The role of MDO within aerospace design and progress towards an MDO capability

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THE ROLE OF MDO WITHIN AEROSPACE DESIGN AND PROGRESS TOWARDS AN MDO CAPABILITY

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ABSTRACT

This paper reviews recent progress made in MDO within the European aerospace industry through the activities of a sequence of international collaborative partnerships of increasing complexity. Firstly, a definition of MDO is provided and its function as a key tool in the context of concurrent engineering is discussed. Issues addressed include the limited support given by many MDO tools to detail stressing, validation of aeroelastic optimisation, the role of product models, the definition and execution of MDO process under user control and trade-off studies for requirement capture. The need for the adoption of standards in the definition of the product model and the likely impact of the CALS philosophy of 'create data once and use many times' are highlighted.

INTRODUCTION

Multidisciplinary design optimisation enables the efficiency of designs to be optimised and supports trade-off studies between the design objectives of diverse disciplines. The MDO process is intended for use within the context of modern engineering design environment, which is characterised by the commercial imperative to reduce time cycles and costs. These commercial pressures, together with the immense volume of design, manufacturing and maintenance data inherent to complex modern equipment, demand a heavily computerised environment.

Current practice, as exemplified by Concurrent Engineering (CE), is to move the design of complex equipment away from a process involving a sequence of specialist departments and to emphasise its multidisciplinary nature through the use of integrated product teams. Both the structural integrity of engineering products and demonstration of the performance of proposed designs are increasingly reliant on the use of computer models created during the design process. Although the software tools existing within individual disciplines may be reasonably mature, the challenge is now to provide the tools necessary to support such an integrated approach.

The scope of multidisciplinary design optimisation (MDO) is limited to the design of products based on the simulation of physical objects in their environment. The use of multiple simulations is a key concept of MDO. This may involve diverse tools such as: fluid flow solvers (to determine local and overall external forces); structural analysis and detail stressing (to determine structural deformations and internal stresses); electromagnetic analysis (to determine radar signatures from local and overall returns from incident beams); cost modelling and tools for design for reliability. The physics modelling may be mathematical or experimental but the simulation of 'human interaction' effects, for example through the use of flight simulators, is excluded.

At a general level, when considering the overall mission performance of an aircraft, tools exist to aid the conceptual design of both military and civil aircraft and are used during the early stages of the project. Although these adopt a fully multidisciplinary approach, only the simplest, Level 1, empirical models are employed to approximate the physics which influences the overall design. Currently most MDO applications, for use in the preliminary design phases of a project, are based on major simplifications in mathematical modelling at level 2, such as beam structural models or panel methods for aerodynamics.

The objective is now to achieve the same degree of integration with level 3, state-of-the-art analyses. The limiting factor in the use of such best, proven models is the capacity of current computation technology. Analyses using computational fluid dynamics, computational electro-mechanics, or detailed finite element models are separately capable of pressing computer resources to the limit, and this is compounded by the introduction of sensitivity calculations and

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optimisation. It is evident from conferences devoted to MDO[1-3] that the move to higher fidelity analysis tools, which have formerly been the preserve of specialist departments, is general.

The software framework one may require to control such a process, user interface issues and the form of product data used to support design, manufacture and operation are discussed in this paper in the context of a series of MDO collaborative activities within the European Aerospace industry. While the conceptual design tools referenced above tend to be close-coupled, it is of interest that the tools used in the various collaborations have all been loosely coupled.

STRUCTURAL OPTIMISATION GARTEUR SM(AG13)

Detail design

One of the problems in introducing MDO is the complexity of the design process itself. Even within the single discipline of structures, finite element programs will be supplemented by a range of data sheets, detail stressing programs and manual methods, all used to establish structural integrity. It is essential for the credibility of an MDO process that it should be able to accommodate the detailed design processes normally used within the company.

The GARTEUR Structures and Materials panel has supported collaborative research activities on Structural Optimisation from 1990 onwards. In particular the GARTEUR Action Group SM(AG13) addressed the use of panel design codes within the overall strength and stiffness design process for aircraft wings. Here, even within the context of a single discipline, the MDO-related issue of multilevel design arises, since the FE-based codes, commonly used to improve overall wing efficiency, may be supplemented by codes for detailed panel stability design and assessment, applied on a panel by panel basis.

