TRANSONIC STORE SEPARATION STUDIES ON THE SAAB GRIPEN AIRCRAFT USING COMPUTATIONAL AERODYNAMICS

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Abstract

Transonic store separation of a Mk82LD bomb from the right side inner wing pylon of the SAAB 39 Gripen aircraft has been studied by means of computational aerodynamics. The studied cases consist of two configurations. One configuration has a 300 gallons drop tank (DT300) attached to the central pylon below the fuselage. This configuration has been wind tunnel tested. The other configuration however has a camera pod (FUNK) attached to the central fuselage pylon. This is the flight tested configuration where photogrametric data from the separation phase has been collected. When store separation simulations were carried out on the FUNK configuration using aero data from the DT300 wind tunnel tests, the results were not good. Obviously, the flow fields below the aircraft are very different in the two cases thus generating completely different captive loads on the Mk82LD bombs. Therefore, in-viscid computational fluid dynamics (CFD) was used to compute both cases, with the bombs in their captive position, in order to provide aerodynamic load differences that could be added to the existing wind tunnel data. With the initial conditions reworked, the data was once again fed to a six-degree-of-freedom (6-DOF) store separation model. Now, the store simulation was in very good agreement with the flight test data. Encouraged by the good results, the study was enlarged to find out how well we could predict the store trajectories by using CFD as a stand alone source for aerodynamic loads. Thus, numerical computations were initiated on models that mimic wind tunnel tests. Also, physical modeling complexity was to be examined in order to find out if viscous modeling would improve the results, at least to an extent that would justify the increased computational costs associated with Navier-Stokes computations. Initially, our aim was also to perform time dependent CFD simulations with automatic re-meshing but these code modules are still under development within the CFD solver and not ready for this paper.

1 General Introduction

On a military aircraft, each external store must be able to be released in a safe and well predicted manner. To predict the store trajectories, we use a 6-DOF simulation model that describes the movement of the aircraft and the store relative to each other as well as an inertial system. The simulation model includes free-flying store aerodynamics as well as interference aerodynamics due to the disturbance from the aircraft when the store is within close proximity of the aircraft. The interference aerodynamics is dependent on several parameters such as the flight condition at the time of the store release, the store position and the overall configuration layout, e.g. what adjacent stores are present. This amount of parameters in the aero data often requires complicated and extensive wind tunnel tests using e.g. a two-sting-rig. Due to time and budget limitations as well as rising wind tunnel costs, alternative ways have been sought out to reduce the lead time needed for the store release predictions. This fact seen in the light of advances within computational fluid dynamics (CFD) has naturally led to an increased usage of numerical techniques being incorporated in the store certification process.

2 Background

During the last five years, CFD has been used as a component in the total store separation certification process at SAAB. Much of its success has been dependent on the advances made within automated grid generation, making turn-around times for the CFD process a very interesting complement to wind tunnel tests. Its strength as a value adding functionality is primarily as an initial analysis tool that can point out which store separation conditions the wind tunnel tests should actually focus on. As store separation analysis are to a large extent still based on older tests of geometrically similar stores, CFD has also provided key parameters to existing aero data when traditional scaling can not be applied [1]. Such an example is demonstrated within this study, i.e. predicting the correct captive store loads gives the store separation model the initial condition it needs to deliver a trustworthy separation trajectory.

3 Models and Computations

Several models of the Saab 39 Gripen have been discretised and computed using different levels of modeling complexity in both geometrical realisations as well as flow physical approximations. These are described at greater detail in the following sections.

3.1 Computational Geometry

The CATIA v.4 format geometry files of the SAAB 39 Gripen were prepared at the advanced design office at SAAB. These files were imported into ICEM CFD by using the direct CAD interface add-on module. The models have been modified slightly in order to simplify prismatic grid generation. In particular, some wedge surfaces have been replaced by thin surface strips that are twisted 90 degrees. By doing this, the prism grid generator will produce better cells since the surface normal of adjacent surfaces has a smooth transition while crossing the twisted strip. Furthermore, to terminate the computational domain, a surrounding far field box is placed at distance of approximately 10 characteristic lengths from the aircraft. A particular difference between the computational model and the real aircraft is that the pylon (P4) below the right intake is not present in the computational model. This discrepancy was judged to be of little importance though.

3.2 Grid Generation

For this study we have used the ICEM CFD Tetra / Prism grid generator. Tetra creates unstructured tetrahedral grids whereas the prism module creates mixed grids made up of tetrahedral and prismatic elements. The ICEM CFD Tetra software is based upon a modified octree approach. Thus, it generates the whole volume grid directly and the surface grid is simply a restriction of this volume grid to all CAD surfaces. By specifying curves, one enforces the triangle edges to be aligned with these and thereby surface discontinuities are realised. In the same way, by introducing points, one enforces triangle vertices to coincide with these and thus sharp corners are captured. The prismatic high aspect ratio elements close to the solid surfaces allow efficient modeling of the high gradients associated with boundary layers. For the viscous computations, a $y^+=1$ grid holding 40 prismatic layers were used. With an initial prism cell height of $2*10^{-5}$ m, the resulting prismatic grid layer expansion factor was approximately 1.2.

