THE USE OF CFD FOR STORE TRAJECTORY PREDICTION

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This paper describes a set of general requirements for a store trajectory simulation tool and gives details of the novel methods that have been implemented within two CFD based trajectory simulation tools, named TSAUNA and MARS, to ensure that they satisfy these requirements. The TSAUNA tool is based on the Euler equations whereas the MARS tool is based on the Reynolds Averaged Navier Stokes equations. Results from the application of the TSAUNA capability to the release of an empty fuel tank from a Tornado aircraft are compared with flight test data. The RANS modelling capability within the MARS tool is used to predict the separation trajectory of a generic MRAAM missile as it exits a shallow cavity, results from this simulation are compared with wind tunnel data.

1.0 INTRODUCTION

The clearance process for external stores is composed of a combination of analytical methods, CFD, wind tunnel testing and flight testing as illustrated in figure 1.

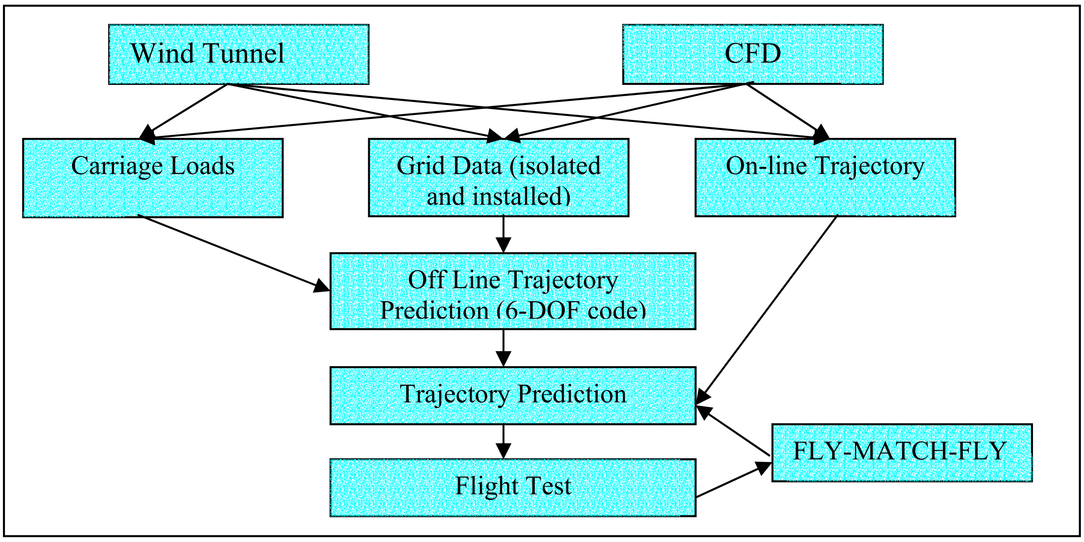

Figure 1: An illustration of all options in the store clearance process

From figure 1. it can be seen that CFD can basically be used to provide the same three services as the wind tunnel, those being:

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- Provide in-carriage loads.
- Provide grid data (isolated and installed).
- Coupled with 6-DOF code to provide trajectory prediction data – miss distances etc.

This paper will focus on the latter of these three, the use of CFD to provide store trajectory prediction data. In section 2.0 an outline is given of the general process for store trajectory prediction using CFD. This is followed, in section 3.0, by a detailed description of the general requirements of any store trajectory prediction capability for it to be used routinely in the store clearance process. Section 4.0 gives a brief discussion of the inviscid store trajectory prediction capability named TSAUNA [1] with a particular focus on the techniques adopted to satisfy the requirements detailed in section 3.0. This discussion will also include a comparison with flight test data for the prediction of the trajectory of an empty fuel tank ejected from an under fuselage pylon on a Tornado aircraft. Following this section 5.0 gives a detailed description of the viscous store release capability named MARS, once again with a particular focus on the novel methods that have been developed to satisfy the requirements set out in section 3.0. Also included in this section is a comparison with wind tunnel data for the prediction of the separation trajectory of a generic MRAAM missile as it exits a shallow cavity. Finally a few concluding remarks are drawn in section 6.0.

2.0 GENERAL PROCESS

The general process for store trajectory prediction using CFD is illustrated by figure 2.

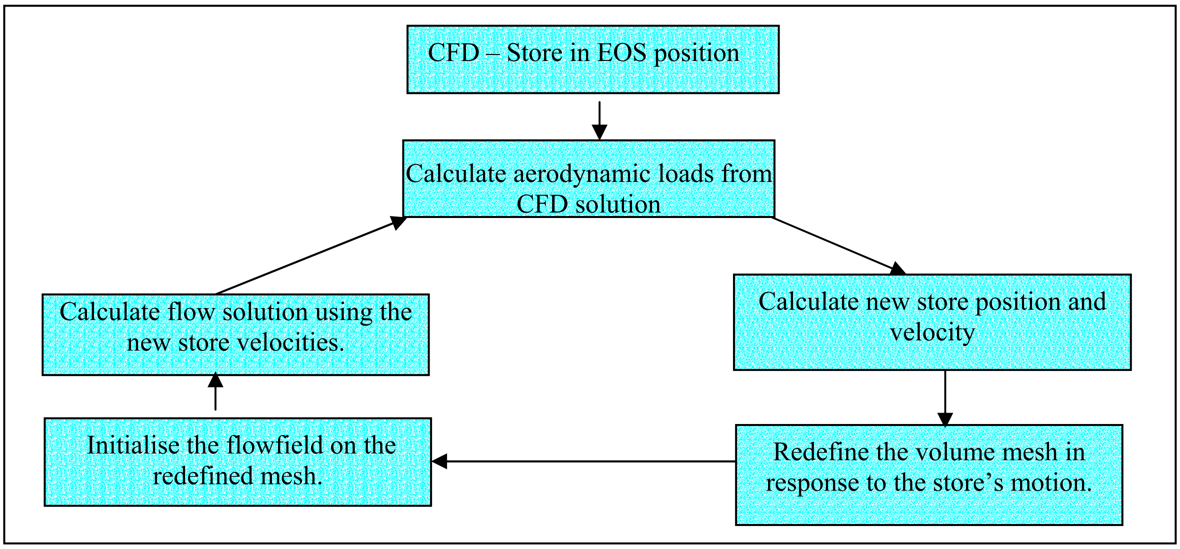


Figure 2: Process for store trajectory prediction using CFD.