Codes for the buckling design of composite panels

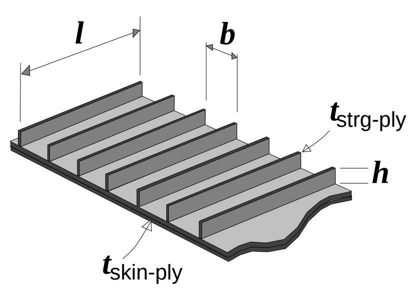

Fig. 1 : Dimensions of compression panel

were available from DASA Airbus, NLR and U.Cardiff and others were purpose-written as required. Structural optimisation codes were available from BAe, DASA, SAAB, Dornier, Aerospatiale, NLR and DERA. The major codes were presented by their originators and compared, and multilevel methods for the integration of panel and overall structural optimisation were investigated.

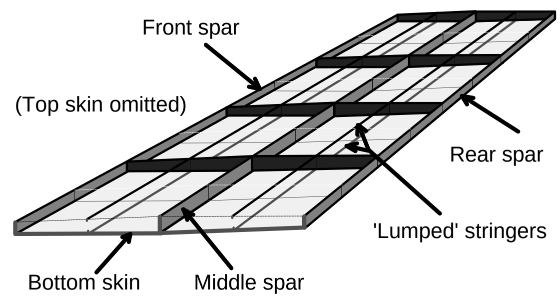

Fig. 2 : Simple wing model

The methods developed were evaluated using civil and military aircraft wings of differing complexity as benchmark problems[4], the simplest being that shown in figure 2. A larger problem of a commuter-aircraft wing, from DASA Airbus, is regarded as an industrial-scale problem and the development of strategies for exploiting composite materials in compression structure were regarded as important.

Overall it was found to be possible to include the detailed design of composite stiffened wing panels against buckling within the overall strength and stiff-ness design process for the wing using relatively simple strategies, although it is acknowledged that interaction effects between adjacent panels are not addressed by these methods.

MULTIDISCIPLINARY DESIGN OPTIMISATION OF AIRCRAFT WINGS GARTEUR SM(AG21)

Aeroelastic Optimisation

GARTEUR Action Group SM(AG21) on multi-disciplinary wing design concentrates upon the integration of strength and aeroelastic aspects of the design of high aspect ratio wings typical of modern regional transport aircraft, as illustrated in figure 3. The DERA contribution is based on the use of the in-house structural optimisation code, STARS[5] which, like several others, embodies aeroelastics as a tightly-coupled functionality. Both the aeroelastic predictions and design strategies to come out of the optimisation will be compared with those of the other partners within the group.

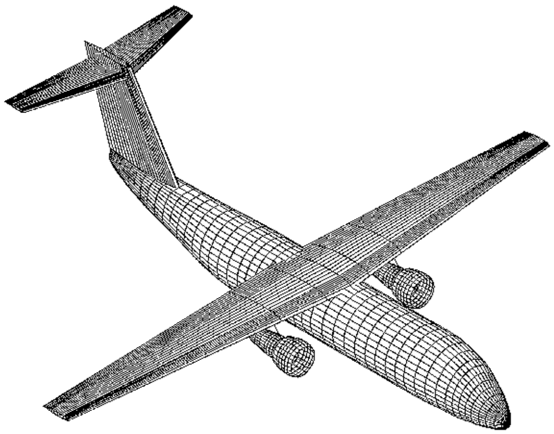

Fig. 3 GARTEUR SM(AG21) model

While several European companies have long had the capability of combining aeroelastic design with basic strength requirements within the context of what are principally structural design codes, the progress of a follow-on GARTEUR Action Group is discussed in providing a forum for the validation and comparison of the capabilities of various companies. Such comparison is felt to be important since, from other collaborative projects, it has been found that significantly different ‘solutions’ can found by different groups

