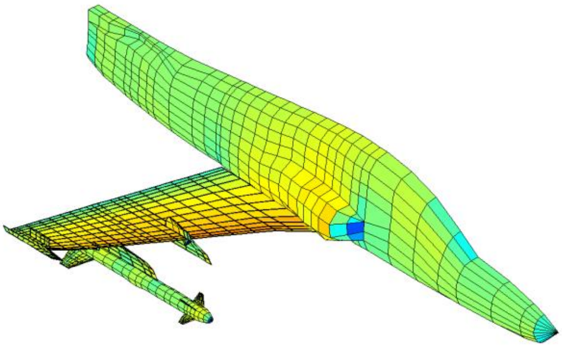

Fig. 13. The ARUV model used for the Katleho release simulations

4.6 The Hawk Mk120 finite element model

The basic requirement for the aircraft dynamics in this analysis is a model of the rigid and flexible dynamics of the Hawk with underwing pylons and the Mk82 bomb fitted on the one outboard pylon. The Katleho is coupled to the aircraft model separately.

In the absence of experimentally measured mode shape data with the correct configuration, the model uses the structural characteristics from the Hawk MSC Nastran finite element model (FEM) supplied to the CSIR by BAE Systems. The FEM was checked by comparing its results against experimentally measured configurations and found to correlate well.

The underwing pylons and wing-tip pod models were activated and the Mk82 mass, centre of gravity and inertia characteristics were incorporated. The FEM is plotted in Fig. 14. Note that the FEM is a “broomstick” model that models the mass and stiffness distribution of the structure. The modal properties of the Hawk generated by MSC.Nastran were imported into Matlab^{TM}.

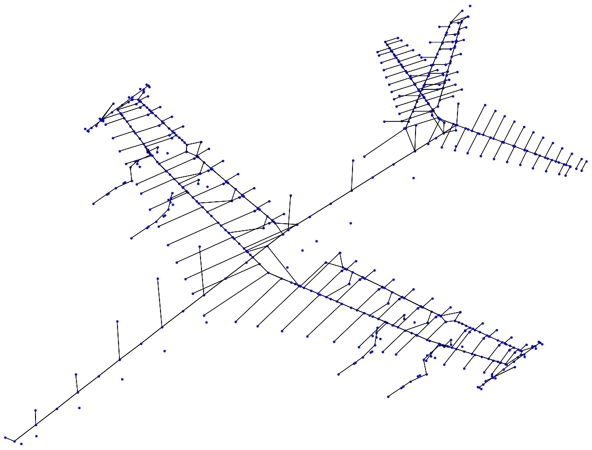

Fig. 14. The FEM model of the Hawk

5 The release analysis process

The procedure followed for the release analyses is presented in Fig. 15. Note that the ejection dynamics and the release dynamics are analysed separately. Data from CFD-FASTRAN is used or interpolated to obtain the carriage loads at Mach 0.8. ARUV was used to compute the aircraft flowfield for all the store release cases.