A CFD computation is performed on the initial configuration with the store in its end of stroke position. Following this the aerodynamic loads on the store are evaluated and subsequently input to a 6-DOF code to calculate a new position and velocity for the store. The mesh is then redefined to account for the new position of the store and a flow calculation is performed on the new mesh taking into account the new velocity of the store. Once a converged solution has been calculated the aerodynamic loads are re-evaluated and the process continues until the required number of trajectory timesteps have been completed.

3.0 REQUIREMENTS FOR ROUTINE USE WITHIN THE STORE CLEARANCE PROCESS.

Many CFD based tools have been developed over the past 10 years for modelling store separation from complex aircraft configurations. The tools are based on a number of different CFD methodologies, each with their own inherent strengths and weaknesses. Putting to one side the CFD methodology implemented within the tool, this section will focus on the following question: *What are the key requirements of a CFD based store trajectory prediction tool if it is to be used routinely within the store clearance process?*

The requirements naturally fit in to the three separate categories of automation, efficiency and accuracy. A list of the requirements based on this categorization is presented below in table 1.

CATEGORY	REQUIREMENTS
Automation	• Low demand on man power for the initial set up phase. • Ease of use – limited user knowledge and experience requirements – low training costs • After initial set up phase require capability to run tool in batch mode i.e. fully automated process that can be executed at the press of a button.
Efficiency	• Elapsed time for a full simulation to be 1-2 hours • Efficient mesh redefinition in response to the motion of the store • Intelligent flowfield initialisation
Accuracy	• Level of physical modelling required: • Euler equations for external store release • Navier Stokes equations for internal store release. • A method is required to take into account the motion of the store relative to the parent aircraft. • A capability is required to monitor convergence in terms of the aerodynamic loads acting on the store.

Table 1: Summary of requirements for a store trajectory prediction tool.

Each of these requirements will now be discussed in more detail. Consider first the issue of automation and usability, in this context the automation of the store trajectory prediction capability can be measured by the experience and resource required to apply the capability successfully. It is clearly desirable that a user of minimal experience could carry out a simulation to the same level of accuracy as an experienced user. A tool that gives excellent results for an experienced user and poor results for someone inexperienced is only of limited use. Similarly a tool that requires significant manpower (more than a day) to set up and run has limited appeal. It is also a key requirement that after an initial set up phase the tool can be run in batch mode with no further requirement for user intervention.

Within the field of store separation modelling the issue of efficiency and, in particular, that of run times is probably the critical issue that will determine whether or not the tool has the potential to be used routinely in the store clearance process. It is the main issue that has prevented Euler codes from being used routinely until the last 3-5 years and it is this issue that will prevent Navier Stokes codes being used routinely until computing power has increased by a factor of 5-10 compared to that available today. In terms of a store separation, tool efficiency is essentially a function of the efficiency of the process for redefining the mesh in response to the store's motion and the efficiency of the flow solution process.

The category of accuracy can be considered in terms of three separate issues, the level of physics in the mathematical model, the order of accuracy of the numerical method and finally the quality of the mesh on which the numerical method is implemented. Different types of separation require different levels of physical modelling to produce results of an acceptable accuracy. Indeed it is probably the case that inviscid modelling is adequate for the majority of external store release simulations. However, for internal store release, where large separations dominate the flowfield, it is necessary to go to the expense of solving the Navier Stokes equations. Whatever the release type, be it external or internal, it is crucial that the physical model incorporates the motion of the store relative to the parent aircraft.

4.0 INVISCID STORE RELEASE

As discussed in the previous section, inviscid modelling is probably adequate for the majority of external store release simulations. Evidence of this has been reported in [2] where comparisons of viscous and inviscid results on a number of challenge test cases have shown very little difference between the predicted store trajectories. Clearly care has to be taken here as different geometries and flow conditions may result in the viscous effects having a much larger affect on the aerodynamic loads acting on the store.

The focus within this section will be on the steps in the development process of the TSAUNA store trajectory prediction capability [1]. In particular, an emphasis is given to the key developments within TSAUNA that have enabled this capability to satisfy the requirements specified in section 3.0. This is followed by the comparison with flight test data of the results from the application of TSAUNA to the release of an empty fuel tank from an under fuselage pylon on a Tornado aircraft.

The TSAUNA software was developed at ARA during the period 1996-1999 by coupling together the SAUNA CFD suite [3] and the TGRID 6-DOF code [4]. The SAUNA CFD suite was developed, under MoD funding, at the Aircraft Research Association. It allows block structured grids, unstructured grids or a combination of both to be formed. The meshing strategy adopted within TSAUNA is to create a hybrid mesh around the aircraft/store configuration. The general principal in creating this mesh is to have the majority of the domain block structured with unstructured grid covering the expected extent of the store's trajectory. With this approach only the unstructured region of grid has to be redefined in response to the motion of the separating store, the block structured region remains unchanged. TGRID is a 6-DOF module that has been developed at QinetiQ Bedford. Store trajectory predictions are calculated by numerically integrating the equations of motion of a rigid body, subject to a user defined data set of aerodynamic loads.

The following three sub-sections will give details of the methods that have been implemented within the TSAUNA capability to satisfy the requirements set out in section 3.0.

4.1 Automation/Usability

As outlined above the TSAUNA capability is based on the use of hybrid block structured/unstructured meshes. Clearly a significant amount of user expertise and time is required to set up the initial block structured mesh around the parent aircraft. However, once this mesh has been created it can be used for any number of different store configurations, since the store will be positioned within the unstructured part of the mesh. This fact is significant since it was always envisaged that this capability would be used on a small number of different aircraft but each with various configurations of store assemblies.

Once the initial mesh has been created the TSAUNA store separation simulation is a fully automatic process that can be run in batch mode with no user intervention.

4.2 Efficiency

The main capabilities developed within TSAUNA to maximize the efficiency of the store trajectory prediction process are as follows:

- Hybrid block structured/unstructured meshing approach.
- Efficient mesh redefinition in response to the store's motion.
- Intelligent flowfield initialization based on the previous flowfield.
- Full coupling with 6-DOF module.

