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An MDO application for a weapon released from an internal bay

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1. INTRODUCTION

Multi Disciplinary Optimisation (MDO) process has always been identified as an essential tool for the development of an aircraft design. Recent engineering emphasis has been on improving the depth of optimisation within a reduced overall time frame, a goal which depends on the level of automation available and the capability and skill of each discipline.

The figure below shows an overview of the general design cycle in the military aircraft manufacturer's world. The large time spans involved in the full process should be appreciated: it may take between ten and twenty years to bring a new project to fruition.

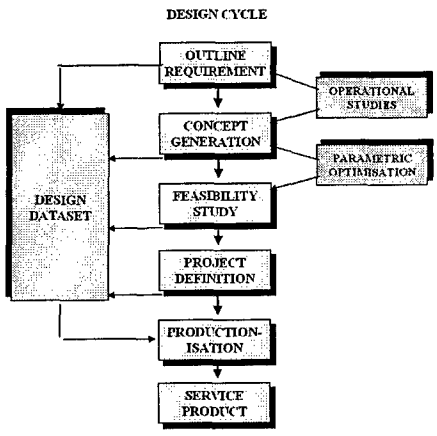

Figure 1.

The design process starts from a set of Operational Requirements, generated and substantiated by wargame scenarios. These requirements get translated into a set of design configurations which attempt to meet the requirements in various ways. Several iterations are needed to then select the final configuration(s).

Initial conceptual design takes place during the first two or three stages of this process and is conducted in a much reduced time scale. This allows many concept options to be examined and a knowledge database to be built up.

One of the key enabling factors for MDO over the past few years has been the introduction and widespread use of CAD within the initial design process. The use of a single model acting as a digital master allows the individual designer to take responsibility for all aspects of the initial layout and use the same controlling geometry for each task.

A fully integrated MDO process should cover all the factors which affect the major aircraft components from different engineering analysis viewpoints, and be embedded within a Synthetic Environment (SE) to meet the automation requirement. As a consequence, the optimisation of any particular concept design remains a complex problem because of the large number of variables to be considered. While the advent of large scale computing capabilities and the development of mathematical optimisation techniques has meant that artificial intelligence methods can now be applied to the configuration optimisation problem, the ultimate success or otherwise will depend on the skill, experience and judgement of the design team involved.

It should be noted that current MDO studies are limited to particular aspects of the overall configuration.

This paper shows the results of a study to demonstrate the advantages of a concurrent design process applied to an internal weapon installation and to report on the lessons learned.

2. STUDY BACKGROUND

For military aircraft, internal carriage is perceived as being one of the key ways of maintaining Low Observability (LO) during missions and offering enhanced survivability. Weapon bays have a significant impact on overall air vehicle configuration, and it is vital to ensure that the key constraints can be evaluated at relatively low cost early enough in the design cycle so as to minimise the overall air system development costs.

The weapon bay environment is one of the high risk features of LO platforms. The aerodynamics of deep weapons bays are characterised by highly unsteady flows, which generate high dynamic pressure levels throughout the bay [1 & 2], giving high aero-acoustic loads, which in turn lead to potential structural fatigue problems and equipment qualification challenges. Methods are required to predict these levels to a calibrated accuracy in order to assess interactively and quickly during the configuration development phase the effect of different options so as to reduce risk in the weapon bay design.

In order to assess the safe separation of stores from the weapons bay, current trajectory prediction methods and techniques also need to be assessed to account for the effects of the dynamic flow within and around the weapons bay.

Paper presented at the RTO AVT Symposium on "Aerodynamic Design and Optimisation of Flight Vehicles in a Concurrent Multi-Disciplinary Environment", held in Ottawa, Canada, 18-21 October 1999, and published in RTO MP-35.

Because these two major items tend to drive the bay shape in opposing ways, a compromise between them needs to be found in order to achieve a bay design capable of carrying and releasing weapons safely whilst maintaining equipment functionality and structural integrity. It should be noted that, once established, the bay cannot easily be altered.

The figure below describes pictorially the situation for stores release.

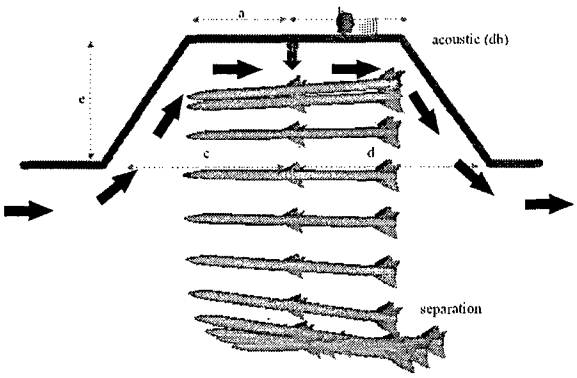

Figure 2.

3. WEAPON BAY TESTCASE

As part of the process of developing the overall MDO process for future design, an exercise has been carried out by the BAe MA&A Future Offensive Air System design group, to examine an internal weapon carriage and release case. The environmental aspects (i.e. acoustic noise levels) and the weapon safe release aspects were addressed simultaneously. This generic study has been performed with the major aim of proving that a more comprehensive and accelerated design process can be achieved by an automatic parallelisation of tasks. It was also a practical test case which identified some constraints and limitations of the optimisation method used.

The bay geometry has a strong influence on both the environment and the behaviour of the weapon during release. The acoustic characteristics of "deep" bays are notoriously very severe and release from "shallow" bays can be quite difficult, depending on the weapon and bay relative geometries. These are obviously simplifications and invariably other factors, such as flight conditions, ejector launchers, missile release controls, bay doors positioning, and noise suppression will also contribute to the overall solution. These additional terms have however been frozen for the purpose of this exercise.

The aim of this study is to demonstrate the design optimisation capability, based on the FRONTIER MDO tool, within the aerodynamics discipline on a simple 2D cavity test case. Although this is not a comprehensive 'multidisciplinary' demonstration, it does span a number of aerodynamic sub-disciplines, including dynamic loads and stores release.