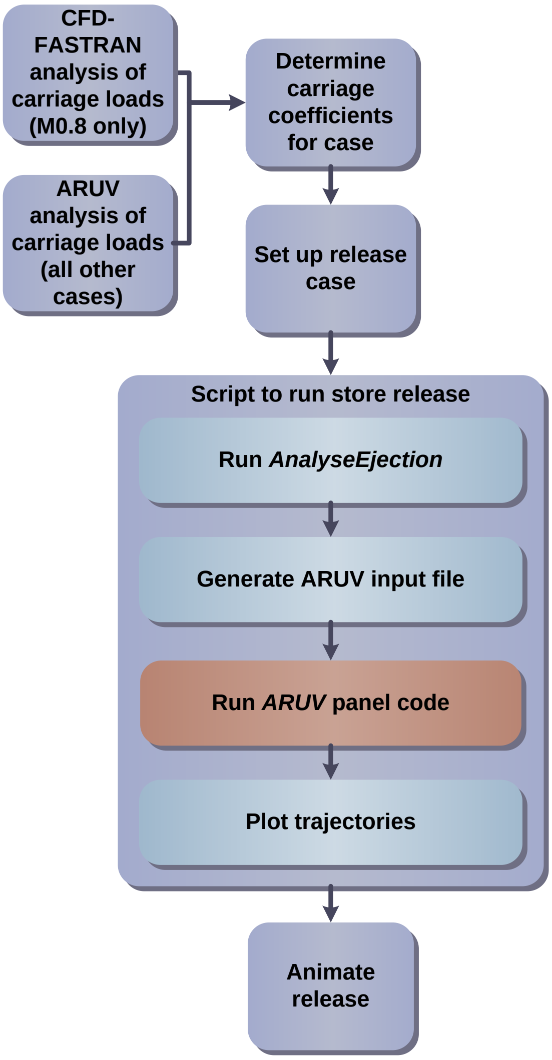

Fig. 15. Procedure followed for release analyses

The approach taken was to first analyse the full flight envelope at the nominal release conditions. At the target release point the sensitivity of the Katleho dynamics to sideslip, roll rate and normal acceleration was investigated. The worst result for each parameter was then combined and evaluated.

This worst-case combination of parameters was then evaluated at the worst release point in the flight envelope as determined by the previous scan of the flight envelope. Further sensitivity analysis was then done at this point, investigating the impact of a reduction in the ERU force, the allowable variations in the Katleho's centre of gravity and the impact of the aircraft's aileron deflection. The very worst-case combination found in this investigation was then tested at other points in the flight envelope.

6 The release analysis results

The results of the analyses were animated and coded subjectively as defined in Table 1.

Table 1. Result code used to grade releases

Result code	Definition
0	Katleho strikes some part of the aircraft
1	Katleho misses the aircraft marginally
2	Part of Katleho moves towards aircraft
3	Part of Katleho "hovers" close to aircraft
4	Katleho accelerates cleanly away from aircraft
5	Katleho accelerates and rotates cleanly away from aircraft

The motion of the Katleho for the intended release point is plotted in Fig. 16 and Fig. 17.

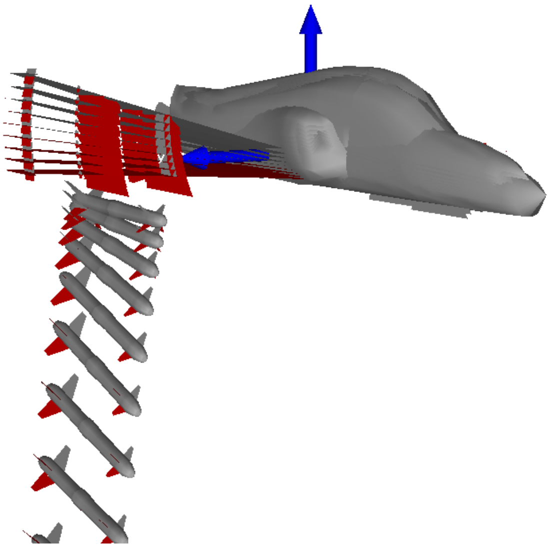

Fig. 16. Release trajectory for the intended release point in inertial axes

Note that the ARUV simulation begins where AnalyseEjection ends, so the store is at a position below the pylon where the ejectors are no longer in contact. Also, note how the aircraft rolls and translates away from the Katleho due to the ERU forces and the mass imbalance that is not trimmed. The Katleho drops and accelerates away cleanly in this case.