As discussed in the previous section, the hybrid block structured/unstructured approach does lose out in comparison with purely unstructured methods in terms of the resource and expertise required in the initial set up phase. However, this disadvantage has to be considered alongside the significant advantage in terms of efficiency and accuracy compared to an unstructured mesh with the same number of nodes. In particular, the use of a block structured approach allows the use of anisotropic meshes over the surface thus giving significant savings in terms of the number of nodes required to give the same level of accuracy as an isotropic unstructured mesh.

A technique has been developed within TSAUNA to efficiently redefine the unstructured region of the mesh in response to the store's motion. The method implemented incorporates the following five techniques:

- Rigid body initialization
- Grid smoothing
- Point addition
- Point deletion
- Edge swapping

Each of these techniques performs a specific role in enabling the unstructured mesh to stretch and deform in response to the store's motion. Further details of these techniques are given in [1]. It should be noted that the use of point deletion prevents the generation of excessive grid density thus improving the overall efficiency of the process.

Further improvements to efficiency have been achieved by using a process referred to as SMART flowfield initialization. This process is based on allowing the flowfield, as well as the mesh, to automatically move with the store, this includes a capability to enable the velocity vectors to rotate with the store. The flowfield initialization provided by this process has resulted in significant reductions in the CPU requirements of the subsequent flow calculation, in some cases run time reductions of a factor of 10 have been achieved compared to starting from free stream values.

Another key development in terms of efficiency is the close coupling of the CFD process with the 6-DOF trajectory prediction code. It was found that by re-evaluating the forces and moments at each of the four intermediate stages of the 6-DOF Runge Kutta integration scheme enabled the timestep to be increased by a factor of four while still achieving a greater level of accuracy than keeping the aerodynamic loads fixed at the intermediate stages and using the original timestep. In fact it was shown that the standard 4^{th} order

Runge Kutta integration scheme became first order if the aerodynamic loads were not recalculated at the intermediate stages.

4.3 Accuracy

The TSAUNA capability is restricted to inviscid modelling based on the Euler equations which essentially limits its application to external release problems. In terms of modelling the motion of the store relative to the parent aircraft, a quasi-steady approach is used with a transpiration boundary condition applied on the surface of the store. The transpiration boundary condition models the relative motion by imposing a flow into or out of each cell face lying on the store's surface so as to match the linear and angular velocity of that point on the store relative to the parent aircraft. Since the motion of the store relative to the parent aircraft is modelled, the effects of this motion such as 'induced incidence' and damping due to rotary motion are also included.

The techniques of grid smoothing and point addition within the mesh redefinition capability ensure the mesh density and quality are preserved during the course of the store's trajectory thus ensuring there is no deterioration in the level of accuracy of the flow solution.

4.4 Results

The TSAUNA capability has been validated on a number of test cases including both standard ejection releases and powered rail releases. In particular the ejection release simulation capability has been compared with flight test data for under fuselage release of an empty 1500 litre fuel tank from a Tornado aircraft. The fuel tank was released from a shoulder pylon with a JP233 store in carriage on the opposite pylon. To duplicate the flight test conditions, the calculation was also carried out at an angle of sideslip. An illustration of the hybrid surface grid generated around this configuration is presented in figure 3. The unstructured region of the hybrid volume mesh contained 900,000 tetrahedra and 150,000 nodes, altogether the complete hybrid volume mesh contained 1.5 million nodes. The release of the fuel tank was run for 9 timesteps of the 6-DOF module taking the store from its end-of-stroke position at t=0.04 seconds to its final position at t=0.22 seconds. The elapsed time to run this simulation is of the order of 10 hours using a parallel cluster of 8 PC's each with a 2Ghz Pentium processor. Figure 4 shows two different viewpoints of a colour shaded plot of Mach number on the surface of the configuration with the fuel tank in its position after t=0.04, t=0.14 and t=0.22 seconds. A graphical comparison between flight test data and the simulated trajectory prediction is presented in figure 5. Ignoring the comparisons of y-displacement and roll-angle, for which the flight test data shows some unexplained characteristics, the theoretical results show a good comparison with the flight test data. Further details of this test case are presented in [1].

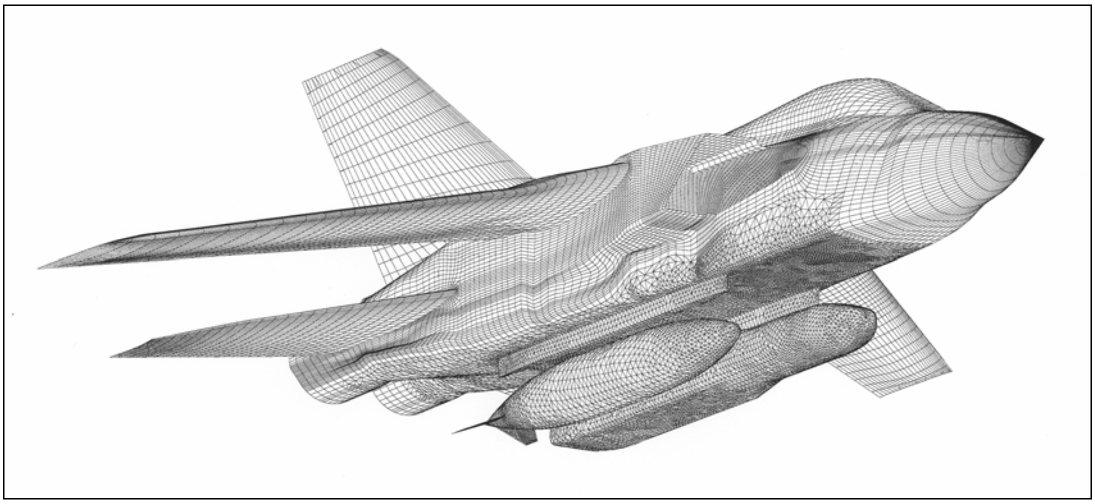


Figure 3: A Hybrid Block Structured/Unstructured mesh on a Tornado aircraft with a fuel tank and jp233 in carriage.