The study aimed at demonstrating the feasibility of linking together a standard aerodynamic CFD tool with a mesh generator and a stores release code through the FRONTIER optimisation tool. Compromises had to be made at the expense of accuracy, in order to obtain quick solutions. The study was limited to a 2D case to ease the CFD processing time, since one current area of particular concern is the affordability (both in terms of supercomputing resource and elapsed time) of unsteady Navier-Stokes methods which are required to model cavity flows. Throughout the exercise, the accuracy of the CFD solutions was also assessed, but this was not a paramount consideration.

4. METHODOLOGY

In this section, we will state the design problem addressed, indicate the role of the general FRONTIER framework in integrating and supervising the design search, and define the analysis tools used to evaluate each design and how they are used.

4.1. THE EXAMPLE DESIGN PROBLEM

The weapons bay considered is represented by the following 2D geometry. The design variables, shown in figure 3, are; cavity base length L, cavity depth. D; and cavity rear face angle θ.

A conventional Heavy Duty ejector system with short stroke length (100 mm) is assumed. The ejector is mounted at the top of the bay and in the middle of the cavity base. On release, the weapon is fired down into the airstream, and is subject to forces from the ejector, the airflow, and gravity.

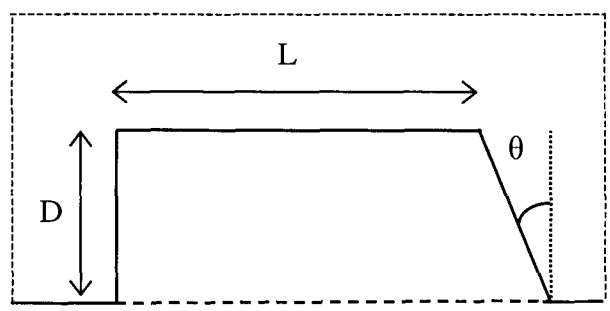

Figure 3.

The problem posed is:

minimise acoustic load A and maximise store separation S;

with respect to (L,D, θ) subject to the simple constraints:

$$1 < L/D < 10.$$

In this example, A is measured using the time history of the pressure at the upper rear corner of the bay. The fluid flow simulation is run for a 'settling period', then the pressure time history is recorded. At the end of the simulation, A is calculated as the total power in the spectrum of this pressure history. This metric keeps analysis simple and calculation time low. More sophisticated metrics may in future include automatically searching for tonal frequencies defining cavity

resonance.

S is the minimum vertical distance of any part of the weapon from any part of the structure, 0.5 seconds after release.

4.2. FRONTIER ENVIRONMENT ROLE

A typical optimisation exercise consists of a number of nonrecurring setup operations, followed by a recurring round of actions which create and evaluate a range of designs. Most of the tools needed are of course provided by the owner of the particular optimisation problem concerned. The role of the FRONTIER environment [3] is to provide systems integration, optimisation tools, and decision support tools.

The optimisation 'search engines' available include hill climber and probabilistic search algorithms. The search can also be controlled by the user. In the current study, we are addressing a multiobjective problem (minimising A and maximising S simultaneously), so a multiobjective algorithm is needed [4].

For each design proposed, the flow solver used for design evaluation expects a geometry input file, so the (L, D, θ) combination which defines each design considered needs to be turned into a full geometry using a geometry creation facility.

Then, the design needs to be evaluated, by activating the required analysis tools in the necessary sequence. Following this, the evaluation results are inspected, and also fed back to the search engine, to provide guidance for further searching.

This set of 'propose-create-evaluate-feed back' operations is continued until terminated by the designer.

4.3. GEOMETRY CREATION TOOLSET AND METHODS

The tools used in this case were the GAMBIT code incorporated within the Fluent CFD code together with a small in-house module to prepare GAMBIT input. In general, this geometry creation step would be carried out by the company's main CAD system, CATIA, using an interface appropriate to the data exchange format demanded by the evaluation tools.

4.4. DESIGN EVALUATION TOOLSET, PROCESS, AND METHODS

4.4.1. Toolset

The toolset included:

- the Fluent Inc. geometry and meshing tool GAMBIT 1 [5]
- the Fluent Inc. CFD analysis tool Fluent 5.1.1 [6]
- the CFD visualisation and post-processing code EnSight [7]
- the BAe NUFA semi-empirical weapon aerodynamics model, capable of operating with a non-uniform flowfield [8]
- and the BAe 6-DoF modeller STARS (Store Trajectory And Release Simulation) as the stores release trajectory prediction tool [9]

4.4.2. Design evaluation process

These tools were used to populate a design evaluation process. The process flow is shown in outline in figure 4.

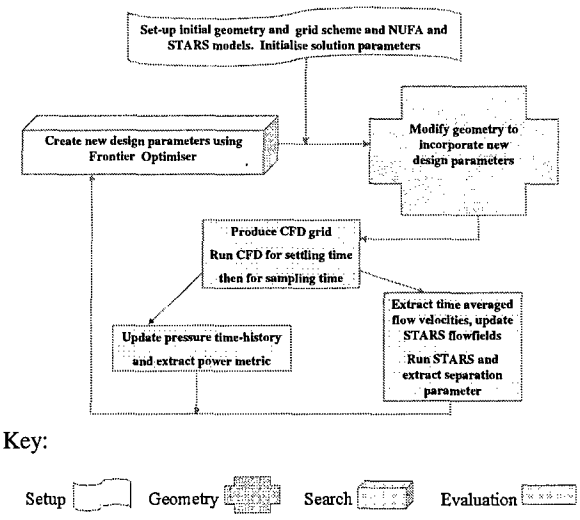

Figure 4.

4.4.3. Methods used for design evaluation

4.4.3.1. Flow modelling

The flow was modelled within Fluent by solving the unsteady Reynolds-Averaged Navier-Stokes equations with a 2 equation k-ε turbulence model using a 'dual time-stepping' scheme. All runs were carried out at Mach 0.90 onset flow at a Reynolds number of 20×10^6. Default Fluent tuning parameters were used. The time-marching inner solution was limited to 20 iterations per time step, while a physical time step of 0.002 seconds was used in order to pick up the primary modes of the unsteady oscillation. In a 'production' case, a smaller stepsize could well be used to capture higher frequencies of interest.

Run length is determined by the frequency resolution needed. In this study, this was not a consideration since total power was used as the metric of interest. However, in a 'real' case, a frequency resolution of around 3.5 Hz would be adequate to pick out frequency ranges of interest. Therefore, a run length of 150 steps, spanning 0.3 seconds, was adopted. Prior to this, an additional 'settling period' of 100 time steps was used, giving a total run length of 250 time steps.