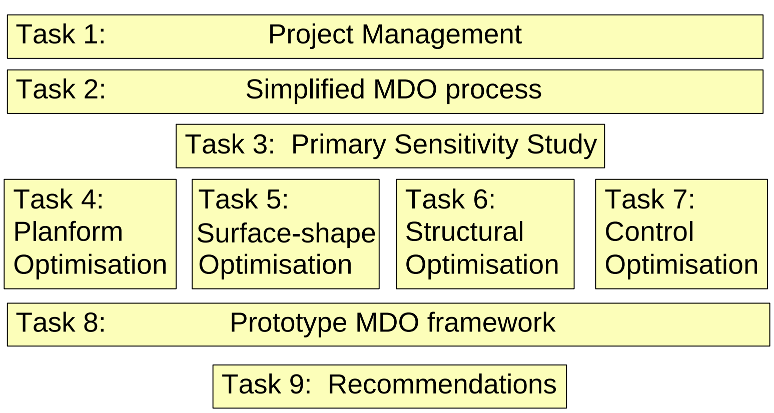

Fig. 5 : Task structure for EU MDO project

MDO OF AEROSPACE VEHICLES EU IMT PROJECT BE95-2056

Project outline

The MDO project represented a first step into multi-disciplinary analysis and design optimisation for many of the partners. The application selected to demonstrate new capabilities developed during the project was based on the A3xx concept currently under development by the Airbus partners. A whole aircraft model was provided for aeroelastic and controls studies, but the design activity was focused upon the wing.

The project was subdivided into a series of tasks shown in figure 5. All partners participated in the definition tasks 1-3 and from then on separate groups were responsible for the investigations conducted by tasks 4-7. The project was supported by the software infrastructure group working in task 8 in which participating partners were drawn from each of these task groups. The final stage of the activity was to draw together the lessons learnt from the project as recommendations in task 9.

Aerodynamic and Structural design

The objective of the work was to develop and demonstrate a capability for the aerodynamic and structural design of a wing which would minimise the direct operating cost (DOC) of the A3xx concept aircraft. The form chosen for the DOC was simply a linear combination of mass and drag relative to that of the reference aircraft *viz*

$$\Delta(\mathrm{DOC}) = 1.0\Delta W + 1.0\Delta D_{econ}$$

where W is the mass in tonnes and D the drag in counts. The majority of the optimisation work performed was based on the use of a few gross wing design parameters, namely: area, aspect ratio, rear spar location, sweep, crank thickness and tip twist.

The initial work conducted by the partners in Task 5 was simply to optimise the wing with respect to the two surface shape parameters, crank thickness and tip twist, and to compare results for aerodynamic drag and structural mass corresponding to this baseline case[8].

The optimisation results in figure 7

show a considerable variation between partners. In particular, significant differences are found depending upon the treatment of fuselage effects and the design of a wing in isolation also changed significantly when the wing was treated as part of a trimmed aircraft model.

Such differences are not a simple matter of right and wrong, but rather depend upon an understanding of the important characteristics of the flow and of the limitations of the various numerical approaches. At this stage in the development of MDO there is little or no interest in close-coupled black-box methods. A strong need was perceived to use familiar legacy codes within a loose-coupled modular framework that enabled the output from every process to be evaluated before proceeding.

While differences in the aerodynamics provide the main contribution to the variation of results, similar difficulties are also encountered resolving differences of design arising from the structural optimisation, despite this being regarded as a relatively mature technology. A reasonable consensus was achieved for the finite element results, but the optimisation, particularly that of the commercial codes, tended to be over-sensitive to details of the method selected and parameter settings and did not necessarily converge to optimum solutions.

The DERA-specific work introduced multiple flight conditions into the optimisation. Aerodynamic analysis