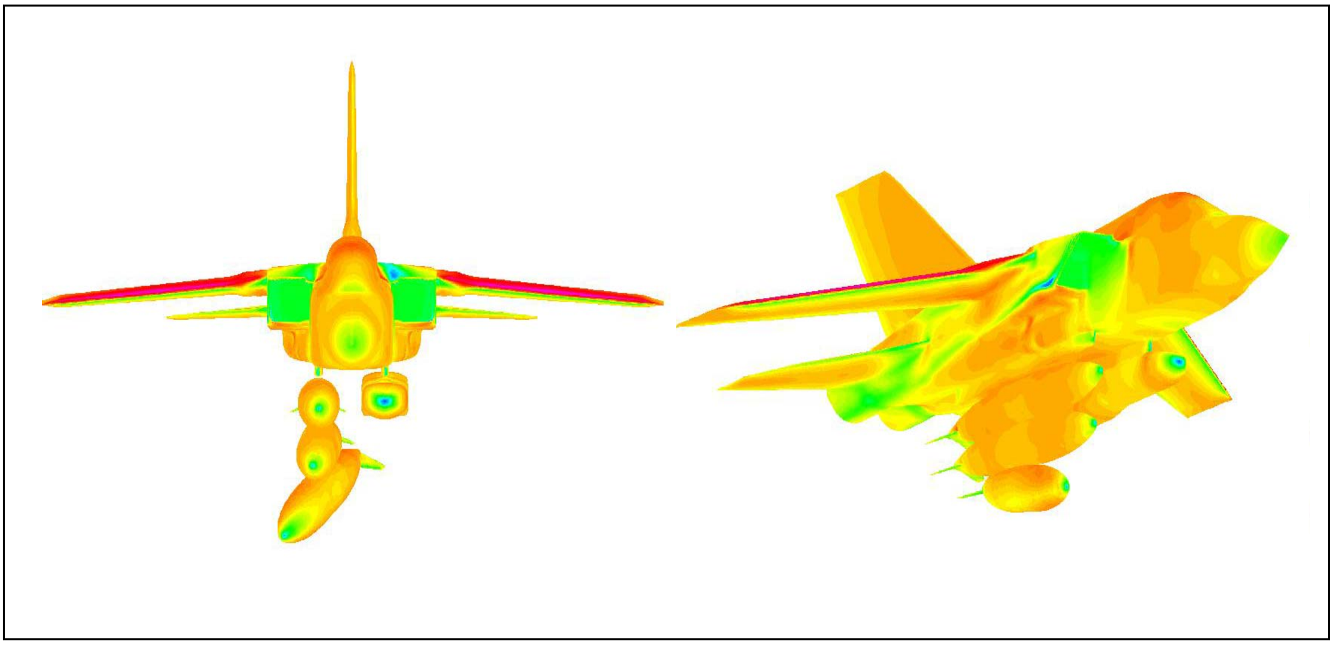


Figure 4: Two views of the release of the empty fuel tank, with colour shaded contours of Mach number over the configuration surface.

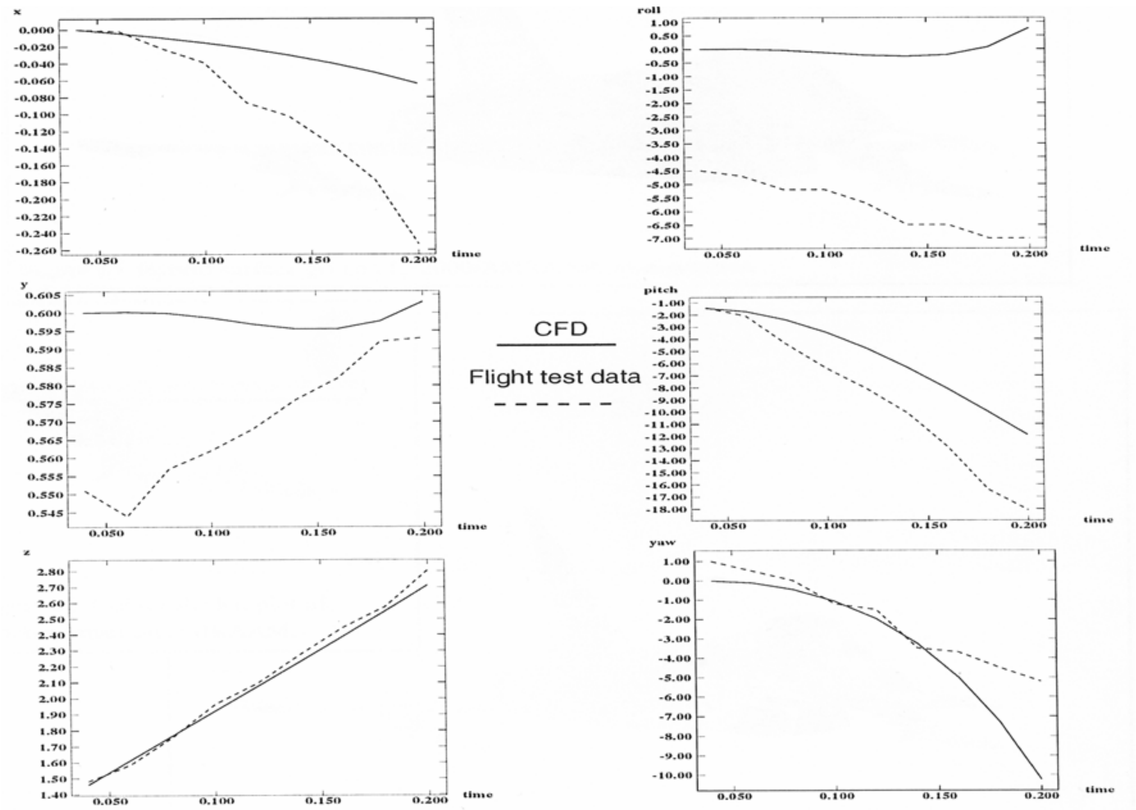


Figure 5: Plots of position and orientation of the fuel tank against time.

5.0 VISCOUS STORE RELEASE

As discussed in section 3.0 the requirement to model store release from internal bomb bays has promoted the need for efficient store trajectory prediction tools based on the Reynolds Averaged Navier Stokes (RANS) equations. Viscous effects are known to dominate the flowfield within open bomb bays due to the large scale boundary layer separation at the leading edge of the bomb bay. Accurate modelling of this free shear layer is crucial to be able to accurately predict the aerodynamic loads on a store as it leaves the bomb bay.