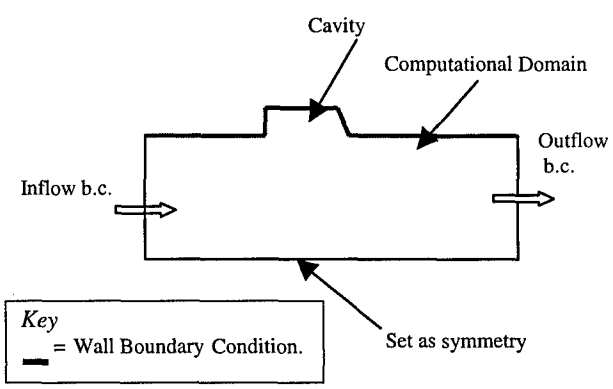

Figure 5.

It is necessary to set flow conditions for the boundaries of the computational domain. These were: prescribed mass flow into the region (based on Mach Number), prescribed pressure at outflow of the region, structural geometry wall boundary condition (upstream, all cavity walls, and downstream), and a symmetry plane condition (i.e. parallel streamwise flow) at the boundary opposite the cavity.

4.4.3.2. Mesh Generation

The mesh generation was carried out using the Fluent mesh generator GAMBIT and was automated using a macro file. An example mesh is shown in figure 6.

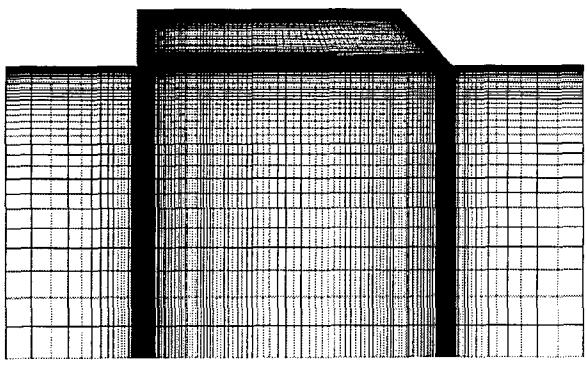

Figure 6.

The meshes used for all the runs in the study were topologically identical, and consisted of 47160 cells.

4.4.3.3. Extraction of power levels from a time dependent solution space.

A monitor was set up to extract from the Fluent solution the pressure level at the upper rear corner of the bay at each time step. The total power in the spectrum of the pressure time history was derived using a simple in-house code. In future, the signal analysis can be made as complex as needed, commensurate with the aims of the study, e.g. specific frequencies can be extracted for assessment of structural response or spectra for equipment environmental qualification.

4.4.3.4. Store release modelling

There are various options for utilising the time-dependent CFD data for a particular bay design, using the trajectory model STARS. One is to take several (or all) 'snapshot' flow fields from the flow solution and then simulate a trajectory for each case, selecting an average or 'worst case' from a safe separation viewpoint to give the optimisation measure. Another option is to reduce complexity by averaging all snapshot flow fields, and simulating a trajectory using this one field. One significant issue was the loss of higher frequency pressure content if this latter averaging process was used.

Separate STARS investigations showed that the effect of pressure variations on the store trajectory is only appreciable at relatively low frequencies (<30 Hz full scale). To ideally model the effective unsteady aerodynamic variation, a low-pass filter would be required and several trajectories would need to be generated from each filtered CFD solution. However, in this exercise, the flow field values of x and y velocity, and mach number are produced at each time step and stored, and direct averaging of these is carried out subsequently to produce a single flow field covering the solution domain. This field then has to be interpolated onto a coarser regular grid of points covering the cavity and the immediately surrounding region using EnSight, to provide input suitable for the STARS simulator.

The flow field data extracted by this method was used with the NUFA package to calculate store loads. (N.B. within the cavity, there are regions of reversed flow i.e. angles >> 90 degrees relative to the weapon. The latest version of NUFA used in this exercise allows for these high local flow angles.) STARS was then used to calculate the missile trajectory. A utility program CRASH was used subsequently to assess safe separation and extract the separation parameter S.

4.5. COMPUTING PLATFORMS USED

The basic modules of the system used are: user interface, process controller, search engine, geometry creation modules, 'A calculation' modules, and 'S calculation' modules.

The architecture supported by the FRONTIER software is such that any of these can reside on any IP-addressable platform reachable on the web. In this case, the primary concern in locating modules is firstly the need to run Fluent 5.1.1 and the geometry creation modules on a SG Origin 2000/120 remotely located; and secondly, the need to minimise data transferred between platforms. This led to deciding to locate the 'S calculation' modules (including STARS) on the Origin too. All other modules were sited on a local Unix workstation. The user interface was, on occasions, run on a convenient Windows NT PC.

The geometry and design evaluation parts of the process are identified in figure 4. These need to be run as a sequence. The FRONTIER environment implements runtime process definition and control, and provides wide area interprocess communications. This is done using CORBA internet protocol, with control and interface layers implemented in Java.

Fluent 5.1.1 can be run on a parallel computing architecture. The SGI Origin used in this study has 120 processors. Previous experience and computing resource availability suggested that each flow solution run should be done using 8 processors. Each time step took around 3 minutes to compute. Together with pre- and post-processing, the total time for one run varied, depending on computer load, between 5 and 10 hours.

5. DESIGN SELECTION

The current study was limited in time and resource, and the design search process used reflects this. The aim was to exercise a simple strategy based on a probabilistic search employing a multiple objective genetic algorithm (GA). We thus implemented two generations of such an algorithm. The initial design set was determined using a quasiuniform Sobol sequence [3]. This distributes the chosen number of designs evenly in the space of the three design parameters. These cases were run and produced 8 measurement pairs (A, S). The search algorithm was then used to select a second generation

of cases. The probabilistic selection mechanism in the GA in this case chose to retain two previous cases and select six new ones. These were then run to produce another set of solutions, giving a total of 14 results for this exercise. A third generation of cases was generated for inspection, but was not run.

6. TESTCASE RESULTS

The geometries analysed are illustrated in figure 7.