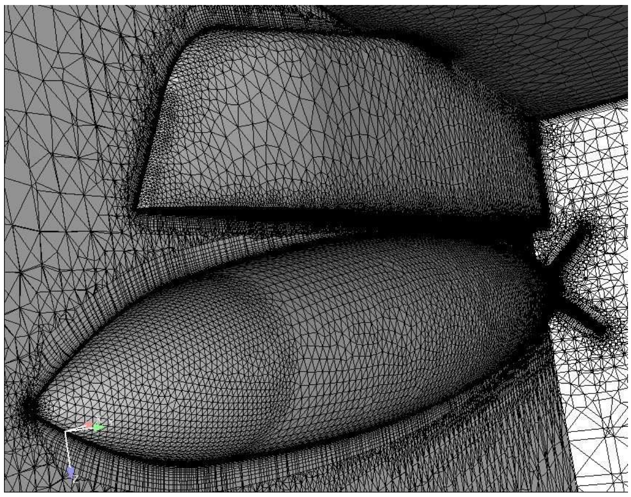

Fig 1. Grid detail of a SAF (Swedish Air Force) pylon with MK82LD bomb in captive position.

In Fig.1, note how the number of prismatic layers are reduced as the thin gap between payload and pylon gets thinner. Typical grid sizes for the tetrahedral grids were approximately 4 Mnodes and for the mixed grids around 22 Mnodes.

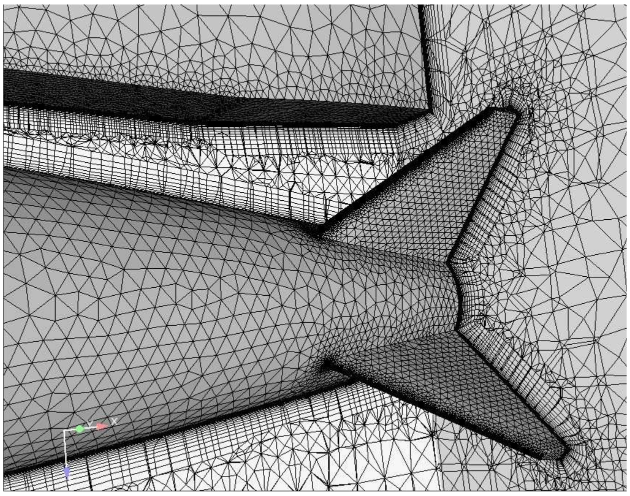

Fig 2. Detail of grid on and around the bomb fins. Note the well resolved leading edges.

3.3 Computational Aerodynamics

All the CFD analysis within this study has been conducted with the EDGE (v.4.1.0) flow solver [2]. The EDGE code is supplied by the Swedish Defense Research Agency (FOI). EDGE is designed to efficiently solve high speed compressible flows. It solves the governing equations on an unstructured hybrid grid which may contain mixtures of tetrahedrons, prisms and hexahedrons. For the solutions presented here, all grids are of either pure tetrahedral type or of mixed prismatic / tetrahedral type depending on what equations are to be solved. In the study, the code has been used in both in-viscid mode as well as viscous mode. In the in-viscid mode, it solves the Euler equations and in the viscous mode it has been used to solve the fully turbulent thin shear layer version of the Navier-Stokes equations. The thin shear layer approximation is reasonable in an external aerodynamics application like this one. To model turbulence, the K-ω shear stress transport (SST) model of Menter was adopted. Integration in time is carried out by a multi-stage Runge-Kutta scheme with agglomorated full approximation storage multigrid convergence acceleration. All viscous solutions have been initiated by a 1st order upwind scheme and utilising full multigrid (i.e. calculations start on the coarsest mesh) with a 3 grid levels W-cycle strategy in order to quickly establish boundary layers. Thereafter, a 2nd order upwind discretisation, based on Roe flux difference splitting employing a minmod limiter, has been used to achieve the final solution. When solving the Euler equations, a central scheme augmented with the famous Jameson-Schmidt-Turkel artificial dissipation has been utilised. The numerical dissipation has to be added for stabilisation. Boundary conditions are imposed on the far field using Riemann invariants. On solid surfaces, slip or no-slip conditions are enforced depending on the physics involved. The engine inlet is modeled by a flow through surface just up-stream of the compressor disc. Likewise, the electrical cooling system (ECS) intakes located in the space between the boundary layer splitter plate and the fuselage are realised in the same way. A mass flow ratio, $C_{A,}$ defined as

$$C_A = \oiint_{\Omega} \rho * U_n \, d\Omega / (\rho * U * A_{min}) \qquad (1)$$

is used to impose an average normal velocity through the engine inlet Ω. In Eq.1, A_{min} is the minimal duct area. On the engine outlet and ECS outlet surfaces, conditions that preserve their respective mass flows are set.