This section will detail the key developments within the MARS store release capability, developed by ARA and QinetiQ, to predict store separation trajectories based on the RANS equations. In particular, an emphasis is given to the techniques developed to satisfy the requirements specified in section 3.0. Results are also presented from the application of this capability to the release of a generic MRAAM missile from a shallow cavity, along with a comparison with wind tunnel data.

The MARS store release capability is based on the SOLAR CFD system [5],[6] and has been coupled with both the TGRID and STARS [7] store trajectory prediction suites. The SOLAR CFD system was instigated in 2000, and since then this suite has been extended and developed by a collaboration involving BAE SYSTEMS, ARA, Airbus UK and QinetiQ to provide a rapid-response complex configuration RANS CFD capability. The SOLAR suite includes an automatic mesh generation capability to produce high quality meshes for viscous flow computations. The meshes are created using an advancing-layer [8] approach to march a near-field mesh away from an unstructured surface mesh composed of quadrilaterals and triangles. Edge-collapsing and enrichment algorithms drive the topology of the layer to change automatically to take into account the underlying concavity or convexity of the region being meshed. The layer growth is either terminated based on reaching unit aspect ratio or when further growth would lead to cells overlapping. A refined Cartesian mesh is then cut to conform to the outer shell of the near field mesh. Thus the final mesh will be largely composed of hexahedra, but will also contain prisms, collapsed elements and arbitrary polyhedra at the cut cell interface between the near-field and far-field meshes. An example of a SOLAR mesh is illustrated in below in figure 6.

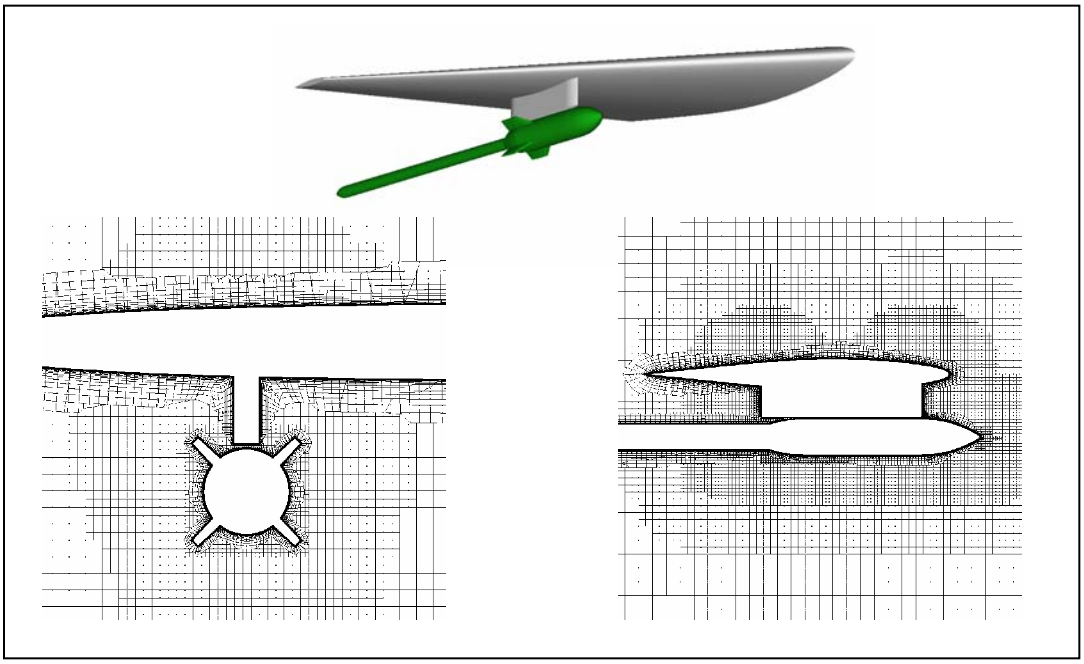


Figure 6: Cutting planes of constant X and Y through a SOLAR mesh around the AEDC wing/pylon/store configuration.

5.1 Automation/Usability

As discussed in the previous section the SOLAR CFD system offers an automated mesh generation capability which only requires the user to provide a geometry in a suitable format and also to position the sources that control the density of the mesh, via a Graphical User Interface. Work is currently in progress to further automate both of these steps so that the original geometry can be taken as the CAD definition and the sources are automatically set up based on curvature.

The MARS store release capability is a fully automated capability that can be run in batch mode, once the original mesh has been created, with no user intervention.

5.2 Efficiency

As highlighted in section 3.0 the key requirements for an efficient store release capability are an efficient capability to redefine the mesh in response to the store's motion and an intelligent flowfield initialisation process. Within MARS a similar capability to that developed within TSAUNA has been implemented to enable the flowfield to be moved with the store to provide a good initial guess at the flowfield around the store in its new position. Once again the velocity vectors are rotated to take into account the rotation of the store, this step is crucial for viscous flows in terms of rapidly establishing the correct boundary layer flow. The following section will describe the approach used for efficiently redefining the mesh in response to the motion of the separating store.

A slightly different approach to the mesh generation process is used for store release simulations compared to other applications. For general applications the advancing layer mesh generator treats the entire surface mesh as if it was a single entity with any intersecting cells being removed as they are created, during the advancing layer process, and the resulting crenellated outer shell smoothed off so as to remove sharp corners which can result in poor quality mesh at the near-field far-field interface. For store release applications the near field meshes on the stores to be released are generated independently of the main parent mesh. Clearly, this approach will produce two separate near-field meshes that may well overlap each other, this is illustrated for the outer shell of the near-field meshes that have been created around a bl755 store positioned under a Tornado aircraft in figure 7. Having created these separate meshes the next step is to combine them in such a way that removes any overlapping cells and smoothes off or decrenellates the outer shell. A software module named RETREAT has been developed to carry out this process. This process is illustrated by two cutting planes of constant x through the near-field mesh in figure 7. So why create two separate near-field meshes, if they are just going to be combined into a single combined mesh that is equivalent to the far-field mesh that would have been created by the standard procedure of treating the surface meshes as a single entity? The reason is, that at each stage of the store release trajectory, we can just move the initial store mesh as a rigid body and use RETREAT to create a non-overlapping near-field mesh.