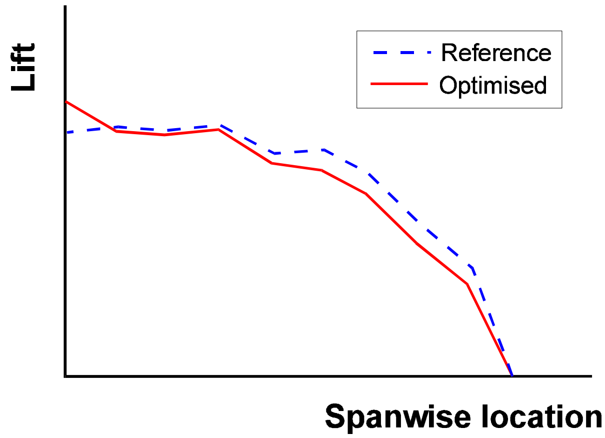

Fig. 9 : Spanwise distribution of lift for heavy cruise

sis of the wing is performed at light, economic and heavy cruise and the drag calculated is combined with the mass given by structural optimisation, to give an estimate of direct operating cost in the form

$$\Delta(\mathrm{DOC}) = 1.0\Delta W + 0.4\Delta D_{light} + 0.2\Delta D_{econ} + 0.4\Delta D_{heavy}$$

Some of the trends were similar in the single and multiple condition optimisation. In particular it was noticeable that the lift moves slightly inboard as in figure 9. This changes the trim of the aircraft, reducing the downforce required on the tailplane, and hence decreases the total lift of the wing. This results in a reduction in the lift-induced drag for all flight conditions.

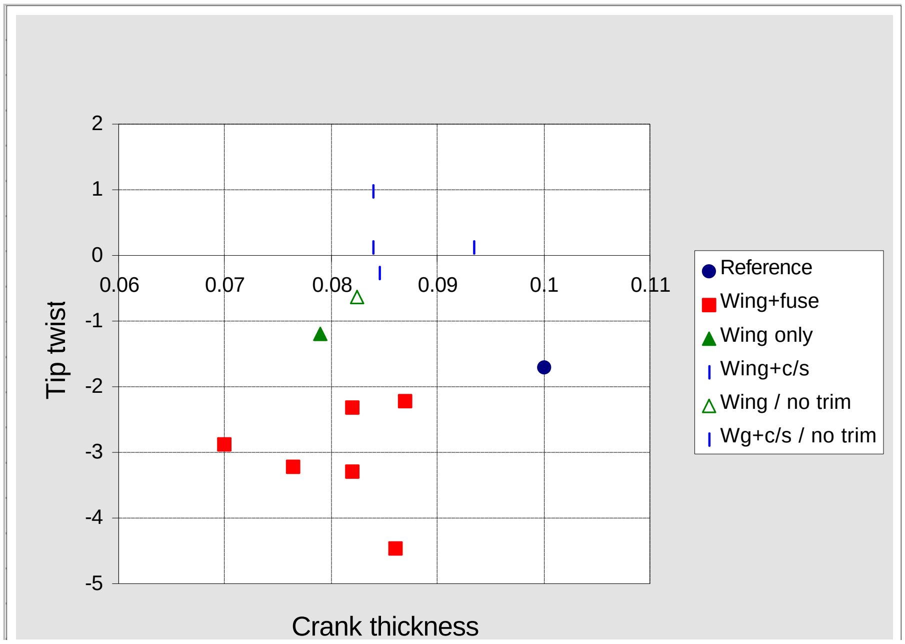

Fig. 7 : Optimum designs calculated for baseline problem

At both economic and heavy cruise conditions there is a weakening of the shock waves which also tend to move inboard. The reduced contribution to the total drag from the shock wave drag is particularly important for heavy cruise. Optimising the wing for the economic cruise condition, in the hope that the design will also prove satisfactory at light and heavy cruise, gives poor results in heavy cruise condition. By optimising the wing for multiple cruise conditions, the drag at heavy cruise is improved without losing the improvement at the other flight conditions.

This task illustrates the need for flexibility within an MDO process, to allow the user to configure the optimisation process to accommodate multiple assessment tools, specific to each problem.

Product models and TDMB

The complexity of the data flow which links the disciplines of aerodynamics and structures, is illustrated in figure 10. This starts with a requirements system, which is assumed to be external to the MDO system, in which some freedom is assumed to exist to fine-tune the relative importance of various aspects of performance. An outline concept is then developed as a parameterised product model. This is followed by various assessments, here shown as aerodynamics and structures, with the possibility of making detailed shape and thickness changes for a given configuration.