3.4 6-DOF Store Separation Model

The Saab mathematical store separation model [3] consists of several modules for calculation of the store motion relative the aircraft. The store relative motion depends on the store free flight aerodynamics, mass- and inertial data, the aircraft interference aerodynamics contribution on the store, the aircraft motion during the separation and the ejection release unit (ERU) force on the store. Furthermore additional effects from store autopilot commands and other devices must be taken into consideration. The free flight aerodynamic data are mostly taken from large scale wind tunnel test data and full scale flight test correlated values, mostly provided by the store manufacturer. The aircraft interference aerodynamics is normally measured in a two-sting-rig wind tunnel test. The influence is calculated by reducing the measured values in a trajectory by the last value where the store is far away from the aircraft. All aerodynamic data are put into multi-dimensional tables wherein the simulation system can interpolate during the simulation. Up to 4-dimensional functions can be used. The ERU module consists of a gas dynamic model of the system, including gas bottle, valves and pipes connected to the pistons as indicated in Fig 3. The simulation starts by opening the valve in the bottle. All the differential equations are solved by the Runge Kutta Merson method where the problem stiffness affects the time step in the solution. Store and aircraft trajectories are visualised by the Saab developed program ICARUS.

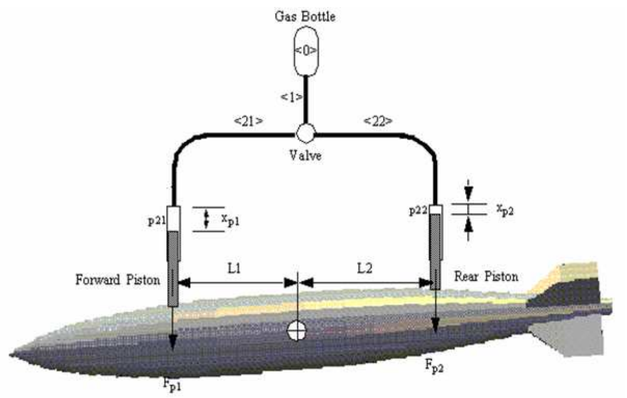

Fig 3. A brief view of the cold gas ERU

3.5 Carriage Load Predictions

For a separation study based on CFD, an initial carriage solution has to be established as a first step. This gives us the initial conditions needed for the store separation simulation. The studied case has a free stream Mach number of 0.9 and a 1.9 degrees angle of attack. In Table 1, the computed carriage forces and moments are given for solutions based on both the Euler as well as the Navier-Stokes equations. Note the significant difference in side force coefficient and yawing moment coefficient of the Mk82 store depending on what store is attached to the central fuselage pylon. It is the basic explanation as to why the store separation simulation is unable to simulate the flight tested configuration using uncorrected wind tunnel data.

P5 store, physics	CT	CC	CN	Cl	-Cm	Cn
Funk, inviscid	0.1525	0.1931	0.6043	0.0003	2.0152	0.1983
DT300, inviscid	0.2483	0.3878	0.5471	0.0011	1.751	0.8802
Funk, viscous	0.1935	0.1900	0.4546	0.0067	1.4937	0.2769
DT300, viscous	0.2451	0.3624	0.4763	0.0089	1.5577	0.8295

Table 1. Carriage loads when the store is attached to a SAF pylon in position 3R

At the actual store separations, the Mk82 bombs were attached to NATO adapted pylons, which protrude further upstream than the SAF pylon. They also have sway braces, which alter the local flow field around the store as well as a slightly different gap distance. This was not a problem when using the CFD solutions as a correctional method as the only geometrical difference that had to be captured was the store change in central fuselage pylon. However, when using CFD as a stand alone method for aiding the store separation simulation it was deemed necessary to model the correct pylon type as the first results with SAF pylons were not very good. Indeed, re-modeling the pylons and taking details as lugs and sway brace feet into account proved to change the carriage loads in the right direction but not to an extent that was anticipated.

3.6 Subsequent Drop Position Predictions

Apart from computing the store in captive position, several vertical drop positions must also be computed when using computational aerodynamics as the only source of capturing the aircraft interference aerodynamics on the store. These results are then added to the free flying data of the store that was supplied by the payload manufacturer. The store positioned at drop distances of 0.0625, 0.125, 0.25, 0.5, 1.0 and 2.0 m from the pylon have been computed. At a drop distance of 5 m, the aircraft interference aerodynamics is considered to be zero. Apart from this, the free flying bomb has also been computed and these results are subtracted from the vertical drop positions and thereby creating the aircraft interference effect. This is then added to the manufacturer's free flying data. By only changing Z, this is of course a minimalist approach. One could also alter the two other coordinate directions and at least compute the store at two attitudes to get a better database for the aircraft interference to be used in the store separation simulation. Nevertheless, it is important to point out that the above mentioned grid extensions are considered of less significance than the number of Z positions. This fact and the aim to keep computational time low led us to only alter Z.