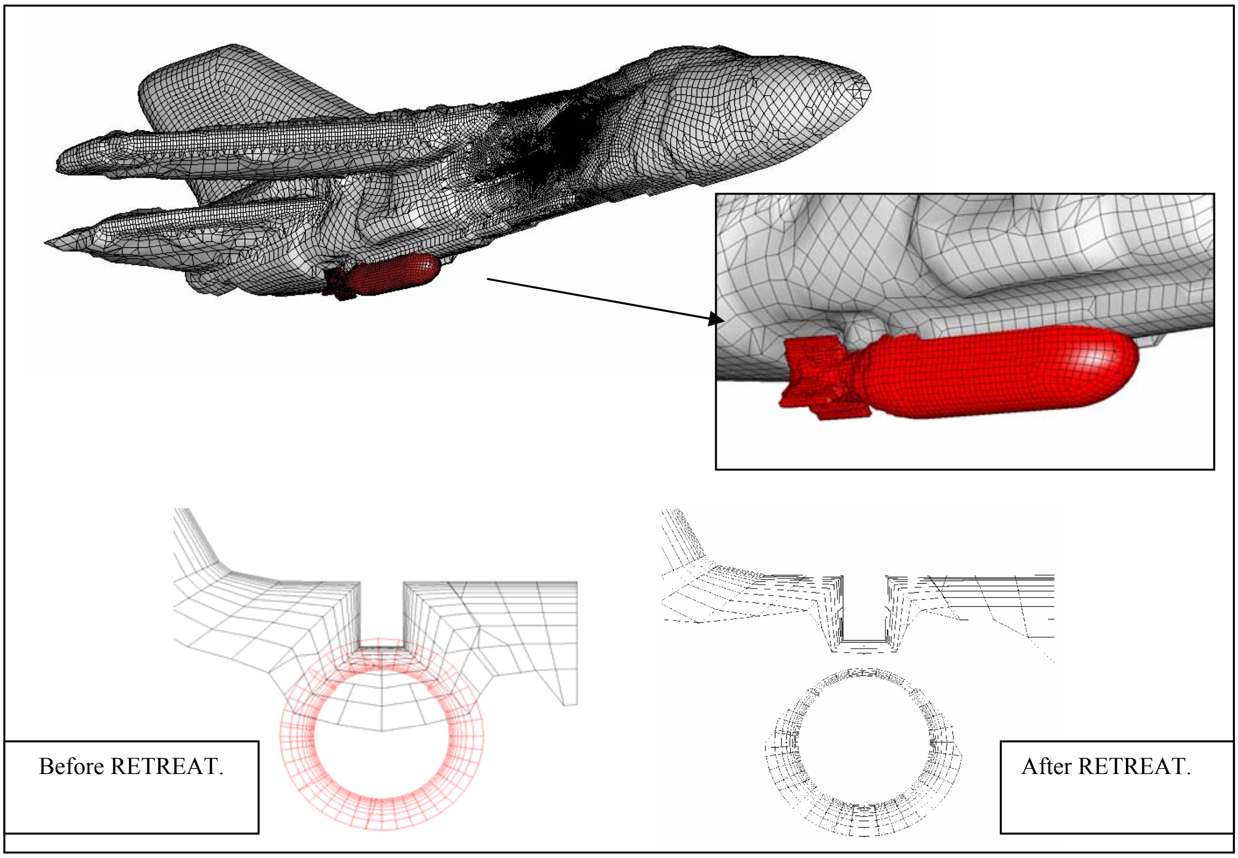


Figure 7: Illustration of the use of the 'RETREAT' module for mesh redefinition.

This approach has several advantages for store release applications:

- The relatively expensive step of creating the near field mesh only has to be done once for the entire release trajectory.
- The near-field mesh around the moving stores can be treated as a rigid body thus ensuring mesh quality is preserved throughout the calculation.
- Different stores can be used in the simulation by simply generating a near-field mesh around them and plugging them into the simulation. Therefore a library of aircraft and store meshes can be created which can be used interchangeably.

As well as the RETREAT module there is also a mesh deformation module named 'PHOBOS' [9] that is able to deform either the near-field mesh, the far-field mesh or the combined mesh in response to the store's motion. This capability is used in the store release process for small scale motions, these often occur at the corrector stages (i.e. stages 2 and 4) of the Runge Kutta scheme used within the 6-DOF module. It can also be used to deform the far-field mesh if the mesh around the moving store has not been modified by RETREAT, otherwise the far-field mesh has to be regenerated and re-cut against the new outer shell of the near-field mesh. The option to deform rather than regenerate the far-field mesh is only used if the mesh is not going to be excessively stretch or skewed by the deformation process.

In combination these capabilities provide an efficient and highly robust process for redefining the mesh in response to the store's motion.

5.3 Accuracy

The MARS store trajectory prediction capability can perform trajectory predictions based on either the Euler or RANS equations, although it should be emphasized that the capability has been developed with the aim of solving the RANS equations.

To model the motion of the store relative to the parent aircraft an approach like that used for TSAUNA cannot be used since the use of a transpiration boundary condition would cause the boundary layer to be sucked into or blown out of the store, both of which are non-physical and likely to cause the flow solution process to diverge. So what options does this leave? A moving mesh unsteady calculation is possible although this approach lends itself more to calculations on a deforming mesh where use of the Geometric Conservation Law (GCL) prevents the creation of non-physical mass sources and sinks during the solution process. The GCL could not be rigorously applied if the mesh connectivity is changing significantly from one step to another, which generally is the case. Further research into this issue is required before one could have any confidence in this method. Within the current capability a quasi-unsteady technique based on a combination of fixed and moving reference frames was preferred, this approach has been given the acronym QUACC (Quasi Unsteady Approach With Convective Correction)[10]. The basic idea behind this approach is to solve the RANS equations in a reference frame moving with the store in the vicinity of the store and solve in the usual fixed reference frame away from the moving store. This leads to a transition region between the two reference frames in which the so called 'QUACC velocity' is decayed. The value of the QUACC velocity at any given node is calculated based on its relative distance to the nearest fixed and moving surfaces. Further details of this method are in [10].