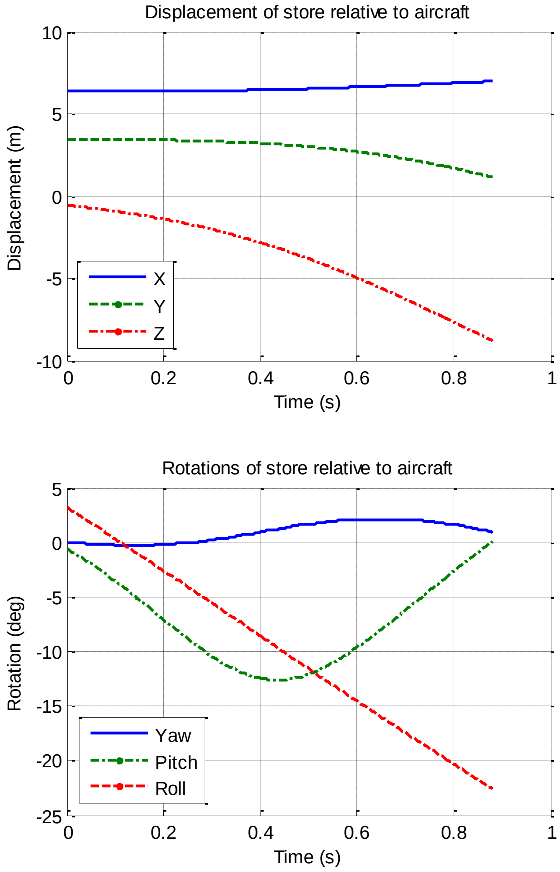

Fig. 17. Release displacements and rotations relative to the aircraft for intended release point

At no point in any of the simulations does the Katleho strike the aircraft and the lowest result code (see Table 1) is 3. Looking at the factors affecting the release dynamics, the following are noted:

1. Dynamic pressure has a significant impact. Higher dynamic pressures reduce release margins.
2. Mach number adversely affects the release when shock waves are present at the Katleho / aircraft interface as these increases the suction at the rear of the store.
3. Rolling the aircraft downwards towards the store at the instant of release adversely affects the release dynamics.
4. A reduction in the vertical g-acceleration adversely affects the release dynamics.
5. Sideslip towards the wing with the store adversely affects the release dynamics.
6. Reducing the ERU force has a significant negative impact.
7. Releasing the Katleho with its CG located at the rear limit of its CG range adversely affects the release dynamics.
8. A negative aileron deflection angle (the aileron deflects upwards) has a significant negative impact.

By themselves, none of these factors are critical, but the worst-case combination of all these factors increases the risk of contact between the Katleho and the aircraft.

5 Discussion

The analysis of the release of the Katleho from the Hawk was challenging due to a number of aspects:

1. The analysis addressed the full carriage envelope including a wide combination of factors affecting store releases. Individual factors did not present a problem, but combining multiple factors simultaneously reduced the separation margins.
2. Locating the long, heavy Katleho on the outboard wing pylon of the small BAE Hawk introduced a number of challenges for store release analyses, including:
    a. The mass unbalance and ejection forces cause the Hawk to roll away from the store when ejecting it.
    b. The short outboard pylon located the store close to the lower surface of the wing and this, combined with the large rear fins of the Katleho, caused strong aerodynamic interference that had a major effect on the release dynamics.
    c. The length of the Katleho meant that while the CG translated steadily away from the pylon in all cases, a rapid downwards pitch rotation of the Katleho in

some cases results in the tail lingering close to the pylon.

   d. The rear fins of the Katleho are located close to the aileron of the Hawk. It was assumed that the ailerons deflect only slightly at Mach 0.8. A large deflection of the aileron during ejection at high dynamic pressures could affect the release dynamics significantly.

3. It was anticipated that releasing a heavy store from the outboard station with the ERU located well ahead of the wing could result in flexible wing dynamics playing a major role in the release dynamics. The ejection dynamics module was coded to investigate this possibility, but surprisingly, the impact of wing flexibility is insignificant. The ERU of the outboard pylon is close to the node line of the wing torsion mode and hence the torsion dynamics of the wing are not significantly excited by the firing of the ERU.

Overall, the dominant challenge to the release is dynamic pressure. The Katleho separates cleanly from the aircraft with good margins. If the robustness of this release is challenged by considering the worst-case of ERU forces, Katleho CG range and aircraft aileron deflection, the store does not contact the pylon. The lowest result code (see Table 1) is 3. As the study is purely analytical and being mindful of Cenko's warning (as discussed in §3) not to place too much faith in computational tools, it was recommended that the maximum jettison envelope dynamic pressure be reduced by 20% until the methodology described in this paper is validated.

6 Conclusions

The process followed to analyse the release of the Katleho from the Hawk Mk120 aircraft is described as a case study in store release analysis. Navier-Stokes CFD and panel codes were both used as applicable to analyse aerodynamic forces of the store in the carriage position and during the ejection sequence. Once the store was in free flight, a three-component look up table based on the store's aerodynamic model was used to determine its loads.

It is found to be important to model the dynamics of the aircraft for this asymmetrical release but the impact of the aircraft's flexible dynamics was found to be negligible in this case.

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