4 Results

4.1 Trajectory predictions using CFD as a correctional method

Our first comparative study is based on using CFD as a technique for capturing the delta effect between the two configurations. As seen from Fig 4, using the wind tunnel data based on a configuration with a DT300 drop tank attached to the fuselage centerline pylon (P5) as a base for a store simulation clearly gives inadequate results when compared to flight test data with a FUNK camera pod attached to the P5. The drop tank exerts a much stronger influence on the Mk82 bomb than a camera pod, making the store simulation fail its attempt to capture the actual drop test. Computing both cases with CFD and adding the difference to the existing wind tunnel data gave a significant improvement as depicted in Fig 5. Comparing the translation and orientation at greater detail from Figs 6-11, it can easily be seen how well the Euler corrected simulation corresponds to flight test data. Simulation of the Y translation is now following the flight test instead of diverging at 0.25 s as before. The yaw orientation is of correct magnitude, although the yaw starts earlier than what flight test shows. The pitch orientation is better in phase but the corrected simulation still predicts a premature nose down movement of the bomb. This causes the pitch recovery to be predicted 0.05 s too early. The only data that becomes impaired by the correction is the X displacement. Investigating the corresponding viscous corrections, it is noted that these lead to slightly less accurate results. In particular, the store separation simulation indicates that the Y displacement is diverging after 0.31 s and that the yaw orientation is clearly from the start already over-predicted. The pitch orientation is somewhat less accurate in phase, predicting pitch recovery 0.07 s too early, but the magnitude of the pitch angle is very well predicted. For both Euler and Navier-Stokes corrected simulations, they follow flight test data well when considering roll orientation and Z displacement.

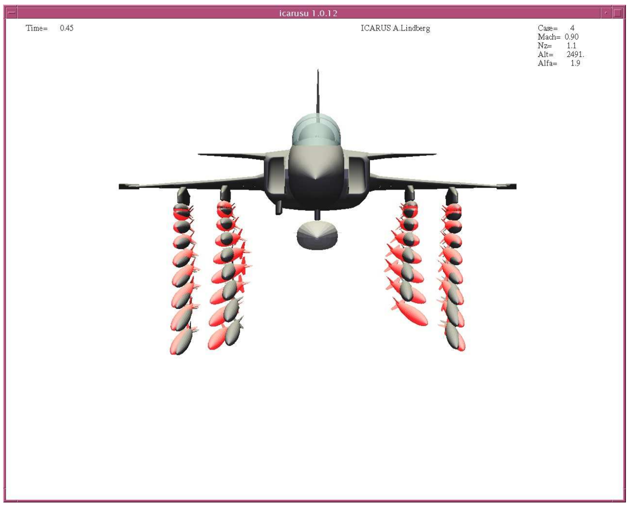

Fig 4. Store separation (simulation red, flight test grey), Simulation time is 0.45 s.

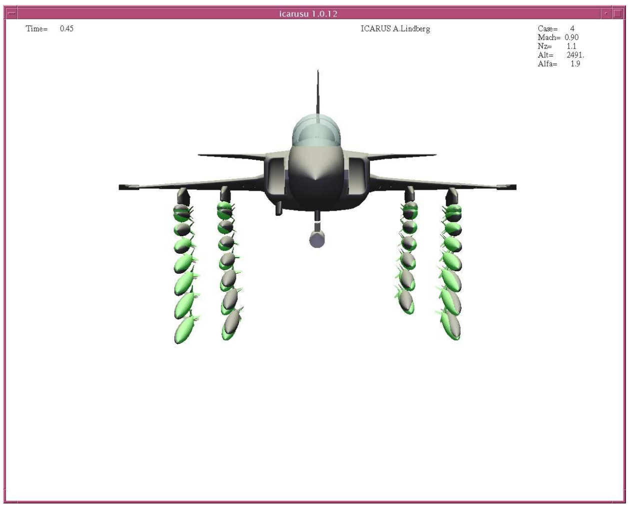

Fig 5. Store separation (simulation green, flight test grey), Simulation time is 0.45 s.