5.4 Results

As mentioned at the start of this paper the main motivation for developing a store trajectory prediction tool based on the RANS equations was to be able to model the separation of a store or a collection of stores from a bomb bay. It would therefore seem natural to choose a test case of this type to validate the MARS capability. The selected test case is the release of a generic MRAAM store from a shallow cavity at transonic conditions. The shallow cavity was chosen over the deep cavity simulation since it was felt that the assumption of a quasi-steady flowfield may be valid in a shallow cavity but would certainly not be valid in a deep cavity. It is also the case that the release trajectory from the shallow cavity was far more lively than that from the deep cavity. The geometry for this configuration with the missile in its end of stroke position is shown in figure 9 along with a cut of constant y through the volume mesh and a cut of constant x through the volume mesh in the region of the missile fins. The flow conditions for the simulation were zero degrees incidence and a freestream mach number of 0.85. The mesh used for this simulation consisted of 2 million cells. The full simulation was run for 16 full timesteps which took an elapsed time of 7 days on eight 2100+ Athlon XP processors. The results presented are a comparison between those obtained using the MARS store trajectory prediction capability and those obtained by applying the TGRID 6-DOF module to a data grid of aerodynamic loads generated by wind tunnel tests. Figure 10 shows an illustration of the release trajectory of the missile as it exits the cavity along with a plot of z displacement against time and pitch angle against time for the missile trajectory. From this comparison it can be seen that the significant pitching up of the missile nose towards the cavity, as predicted by the wind tunnel data, is starting to take place. It is assumed that this effect is cause by the interaction of the store with the free shear layer that has separated from the leading edge of the cavity. The fact that this effect can be predicted by a quasi-unsteady RANS CFD approach is a significant result as it implies that, for a shallow cavity at least, the small scale unsteady fluctuations caused by the inherent unsteadiness of the cavity flowfield can be neglected for a store trajectory prediction. Obviously further research is required in this area to investigate exactly what effects are and are not being modelled by the current approach.

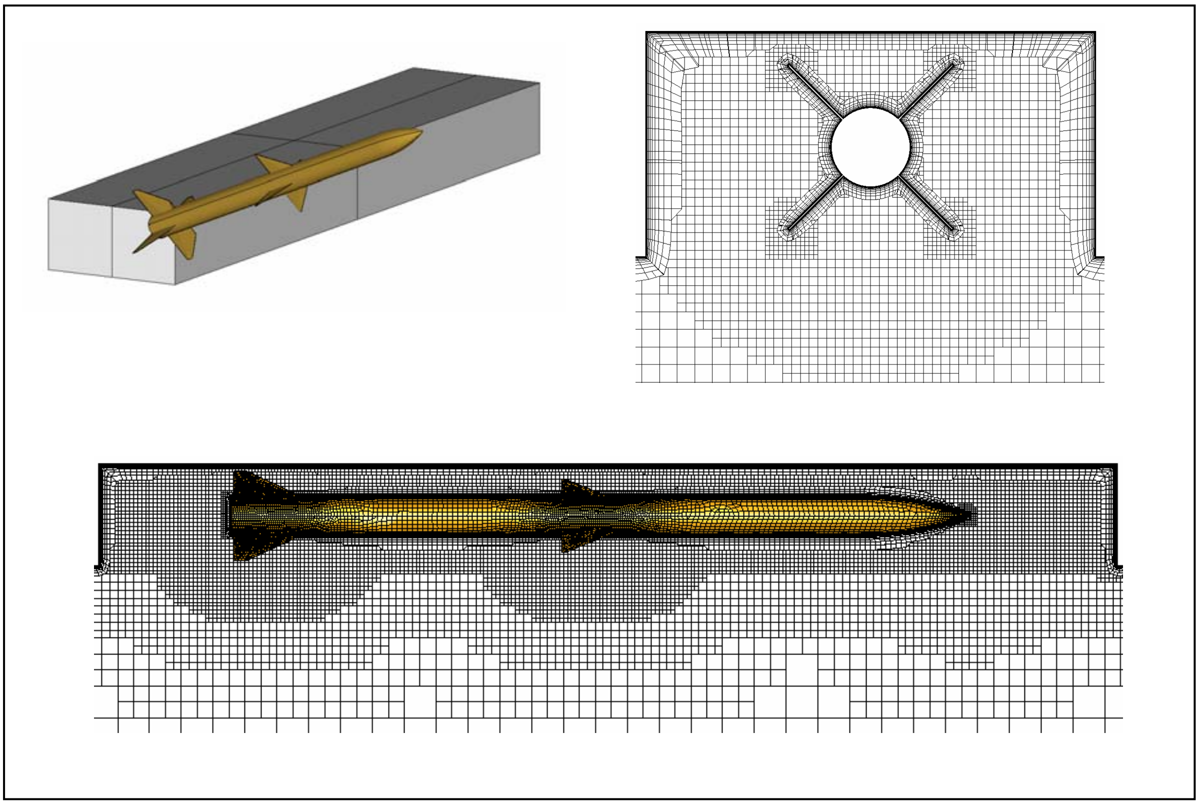
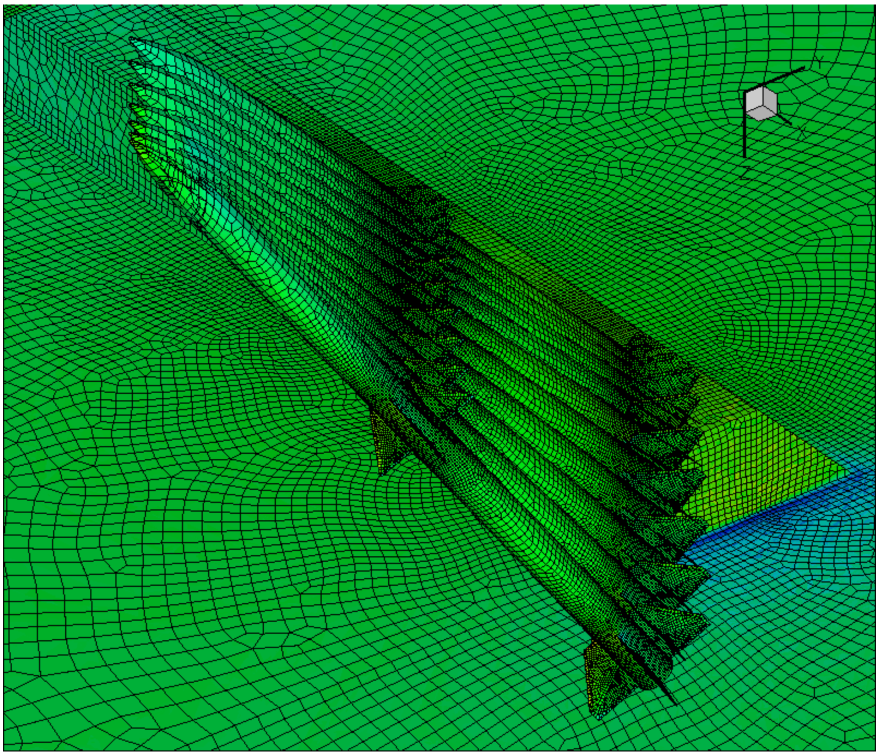