Referring to figure 10, it is clear that large amounts of data, which may well be stored in separate databases, must be communicated between the component parts of the MDO system. The key issue for data transfer is the setting of common standards for the interpretation of information across disciplines. For MDO, the standards must cover all aspects of product geometry definition and design requirements, together with specific discipline-based data that reflects the constraints upon the design.

During the early meetings of the MDO project, a series of key activities were decided upon which defined the nature of the project. One was to adopt the BAe program TDMB[7] (Technical Data Modeller & Browser) as the repository for the product model. TDMB provides a text editor user interface which supports an definition of data objects and then expands to store instance data capable of representing several variants of the product together with performance data derived from aerodynamic and structural analysis.

A fully parameterised representation of the aircraft configuration was developed, with tools to generate aerodynamic data, finite element models and aeroelastic models used for performance assessment. This data-representation serves the project by providing partners with a common product model upon which design studies were based. The data models defined in TDMB will be exportable to the STEP/EXPRESS data definition language to enable future migration to other systems which conform to evolving standards for product models. The wider use of data which conforms with the STEP standards[6] is an important element of achieving the CALS objective of ‘creating data once and using many times’ through the product life cycle.

MDO process

A major factor which will influence the overall success of any MDO implementation is the approach adopted to the co-ordination and scheduling of the diverse range of activities necessary to complete a full design cycle. This aspect of MDO must be adequately defined in the early stages of the development process in order to draw together the different disciplines and allow concepts to be explored.

A framework specification document was written by the Task 8 partners and various software tools were provided. These include tools for: software version management, data definition, database technology, process definition, process execution on distributed networks, data visualisation and optimisation.

Several alternate frameworks were employed and evaluated against the user and system requirements previously developed. The frameworks assessed included commercial MDO frameworks and toolsets, a process-driven Workflow Management tool and Network middleware.

The frameworks tended to operate with a pre-defined sequence of operations and failed to provide the user with sufficient flexibility to reconfigure the process during the early exploratory phases of a design study. The interactive definition of a complex process is a prime requirement of any optimisation framework.

The strength of work flow management tool is the traceability and control it offers, whereby only approved users may initiate processes and that only provided the input data has not been invalidated by changes by an upstream process. Network middleware systems enabled the computer resources of the network of machines to be utilised with the facility that one may expect of a single machine, but tended to require user-intervention and were weak at running chained processes.

As may be expected the purpose-written MDO frameworks provided the most flexible integration support but did not necessarily distinguish the process support aspects (including the registration of tools, the definition of process chains and their execution) from data management (product models and requirements) or from embedded tools (for the visualisation of various categories of data or optimisation functionality). Further development is needed if the frameworks are to operate in a standards driven environment accessing data from corporate data bases.