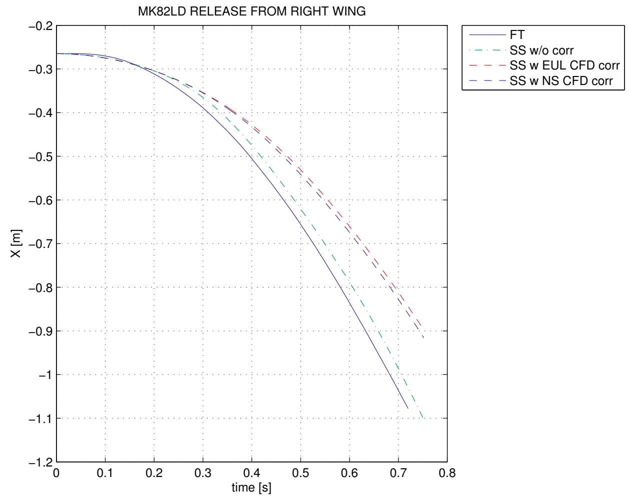

Fig 6. Relative X displacement

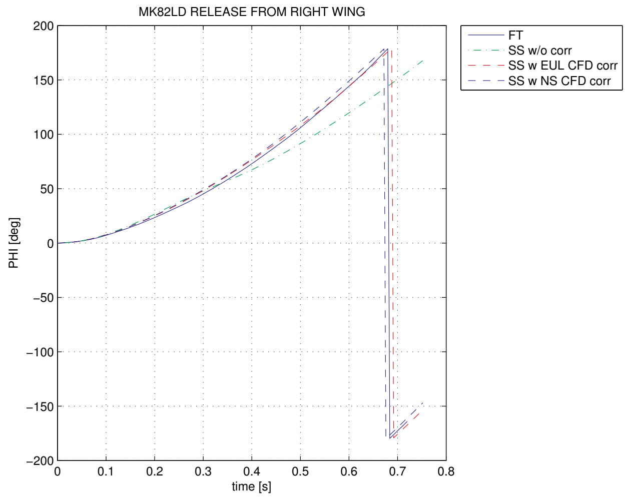

Fig 9. Relative roll angle

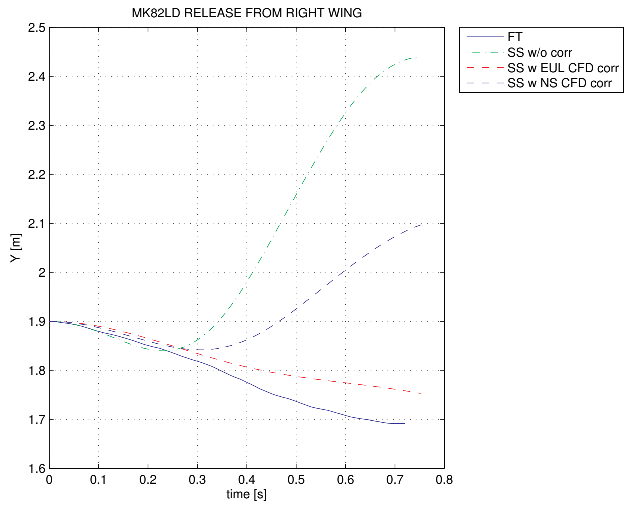

Fig 7. Relative Y displacement

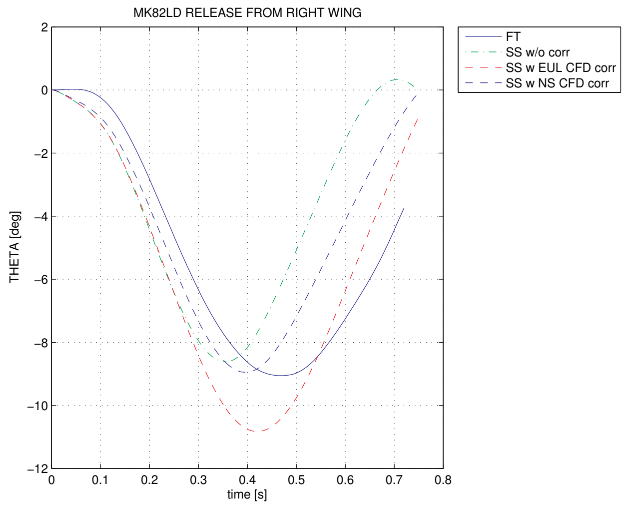

Fig 10. Relative pitch angle

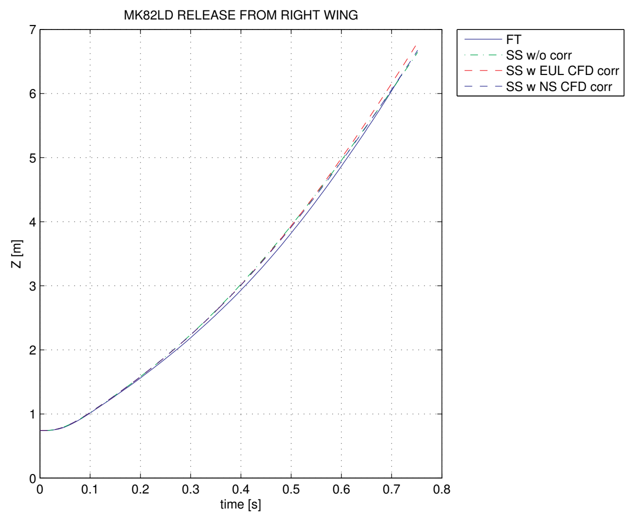

Fig 8. Relative Z displacement

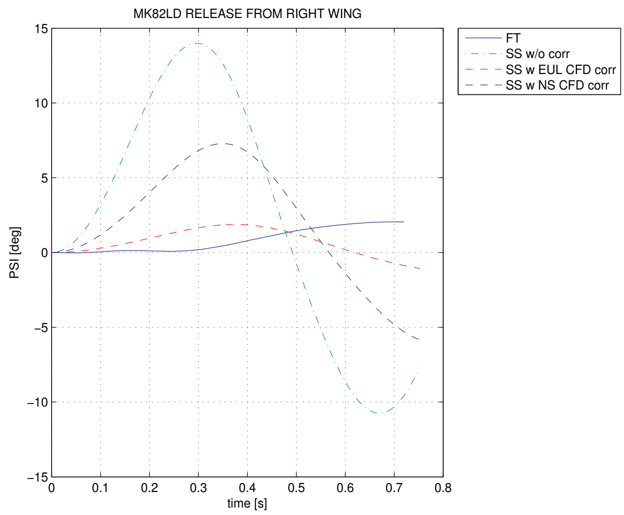

Fig 11. Relative yaw angle

4.2 Trajectory predictions using CFD as a numerical wind tunnel method

In Figs 12-17, the outcome of using computational aerodynamics in a grid based approach is depicted. This grid approach is naturally a coarse one, only altering the drop distance. Initially the drop configurations were solved using a central scheme for the Euler equations ('SS C EUL CFD') and an upwind scheme for the Navier-Stokes equations ('SS U N-S CFD'). Evidently, it can be concluded that as a stand alone method for this case, CFD based predictions give the general trends but the accuracy is not very good. This is in particular a result of the captive yawing moment that is over-predicted by large. The reason for this is not known. Note that the store separation based on the Navier-Stokes equations gave the worst results. As any natural explanation was not found, it led us to examine the influence of solution scheme since it was the only difference in solution strategy. The captive position and two vertical drop positions at 0.125 and 0.25 m were recomputed with the central scheme. Moreover, the upwind data for Z=0.0625 was removed. This led to a notable improvement in yaw orientation and Y displacement, as seen from the ('SS C N-S CFD') trajectory data. Most probably the trajectories would have been even better if all vertical positions had been recomputed with the central scheme. Why the two schemes show such a discrepancy in the yawing moment is not understood. Nonetheless, even if the central scheme provided some improvement, the yaw angle orientation is still not following flight test data. The incorrect initial condition makes the remaining store separation simulation trajectory disagree with flight test data. It is also the main cause of the diverging Y displacement. The roll angle is another poorly predicted quantity but it is perhaps not so interesting. The important pitching angle is over-predicted and out of phase. This is due to the strong initial nose down moment. Although the data might seem inaccurate, one should remember that the initial 0.3 s phase is the important one, where the agreement is quite good apart from the yaw orientation.