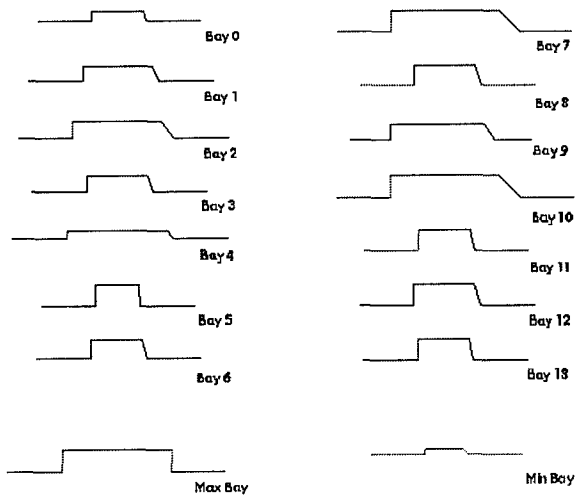

Figure 7.

The associated set of results is given in figure 8.

Design	Length	Depth	Theta	Acoustic	Separation
0	4.7569	0.8765	11.2941	5.5344E+11	3.4416
1	6.5137	1.2529	22.5882	5.1784E+11	11.726
2	8.2431	1.6235	33.7059	4.6454E+11	28.569
3	5.6353	1.4353	16.9412	1.2505E+12	12.726
4	9.1216	0.6882	39.3529	3.6439E+11	-1.177
5	3.8784	1.8118	5.6471	1.3923E+12	9.906
6	4.7569	1.6235	11.2941	1.1201E+12	9.034
7	10	1.9176	43.2353	5.9031E+11	1.151
8	5.6352	1.8118	16.9411	8.2732E+11	11.867
9	8.6824	1.4353	33.3529	5.1917E+11	5.9964
10	10	2	45	6.1934E+11	1.788
11	4.7568	1.9176	11.2941	1.3482E+12	10.102
12	5.6353	1.8118	16.9411	8.2732E+11	11.864
13	4.7569	1.8118	11.2941	1.3E+12	10.018

Figure 8.

N.B. Acoustic (A) is the total power in the pressure spectrum; separation (S) is the minimum separation distance (as defined earlier). A negative value of separation indicates that the missile has passed through the bay geometry.

Designs 0 through 7 were generated at the beginning of the exercise, designs 8 through 13 were the first generation of new designs created by the optimiser. The aim of the optimiser was to minimise A while maximising S. As can be see from figure 8, in general, the new designs generated have improved S without adversely affecting A. Clearly, the number of cases which has been run in this exercise is too small to achieve a meaningful optimisation. However, in the context of this study, it was not affordable to run any more solutions and this should be an area for further work.

The following graph (figure 9) plots the case results showing the relationship between the acoustic metric 'A' and the separation metric 'S'. Clearly, there is no identifiable trend and as already stated, after so few design cases we would not expect to see one. Many more design cases would be required to define the boundaries of the solution space in terms of A and S and ideally to observe the points in figure 9 tending to an area close to the top left hand corner. (i.e. minimum A for maximum S).

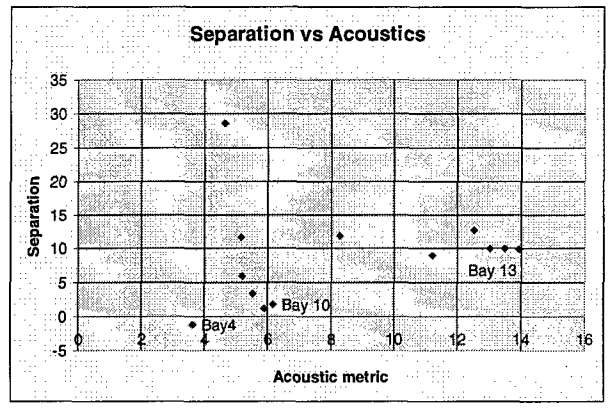

Figure 9.

Pictures of the *time averaged flow-field* (showing streamlines and contours of Mach Number) and store trajectory for four of the design cases is presented in Appendix I. The cases chosen are representative of the various flowfields and trajectories observed. As can be seen from these figures:

Bay 4 exhibits the aerodynamic characteristics of a 'shallow' cavity (L/D~13) with 'low' (comparatively) acoustic levels but with high flow angularity at the missile nose and tail (due to flow entering the cavity) which induces a nose up pitching moment on the missile. An unacceptable trajectory is achieved.

Bay 13 exhibits the aerodynamic characteristics of a 'deep' cavity (L/D~2) with 'high' acoustic levels predicted. However, the relatively low speed recirculating flow regions which occupy the entire bay and the approximately horizontal shear layer lead to a good release trajectory for the store. (Little pitching moment is generated on the store).

Bay 10 exhibits flow characteristics somewhere between those observed in bay 4 and bay 13. (L/D~5) When the missile is released, its nose passes through a recirculating flow region then through the shear layer which is approximately horizontal. However, the missile tail sees an angled shear layer which generates a tail up pitching moment on the store. The release trajectory appears to be unacceptable.

Bay 2 exhibits flow characteristics somewhat similar to Bay 13 though the vortex now occupies the whole cavity. The large resulting separation makes this case worth study and display. Although the general characteristics are those of a deep bay, the actual flow induces a pitch down moment on the store nose, due to the angled shear layer. The trajectory plot in figure A4.2 is somewhat curtailed. It illustrates the

complexities of metric definition, because this trajectory would be good for store jettison purposes, but not as attractive for the weapon's normal operational purposes.

The aerodynamic trends observed in the cavity are in good agreement with the trends identified in more accurate cavity simulations. It is acknowledged that neither of the metrics used in this assessment was ideal. In further studies we may require acoustic power (at some suitable location) against perhaps the store downward velocity.

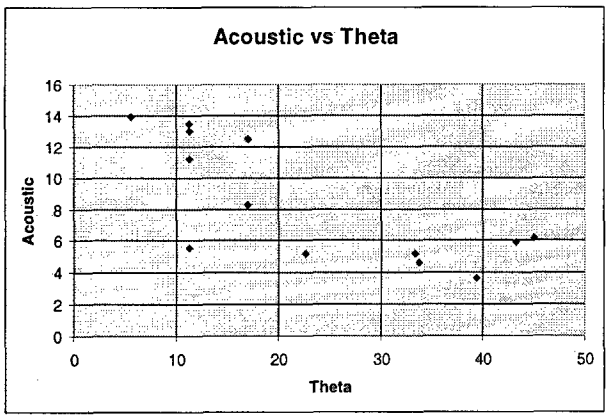

Figure 10.