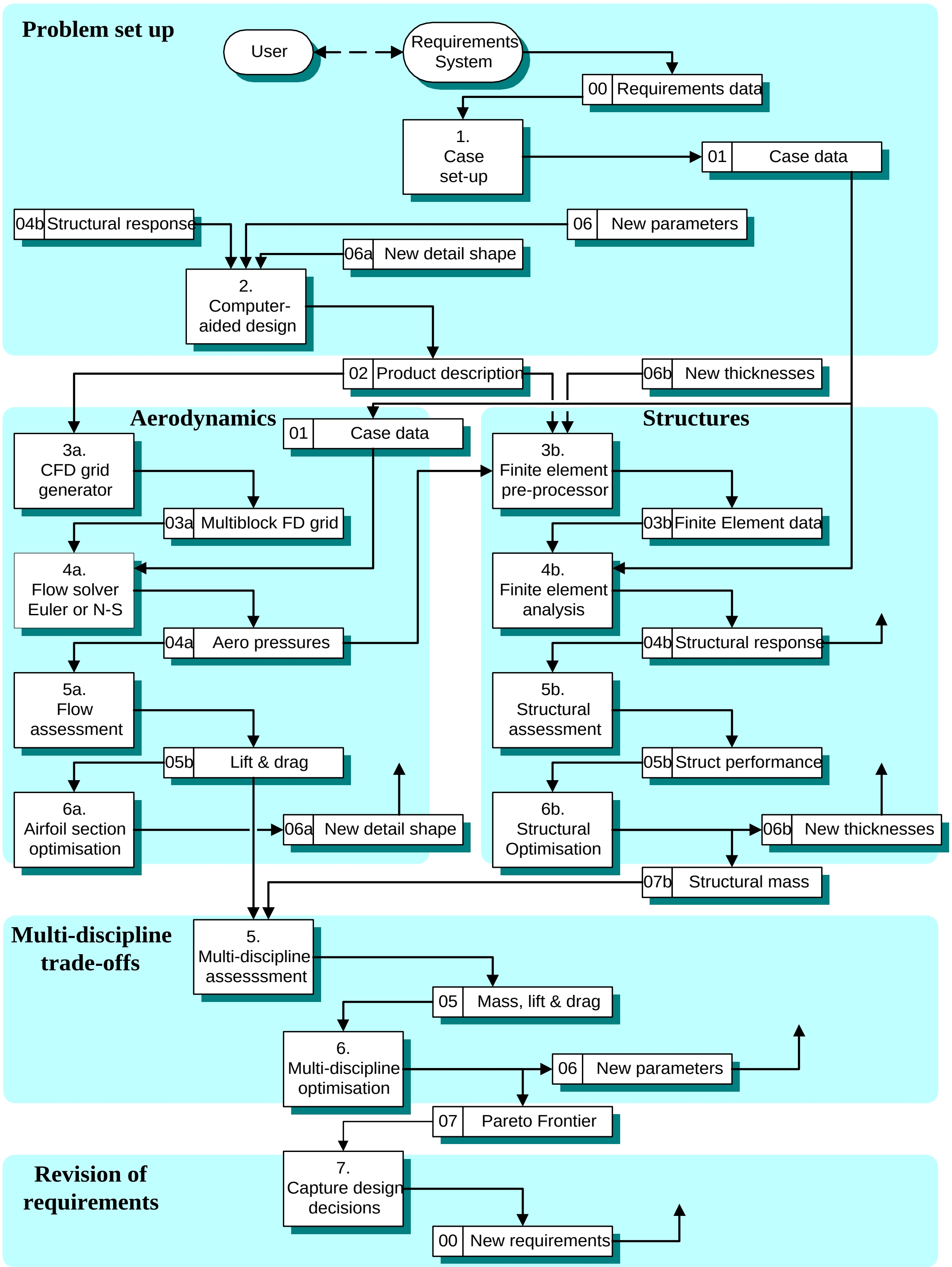

Fig. 10 : Data flow showing multidisciplinary tools

The role of the optimiser

The role of the optimiser has also been the subject of slight variation within the various partner frameworks. At the simplest, the optimiser calls for function evaluations, possibly including gradients, at a sequence of design points and, in effect, controls the process. As the function evaluations call for increasingly time-consuming analyses with complex data interactions and, possibly, requiring user-intervention, this becomes a less attractive option.

An alternative approach is still to start the design cycle with the optimiser initiating a design change, but to return control to the framework for the performance assessment phase. The optimiser must then be capable of being restarted once the performance assessment is complete. In software terms, the optimiser may then appear as just another MDO process, to be called as required, but its controlling role within the process of design should still be recognised.

FRONTIER / ESPRIT PROJECT 20082

Project outline

Finally the contribution of the EU project Frontier[9] towards the capture of requirements is described. It is almost inevitable that any MDO problem, as initially formulated, will not automatically lead to the required product, since impact of constraints and the balance of conflicting requirements will not be fully understood at the outset. In this project, a Pareto-frontier approach is used together with multi-criterion decision making (MCDM) software to capture customer preferences. Clearly, if cost were a criterion, this leads to a cost/performance assessment which is a key input to any requirement capture process.

Although Frontier is a relatively small project, it is of the widest scope in that it considers design against multiple objectives. The project partners consist of universities who are, in the main, acting as suppliers of new technology and industrial partners who are providing user trials relevant to their industry sector.