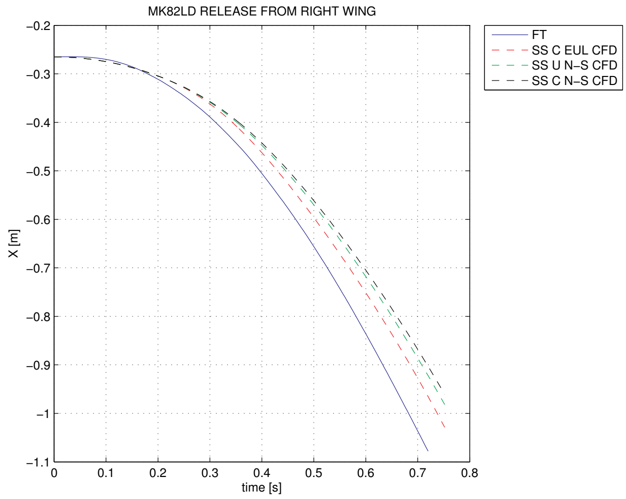

Fig 12. Relative X displacement

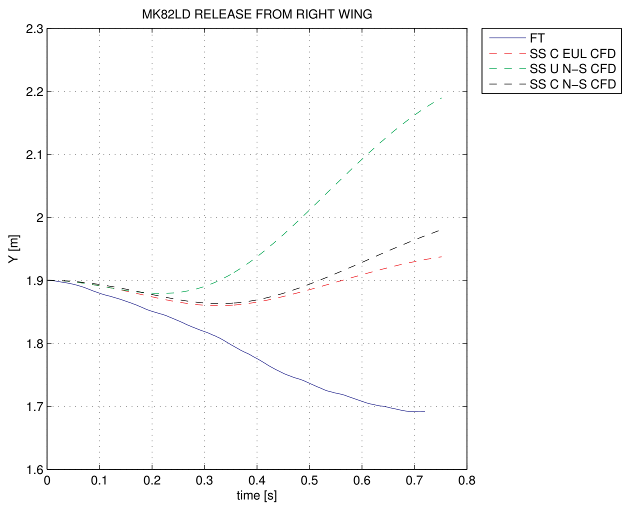

Fig 13. Relative Y displacement

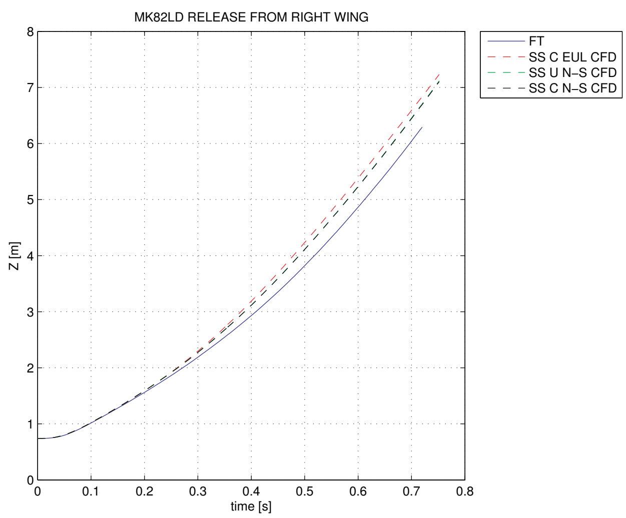

Fig 14. Relative Z displacement

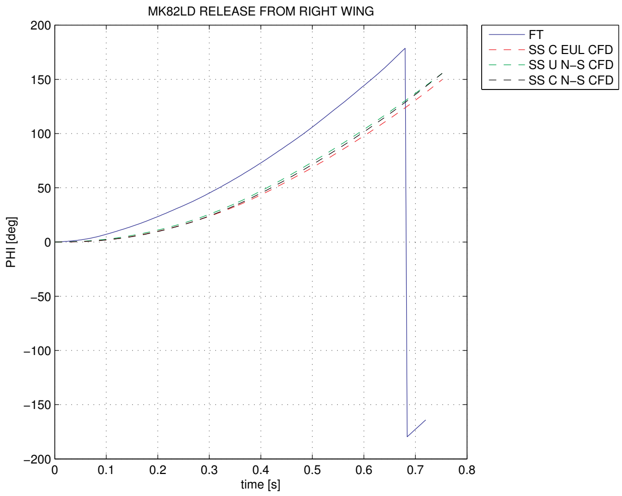

Fig 15. Relative roll angle

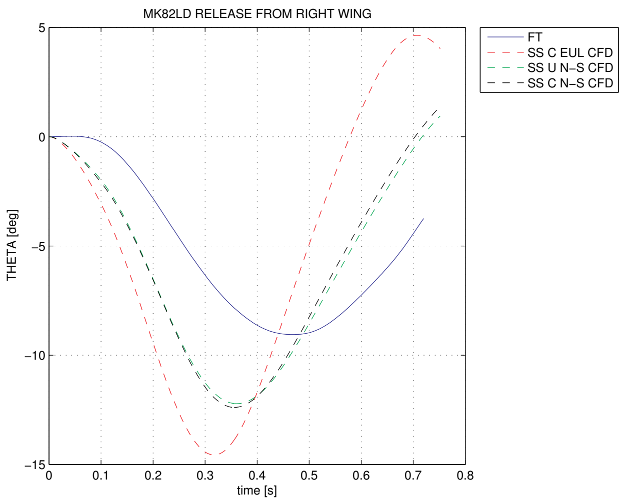

Fig 16. Relative pitch angle

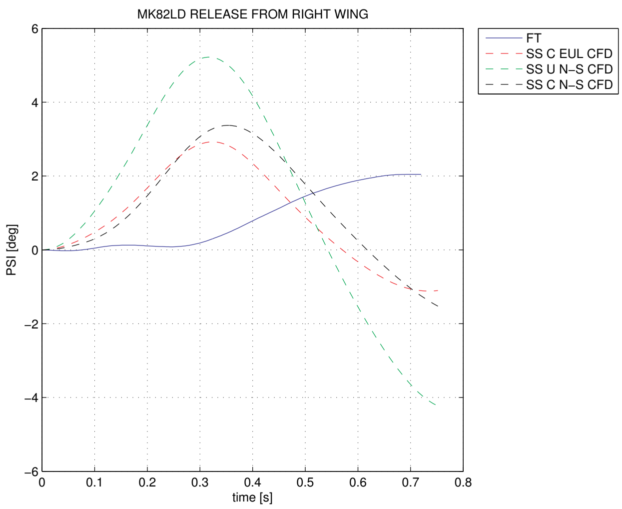

Fig 17. Relative yaw angle

4.3 Trajectory ensemble visualised using ICARUS

A final and often very useful tool in judging if the computed store trajectory seems plausible is the visualisation tool ICARUS. Here we can display all trajectories at once, giving insight to the merits of the different methods. In Figs 18-20, the color codes used are as in Table 2.

Flight test	Grey
In-viscid correction	Red
Viscous correction	Yellow
In-viscid CFD	Cyan
Viscous CFD	Green
Uncorrected WT data	Blue

Table 2. Coloring of stores

From the trajectory plots in Figs 18-20, it is easy to see that the store trajectory corrected by the in-viscid method supersede all the others. It is the only trajectory that does not have the Y displacement drift. The viscous correction has the drift as a result of the over-predicted initial yawing moment. Although far from the accuracy of the in-viscid correction, it is an improvement to the non-corrected simulation.

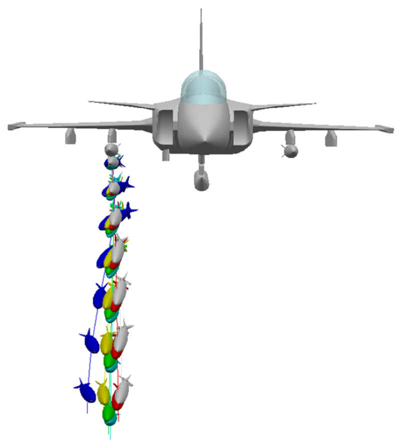

Fig 18. Frontal view of store trajectories

The two trajectories based on CFD as a tool alone to provide aircraft interference aero-dynamics are both hampered by their initial over-prediction of yawing and pitching moments.