As a further check on the qualitative accuracy of the solutions, the acoustic measurement was plotted against the cavity rear wall angle (figure 10). This replicates experimental trends observed in wind tunnel tests (outside this exercise) of reducing acoustic levels with increasing rear wall angle.

An initial exploration has been made of the use of a neural net model as a cheaper computational approach. The net was manufactured from the results of the 14 cases already shown. The neural net used had 3 inputs, 2 hidden layers of 8 nodes, and 2 outputs. The result of using this for around 400 design evaluations is shown in figure 11. The net model is clearly strongly influenced by the Bay 2 result.

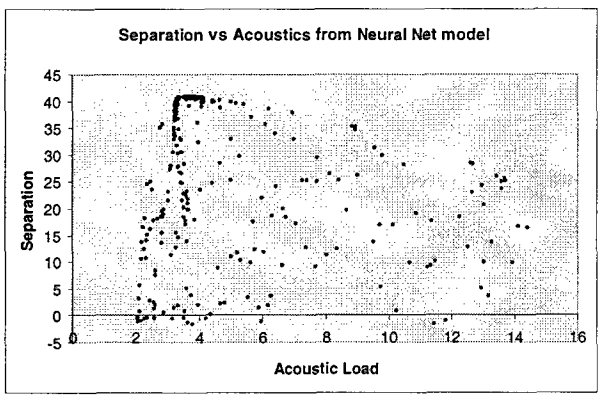

Figure 11

The function of this information would be to guide the selection of another set of full scale evaluations, and in turn use these to improve the net model.

7. LESSONS LEARNED

The exercise was intentionally quite short. It proved successful in highlighting that the process is potentially extremely useful during the early stages of a new design. The main aim of the exercise was to demonstrate the technique and establish confidence, particularly in the systems integration and automation aspects of the task. The validation of accuracy of the method is a subject for separate later assessment. The main lessons are in the following areas.

- CFD turnround times

In order to achieve a practically usable optimisation, considerably more sets of cases will need to be selected and run. The whole of the exercise has demonstrated quite clearly that a practical MDO process which matches the required design cycle timescales can only be implemented for bay installations if faster CFD turnround times are achieved. Defining acceptable levels of simplfication can assist here, together with rules for number of cases required for a given study.

- Search methods

Techniques for characterising the results from a limited set of CFD solutions and extracting maximum knowledge from them are needed. We need to develop a process in which a phase of using a limited number of expensive high fidelity simulations is alternated with a phase of using many more evaluations based on much cheaper models developed by extracting features and information from the accurate runs. The neural net approach illustrated above is one candidate. Ways to integrate CFD calculations with past evidence, theoretical, empirical or semi-empirical, also need to be found. A knowledge database needs to be developed.

- Initialisation

One of the problems with the CFD solution process has been the need to initialise and settle the solution for each case before the measurements can start to be taken. Ways of using the previous CFD solutions to initialise the next test case and hence shorten this process also need to be identified and assessed.

- Results storage

The need for an efficient storage of the CFD output is also required. Two extreme approaches need to be investigated: a) utilise a cheap memory storage system and increase the total storage space, and b) reduce the data size, by novel and extremely effective compression techniques.

- Flow / trajectory coupling

Ways to handle unsteady flow fields within quasi-steady trajectories also need to be addressed. Given the relatively short time required to calculate a trajectory compared to the current overall case run time, it is conceivable to consider a series of trajectory calculations for each CFD solution, but a means of reducing the number of trajectory calculations should be addressed.

- Signal analysis

Appropriate techniques need to be selected for any given exercise. Automation of some engineering tasks such as

cavity resonance frequency identification could increase process usefulness.

8. CONCLUSIONS

It can be appreciated from the foregoing that the design of a modern combat aircraft is quite a complex process. There are many conflicting issues to be resolved whilst trying to satisfy the dominant requirement. The execution of the process requires a wide range of skills and an overall appreciation of a large number of contributory topics. Work needs to continue into the application of artificial intelligence for the optimisation of future aircraft developments and weapon installations.

The use of MultiDisciplinary Optimisations or assessments needs to be encouraged, although it needs to be tailored to the resources available. This process cannot fully replace the engineering judgement and skill, but it can help in making decisions and choices. In some circumstances the MDO process needs to be limited to a parametric what-if rather than an intensive optimisation; nevertheless, the method can be extremely powerful and cost effective. Parallel developments in computing hardware and software need to complement this process.

What will eventually come about is a matter for speculation, but whatever the future, the need will remain for the military aircraft design to be responsive to time constraints.

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- G.Appleyard and I.Horsfield from the BAe MA&A Concept Engineering team.

APPENDIX I – Flow Visualisation

Figure A1.1 – Bay 4 (L/D = 13.25, θ = 39.35 degrees) Flowfield coloured by Mach Number