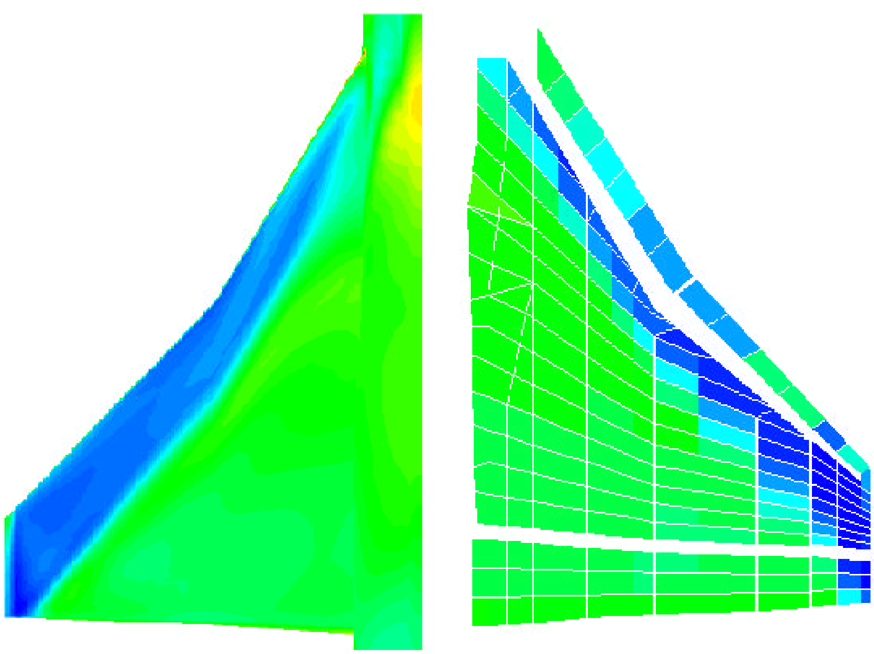

Fig. 12: DERA 'user trial' model

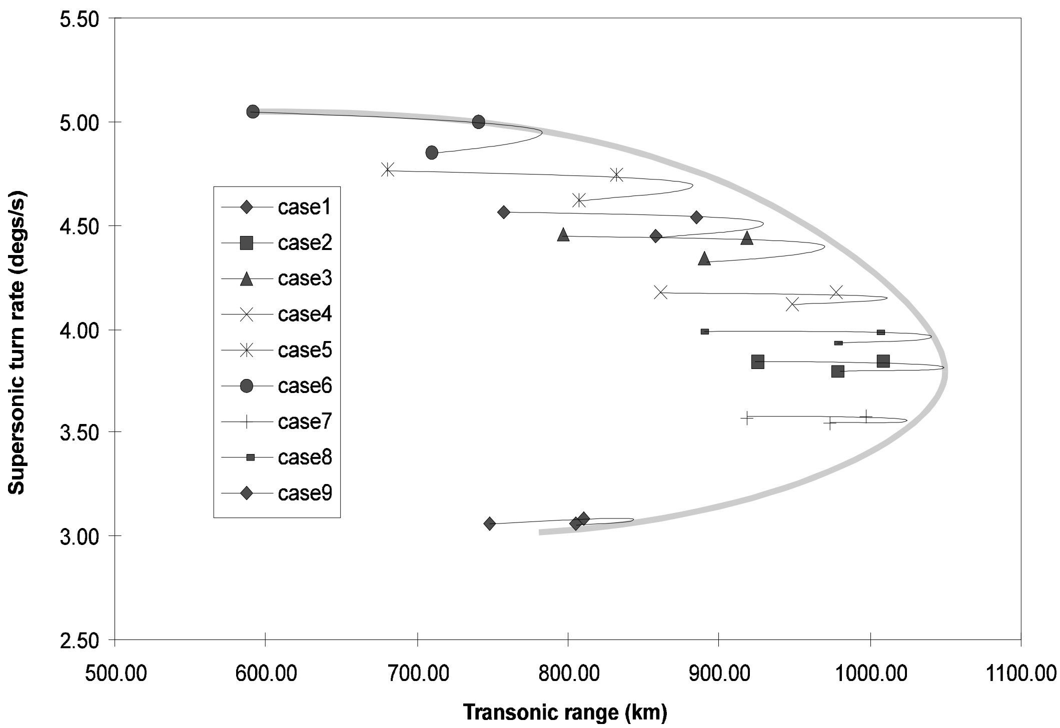

Fig. 13 : PARETO boundary

Requirement capture for military aircraft

The user trial to be conducted by DERA in partnership with BAe is based on the design of a military wing and seeks to achieve an acceptable compromise between aircraft range and turn performance. Figure 12 shows the pressure distribution calculated from CFD on the left with the finite element mesh and loading derived from it on the right. In this instance the aerodynamic model is taken as the master model, but in the longer term it would be expected that both the aerodynamics and structures models would be derived from a common product model.