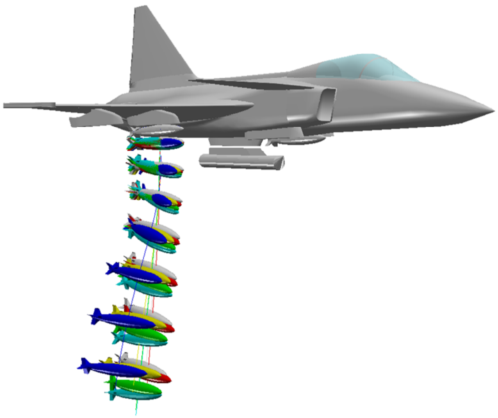

Fig 19. Oblique-angled side view of the store trajectories

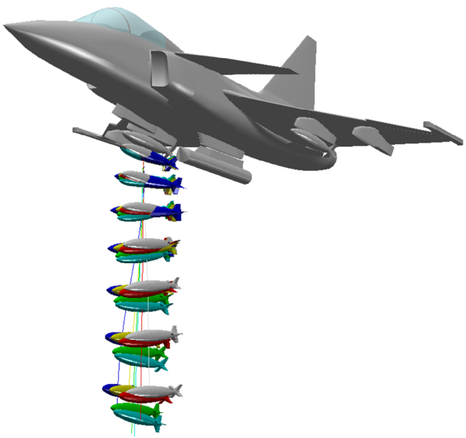

Fig 20. Oblique-angled view from below of the store trajectories

4.3 Solution Metrics

In the present study, the time to produce a grid within ICEM CFD ranged from 4 hours for a tetrahedral mesh holding 4 Mnodes to 20 hours for a mixed tetrahedral / prismatic mesh holding 22 Mnodes. The preprocessing (agglomeration/coloring/partitioning/boundary condition setup etc.) of these grids took yet another 2-5 hours depending on size. All cases were computed on a single node of a Sun Microsystems Sun Fire V490 system with 1350 MHz processor clock frequency. The actual flow solutions were established on a 136 Xeon processor in-house cluster, running at 3.4 GHz. The Euler grids were decomposed into 16 domains whereas the Navier-Stokes grids were partitioned into 32 domains. An in-viscid solution was established in 4 hours and the viscous computation took approximately 70 hours. Thus a complete Navier-Stokes vertical drop sequence could be established in a week. However, the results in this study do not motivate the use of this model complexity. Here, our results indicate that the Euler equations are fully sufficient. They also require a fraction of the time which is a great value in itself. To what extent this can be extrapolated to other configurations can only be answered by more numerical experiments. The time for each store separation simulation is negligible in comparison to the computational aerodynamics.

5 Future Work

As a next step in our attempts to provide reliable input to the store separation simulations, we intend to investigate the possible gain one can achieve from using time dependent computational aerodynamics. With such a solution method, the store separation model will be provided with more tightly coupled input that possibly will lead to more accurate simulations. Nonetheless, such a technique will inevitable generate even more computational work and probably making it too time consuming. Although re-meshing will be kept to a minimum by using grid stretching techniques, the work load associated with the discrete volumetric model will not be of subordinate significance.

6 Conclusions

From the study undertaken, it has become evident that an accurate prediction of a store is far from trivial. From this test case, it has been concluded that computational aerodynamics is a useful tool when using it as a correction method. This is also in compliance with general knowledge on how to gain the most from a CFD analysis. From the performed computations, it also became evident that solving the RANS equations did not deliver improved results that could justify the added work needed. In fact, for this case the in-viscid results were better. In the second phase of the study, when CFD methods were used as the only source for determination of the aerodynamic influence on the store, the store separation results became worse. The quasi static approach is perhaps not the most sophisticated but nevertheless great effort was put into the task to achieve credible store separation simulations. Different modeling complexity of the pylon was tried but no computation gave carriage loads that led to store simulations in accordance with flight test data. Furthermore, an increasing number of drop positions were computed to aid the simulation but accurate store trajectories could not be established. Although they are not accurate enough to be used as a basis for certification, they can be used as guidance of a wind tunnel program. Also, even if the dynamic simulation had been ready to use it might not have been the solution to our problems. This is to say that it is not only the aerodynamics on the store that has a major effect on the trajectory. In order to obtain good agreement with flight test data, it is of great significance that the following issues about the store separation model are considered:

- It is important to take the aircraft wing and launcher structural dynamic properties into consideration.
- The ejection release unit (ERU) must be modelled completely with the gas dynamics laws, including all pipes, valves and other devices. The total impulse from the ERU is dependent on the store mass and the flight case.
- The real store might have been misaligned to the piston force vector, for example due to a high load factor or a deviating CG position.
- The aircraft flight path change during the separation phase, for example the roll response caused by the ejection force and loss of mass during multiple releases, is important to model correctly to obtain good agreement with flight test data.

Any of these could of course be a partial cause to the mismatch between simulations and the recorded flight test data in general.

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References

[1] Persson I., *Analysis of payload interaction differences using computational aerodynamics*. Classified SAAB report TDA-2004-0030, 2004.

[2] Eliasson P., *EDGE, a Navier-Stokes solver for unstructured grids. Proc. To Finite Volumes for Complex Applications III*, pp 527-534, 2002.

[3] Lindberg A., *Store separation – An introduction to the methods used at SAAB*. Internal SAAB report GMFL-1999-0050, 1999.

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