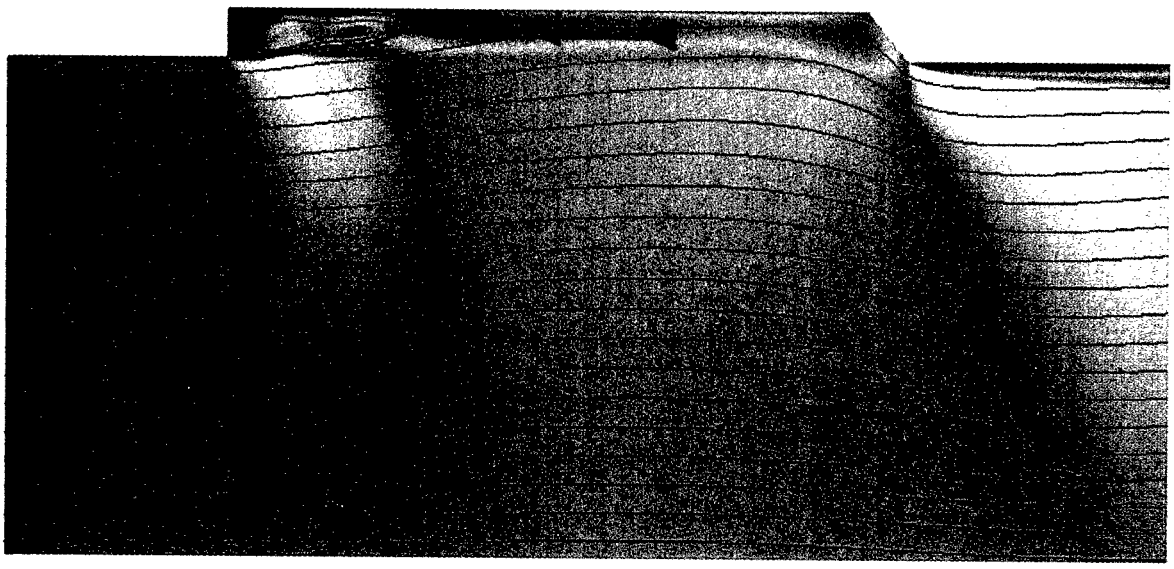


Figure A1.2 – Bay 4 (L/D = 13.25, θ = 39.35 degrees) Stillshot of Trajectory

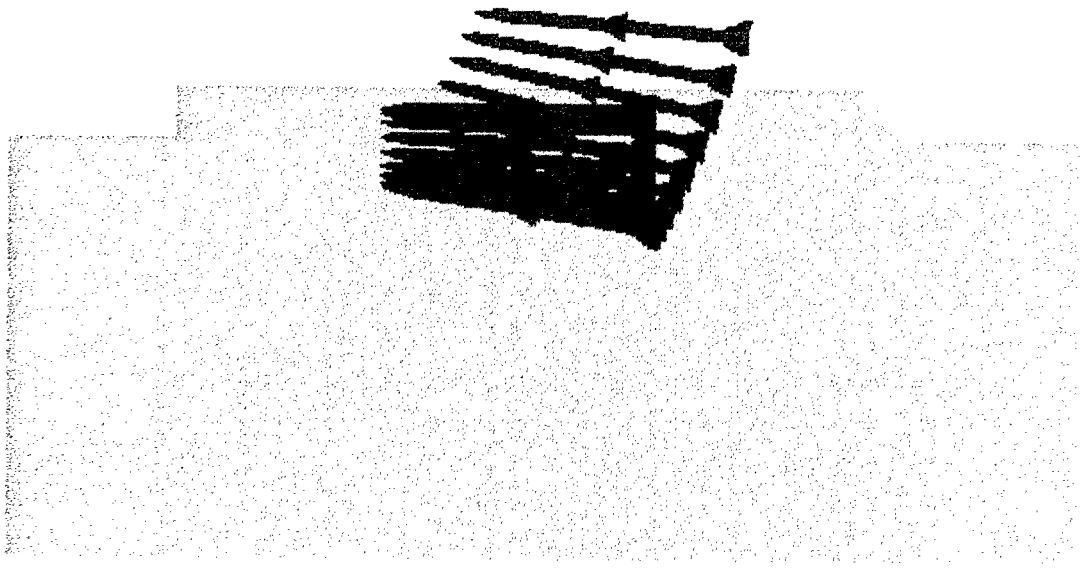


Figure A2.1 – Bay 13 (L/D = 2.63, θ = 11.29 degrees) Flowfield coloured by Mach Number