The approach taken is a multilevel Pareto-optimisation in which the wing thicknesses (wing-box depth) at various stations are used as top-level variables linking the structures and aerodynamic disciplines. The structural optimisation simply the sizes the composite covers and sub-structure for each geometry, while the aerodynamic optimisation modifies the airfoil shape to maximise a weighted sum of lift to drag ratios corresponding to a supersonic turn condition and transonic cruise.

The supersonic turn rate and transonic range shown in figure 13 are then calculated from the drag, mass and fuel volumes. Each curve corresponds to a given spanwise thickness distribution but with the aero-dynamic shape optimised to give differing levels of transonic to supersonic performance. In general the thicker wings give greater range due to their increased fuel capacity, but ultimately (case 9) higher drag will reduce the range.

The Pareto frontier itself, indicated in grey in figure 13, bounds the region in which it is possible to design products to meet the conflicting requirements. The best products have performance characteristics which lie close to the ‘top-right’ part of the boundary. From here it is only possible to improve one characteristic at the expense of the other.

The use of genetic algorithms is to be assessed as a method of achieving convergence to the boundary of the region. Typically such direct search methods require many function evaluations, each one of which will call on a full structural optimisation for mass as well as an aerodynamic minimisation of drag for two flight conditions.

The fact that these tasks are computationally intensive makes the activity appropriate for high-performance computing in the longer term, but to reduce the computing costs during this project, response surfaces have been calculated for the wing mass and drag. The Pareto frontier may then be calculated on the basis of the cheaper response surface information rather than from further calls to the underlying design software. This will enable sufficient computing resources to be devoted to the assessment of genetic algorithms within the Pareto frontier approach and to evaluating the MCDM software tool for deducing the weightings attached to the various design objectives from customer preferences. This aspect of the Frontier project is of particular interest as it extends the scope of MDO so that it assists with identification of the design requirements that the product should meet.

CONCLUSIONS

A number of developments relevant to the practical use of MDO have been identified By reference to a sequence of collaborative research activities within European aerospace industry. A definition of MDO as incorporating state-of-the-art analysis tools is provided and its function as a key tool in the context of concurrent engineering is discussed.

It is believed essential for the credibility of an MDO process that it should be able to accommodate the detailed design processes normally used by engineers within the company to assess and validate their products. Scepticism as to the results from each step of an MDO process is vital and the comparative studies conducted by partnership have often produced widely varying results. The validation of methods such as within the GARTEUR activity on aeroelastic design is seen as an essential activity.

The central the role of the product model is highlighted and the desirability of using STEP to standardise the form in which product data is shared and exchanged amongst processes is to be emphasised.

A good framework for MDO which provides a flexible user interface for the definition, execution and monitoring of MDO processes is essential and further development of clear architectures for such software is still required. While conceptual design tools are often close-coupled, loosely coupled systems appear to be more appropriate to MDO in that they assist the verification of results by specialists. Some loss in process efficiency or even the generation of sub-optimal designs is acceptable provided the design process is understood and credible. The use of trade-off studies and Pareto optimisation methods to assist in the capture of requirements also offers worthwhile benefits.

MDO is seen as providing the means to avoid the fragmentation inherent in established methods which extends the time required for the design cycle and limits the efficiency of final designs. MDO permits the constraints of a diverse range of disciplines to be reflected from the earliest stages of the design process. This approach will facilitate the design of higher performance products with improved cost, structural integrity and maintainability. The methods will also offer the opportunity to maximise the exploitation of new materials technology within designs while minimising risk, and will have significant impact on project design times and cost.

ACKNOWLEDGMENTS

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