Figure 9: An illustration of the SOLAR mesh created around the missile/shallow cavity configuration.



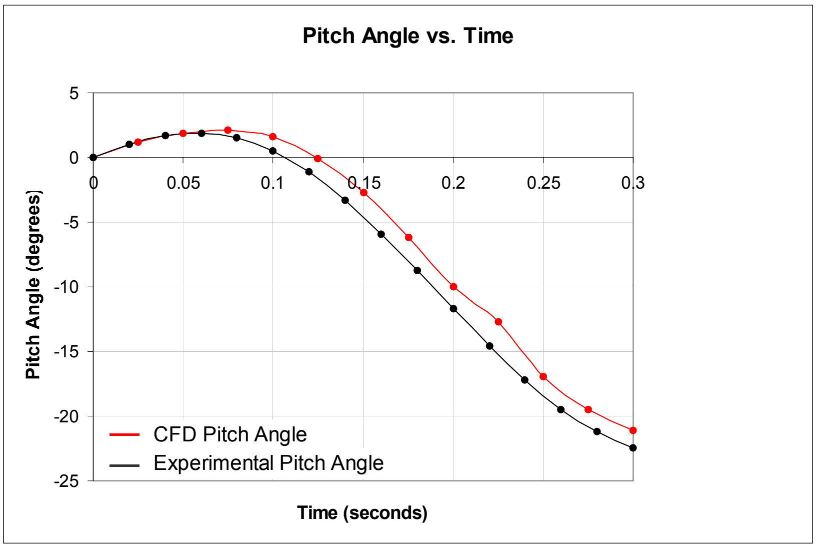


Figure 10: Trajectory details for the release of a generic MRAAM missile from a shallow cavity.

6.0 CONCLUSIONS

To be of use in the store clearance process, CFD based store trajectory prediction tools require a high level of automation, efficiency and accuracy. Novel techniques have been developed at ARA in an attempt to produce tools that meet these requirements. These techniques have been implemented within the TSAUNA and MARS store trajectory prediction capabilities.

The inviscid capability within TSAUNA has been successfully applied to the release of an empty fuel tank from the under fuselage pylon of a Tornado aircraft at transonic conditions.

The application of the quasi-unsteady RANS capability within MARS, to predict the release trajectory of a generic MRAAM missile exiting from a shallow cavity at transonic conditions, has also shown encouraging results.

Currently due to time constraints only inviscid CFD can be used routinely within the store clearance process, however, viscous tools are now available for one off calculations and will become viable for routine use over the next 3-5 years, using current predictions of the expected increase in computing power.

ACKNOWLEDGEMENTS

Initial work on the release of the MRAAM from a shallow cavity was carried out with support from the UK Ministry of Defence. The author would also like to acknowledge the significant contribution of Andrew Jackson, David Martineau and Graham Doig.

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DISCUSSION EDITING

<u>Paper No. 15:</u> The use of cfd for store trajectory prediction

Authors: Sean Stokes ARA

Speaker: s.a.

Discussor: James Grove

Question: 1. What was the length to depth of the cavity?

2. Which wind tunnel model was used to compare to the CFD results.

Speaker's Reply: 1. Ten (10)

2. DERA generic cavity wind tunnel model.

Discussor: Alex Cenko

Question: There are two experimental techniques – the grid method and the CTS. Your approach which is similar to most CFD practitioners, uses the CTS type approach. Why is that?

Speaker's Reply: The mesh redefinition and flowfield initialisation techniques could equally well be used to efficiently create a grid of CFD data.

With regard to using the CTS like approach, one of the main focuses of the work has been to develop quasi-unsteady methods to model the dynamic effects of the store separating from the parent aircraft – hence the approach adopted.

Discussor: Francois Fortin

Question: 1. Did you concern yourself with the grid density discontinuities?

The re-contact agrees with stalling experiments for shallow cavities.

3. Did you do the deep cavity case.? Even though it is unsteady, its time average could be the main physics and fit into your pseudo steady approximation.?

Speaker's Reply: 1. Methods have been developed and are being further developed to minimize the change in grid density at the interface.

3. I agree that it would be interesting to look at the application of our approach to a deep cavity. Currently we have no sponsor to continue the work.

Discussor: Ronald Deslandes

Question: Sean, do you completely neglect the transpiration terms when you are computing the viscous version?

Speaker's Reply: No, a multiple reference frame approach is used to model the relative motion of the store to the parent aircraft. So, for a node on the surface of the store the flow velocity matches the store´s velocity – as with transpiration.

This approach is an extension of the transpiration approach to include field terms.

Discussor: Fred Mendonca

Question: What does the trajectory calculation loose from running steady store CFD, or differently sated, what would be gained from running fully transient time accurate CFD?

Speaker's Reply: I guess the answer to this question is different depending on the case that is being considered.

If the unsteady perturbations, that are inherent to the cavity flow, significantly affect the aerodynamic loads on the store, then some averaging will be required to perform a trajectory simulation – or a large number of trajectories will have to be run.

So, in conclusion, I think the two approaches would need to be compared for a number of cases to get a feel for the validity of the quasi unsteady assumption, for cases where the flowfield is inherently unsteady,

However, for this comparison to be useful I think a number of transient releases would have to be performed starting with different snapshots of the initial in- carriage flowfield.