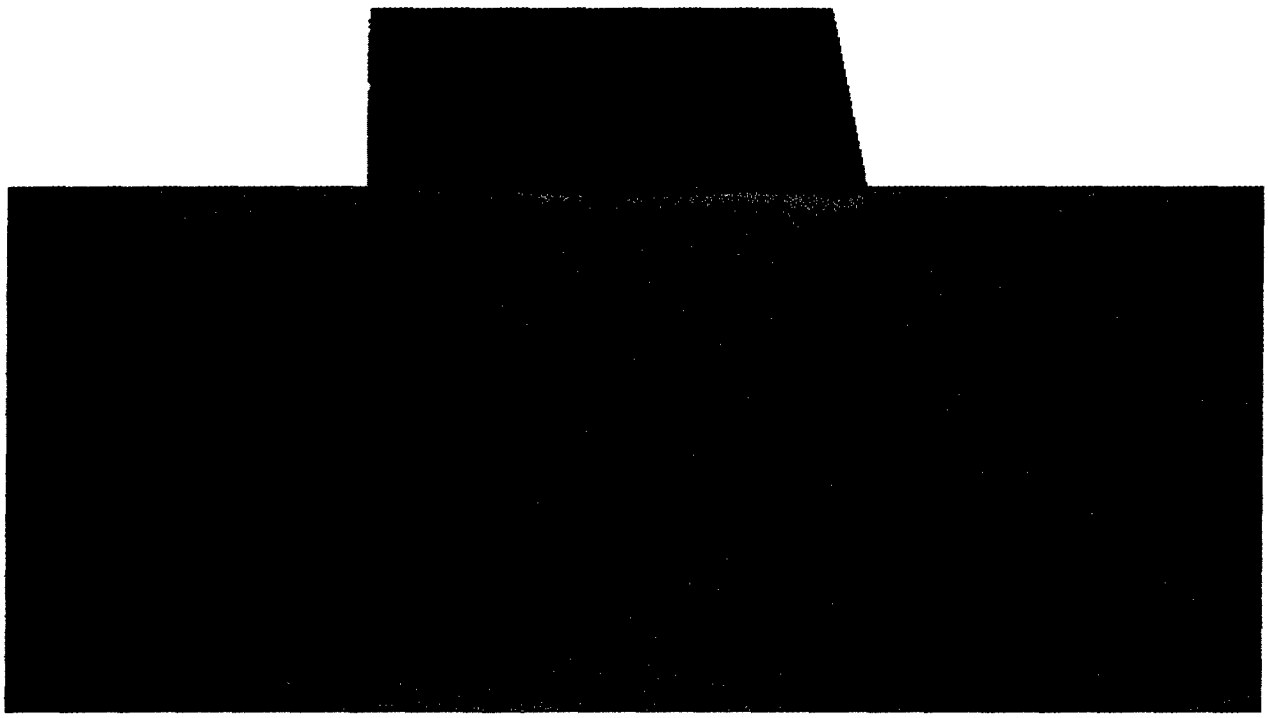


Figure A2.2 – Bay 13 (L/D = 2.63, θ = 11.29 degrees) Stillshot of Trajectory

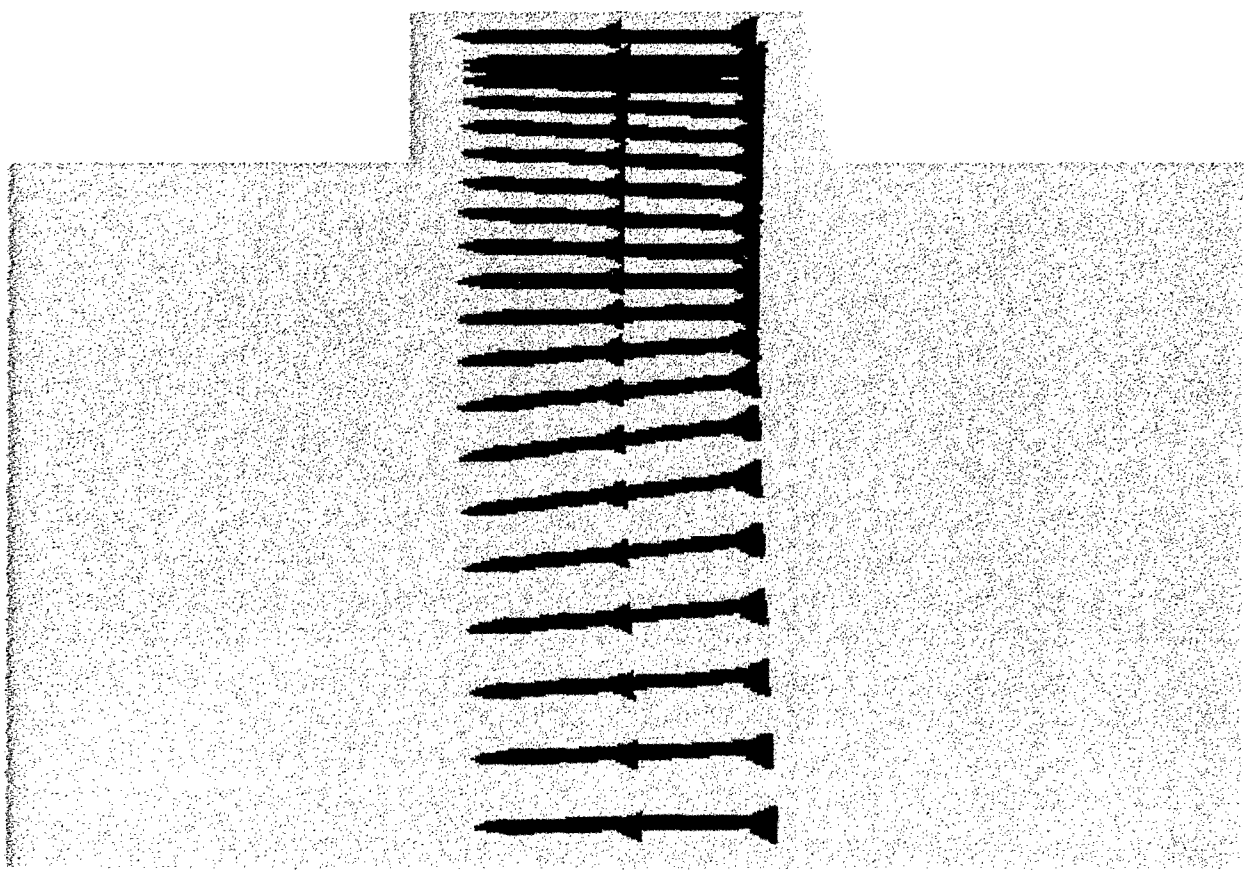


Figure A3.1 – Bay 10 (L/D = 5.0, θ = 45 degrees) Flowfield coloured by Mach Number

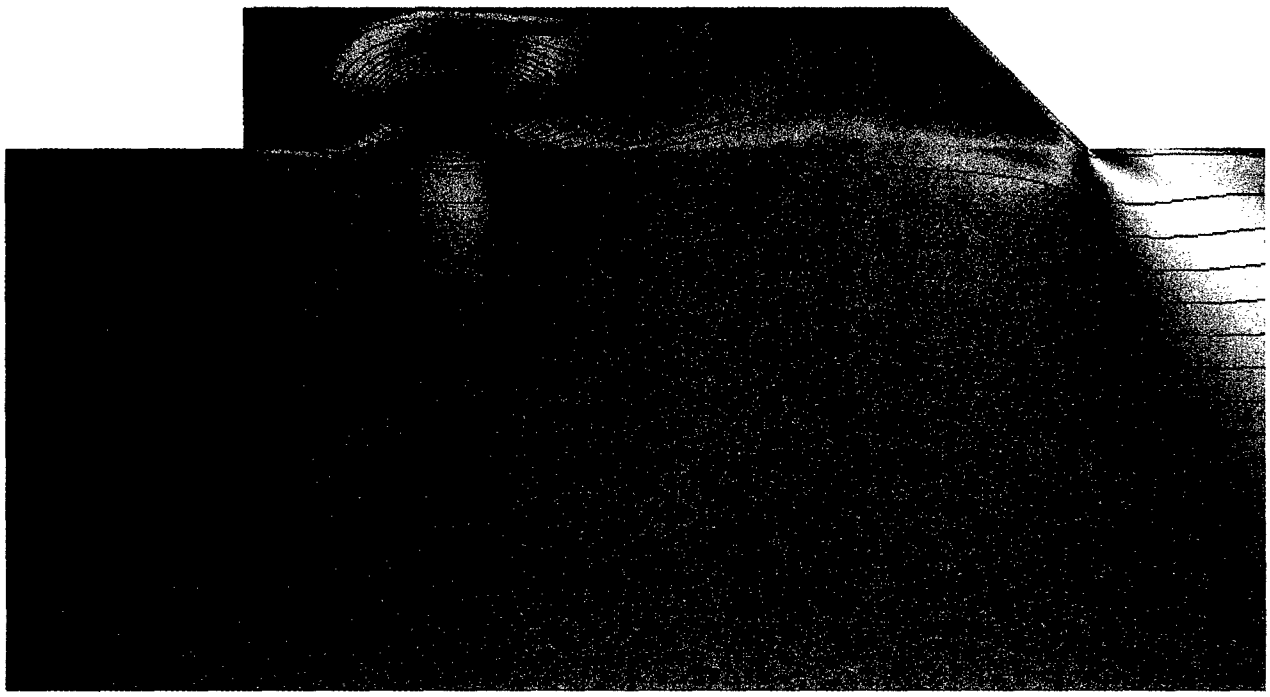


Figure A3.2 – Bay 10 (L/D = 5.0, θ = 45 degrees) Stillshot of Trajectory

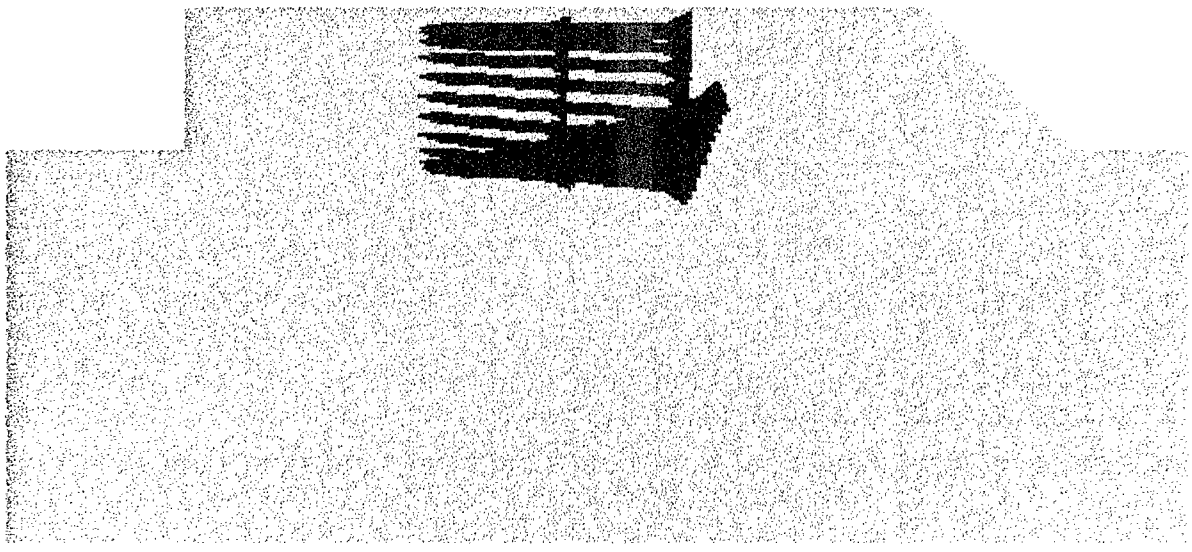
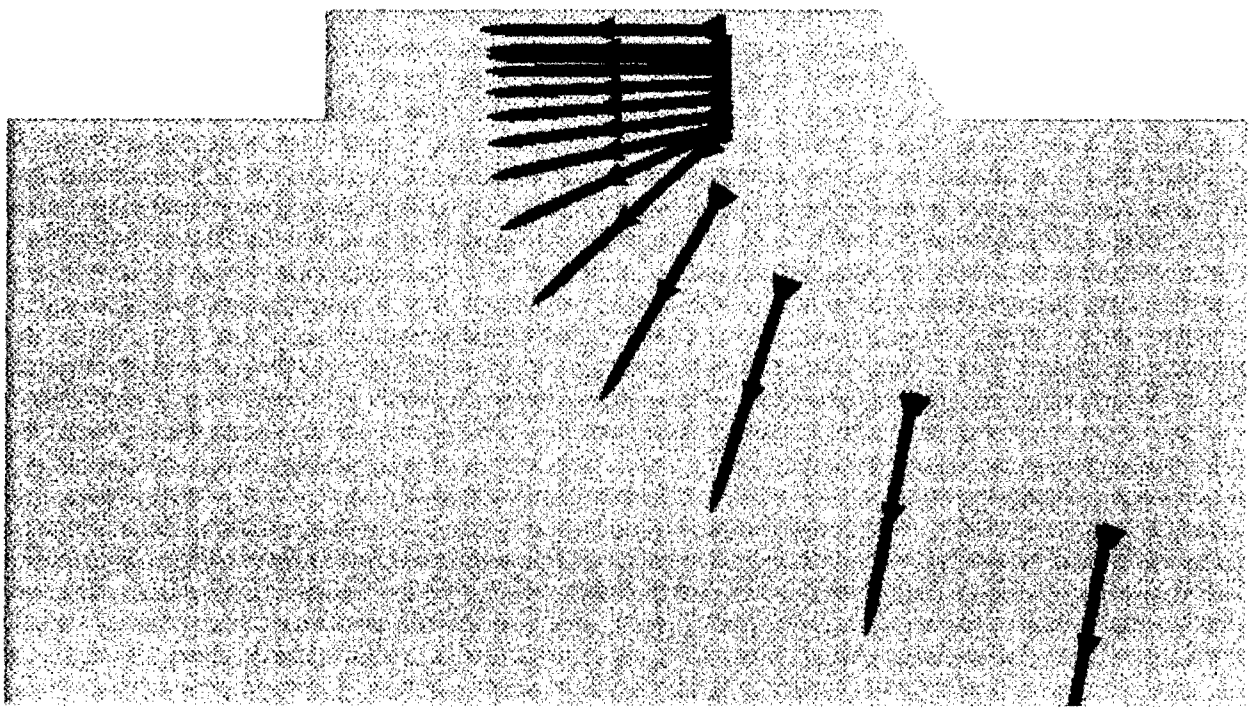


Figure A4.1 – Bay 2 (L/D = 5.08, θ = 33.71 degrees) Flowfield coloured by Mach Number

Figure A4.2 – Bay 2 (L/D = 5.08, θ = 33.71 degrees) Stillshot of Trajectory



DISCUSSION

Session II, Paper #14

Mr Ohman (IAR/NRC, Canada) asked what effects angle of attack would have on the results presented.

> **Mr Moretti** noted that angle of attack has been considered but that its effects were not included in this presentation.