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MULTIDISCIPLINARY DESIGN ANALYSIS AND OPTIMISATION OF AEROSPACE VEHICLES: INCORPORATION OF MANUFACTURING INFORMATION.

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Abstract

The Paper describes a metal and composite recurrent cost model of a large civil aircraft wing structure for a multidisciplinary design, analysis and optimisation (MDO) environment. The work was part of a recent European MDO project (BE95-2056) which investigated methods for the integration of structures, aerodynamics, dynamics and manufacturing cost at the preliminary design stage.

The paper discusses the cost modelling approach, which is based on parametric and process cost model methods, and the integration of the cost models into an MDO process. Several methods to integrate the manufacturing cost into the Direct Operating Cost (DOC) were investigated. Results for the cost models and DOC optimisation are shown.

A framework has been successfully developed which allows the incorporation of manufacturing cost models into an MDO environment. It allows a designer to evaluate cost changes with respect to specific design changes such as rib pitch, stringer pitch, wing area and wing sweep.

Introduction

Multidisciplinary design, analysis and optimisation (MDO) methodologies have traditionally been applied at the preliminary design stage often trading weight against drag. The objective was to improve direct operating cost, range, payload or speed by reducing structural mass without compromising drag. However, whilst lower aircraft weight is important the process must take into account all the development phases including the manufacturing processes and their associated costs.(1) This is required because all the major design decisions have important knock-on effects and their influence cascades down the product introduction process. In the case of a commercial aircraft, for example, the selection of the number of engines, the shape and size of the wing and wing components, the manufacturing methods, etc. must be determined very early in the design cycle. All the successive decisions with respect to design details, manufacturing and assembly options depend critically on these initial choices.

Unfortunately these important decisions have to be made when least is known about the final design.(2) Thus a large proportion of the cost of a new product is committed very early at the conceptual and preliminary design stages, long before the actual product development costs occur. As Boothroyd et al(3) have pointed out, in this way the design process accounts for only 10% of the product cost, but indirectly influences up to about 70%. Hence it is important that all the factors which contribute to the total cost of a product are considered at an early stage in the design. Manufacturing costs are clearly one of these factors and it is essential that they are included in any MDO method which is intended for serious use in the aircraft design community.

The integration of manufacturing in the MDO process allows the designer to explore the influence of complex design issues relating to:

- the reduction of aircraft manufacturing cost for a specific design option
- variations in manufacturing processes
- the introduction of light weight advanced materials, such as composites
- etc.

A unique opportunity to incorporate manufacturing issues into an MDO environment and to apply the results to a realistic large scale aircraft was offered by a recent European MDO project. A full overview of this MDO project is given in a companion paper(4). It explains how all the factors which influence the design of a modern aircraft can be drawn together into a single process. The present paper concentrates on the issues relevant to the incorporation of manufacturing costs only. It shows how these costs can be defined in terms of parameters. These parameters allow detailed investigations to be undertaken to explore their influence on aircraft Direct Operating Costs (DOC).

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Development approach for the MDO cost model

The full development of an integrated MDO system in which manufacturing costs are only one of a number of critical design components is illustrated in the companion paper(4). The current paper is devoted to explaining the methodology adopted for creating manufacturing cost estimates and the method used to incorporate these into the MDO process. In order to make significant progress during the course of the MDO project a reduced problem was introduced which created a simplified DOC model from that described in reference (4). This is shown in equation (1) below where it is seen that structural mass and aerodynamic drag only are used as representative of the DOC model. However, the methodology described in reference (4) is preserved such that the MDO process involves the minimisation of the DOC objective function subject to a series of design constraints. The method, as discussed later, requires a multi-level process in which manufacturing costs are taken into account, primarily, at a sub-level. By proceeding in this way there is no requirement to incorporate manufacturing costs into the top level DOC. This approach does have the drawback that cost now plays no role in the final assessment of the Direct Operating Costs which could be seen as a weakness of the current approach. In order to explore the effect of having a direct contribution of cost in the top-level DOC a number of trials have been performed and are reported below.

As with the problem specified in reference (4), the research was applied to the wing of the P500 aircraft which was taken as representative of the A3XX wing. Although the P500 is different from the A3XX the model used provides a detailed structural representation of a very large civil airliner wing with a high degree of granularity. Thus the cost estimation procedures generated by the research presented herein is fully applicable to any similar wing and able to include manufacturing costs for detailed components.

The European MDO project, therefore, offered an excellent opportunity to study the impact of manufacturing on a realistic preliminary design problem. The development of a preliminary design manufacturing cost model and its integration into the MDO process was one of the key activities of the Cranfield College of Aeronautics Structures and Materials group, in co-operation with BAe and CASA. At the early development stage, several requirements were identified. A cost model for the MDO project had to provide:

- A manufacturing cost estimation for both metal, composite or hybrid wings.
- A generic, company independent model which can be used by all 14 project partners.
- A model which can be easily customised or expanded by individual partners to the needs of their company.
- A clear visualisation of the cost changes with respect to design changes.
- An integration of the cost model into the MDO software.

The involvement of industrial companies made it possible to asses and discuss different manufacturing processes and approaches. However, a number of practical problems were encountered. Some of these related to the confidential nature of company cost information, others to the fact that manufacturing and assembly processes are influenced by company policies, market trends or company infrastructure. Hence it was difficult to develop a cost model which suited all the project partner's specific needs. For this reason it was decided that adaptability and expandability of the cost model were important requirements.

Cost estimation methods

Although a number of cost estimation processes have been advanced for generating cost estimates for aircraft structures, two might be seen as particularly relevant. These are the parametric and process cost models. Both of these approaches have been compared in detail by Rais-Rohani and Dean(1).

Parametric cost models are widely used in industry. Their formulation is relatively easy, but their accuracy depends strongly on the accuracy of the manufacturing data and manufacturing history on which they are based. Hence, when estimating the costs for processes involving new manufacturing technologies or materials, the accuracy is often poor as little historical data is available. The use of parametric cost models requires a good understanding of what the cost drivers are for the manufacture of specific product. The cost driver information and its relationship to designer controlled parameters needs to be translated into a quantitative form which is meaningful for MDO purposes. A frequently used and easily defined cost driver for aircraft based parametric models is weight. Weight based cost estimation relationships, however, do not always accurately represent the actual manufacturing cost and it may not provide accurate sensitivity data for the MDO process.(5) Often a weight reduction will result in a cost increase due, for example, to a requirement for more machining time, closer tolerances etc. . An example of this type of cost augmentation, with weight reduction, is shown in the results section below. Hence fabrication costs are better correlated to structural layout and complexity than to weight. Accurately representing all the details of manufacturing complexity is difficult for a parametric model, as it must include all the product and process specific parameters (drivers) which can influence the parametric cost model.

Manufacturing process cost models require a thorough understanding of the manufacturing processes involved. They are based on a detailed estimation of the main manufacturing cost categories such as material use, fabrication, assembly. These type of models also focus on labour and process time and cost. The models are formulated in such a way that they cover costs associated with individual processes and assembly operations. For the estimation of the full production cost, the recurring and non-recurring manufacturing costs are identified and calculated separately. Manufacturing process cost models are more accurate than parametric models, but need much more detailed information at the start of an estimation process. Thorough identification and analysis of the separate manufacturing processes is necessary.

MDO cost model approach

The analysis of the available cost models indicates than none are not well suited for providing an MDO cost model. These existing models have neither the flexibility nor the level of detailed required to handle the complex wing design problem In consequence a new model was developed which combines aspects of both parametric and process cost models. The model follows a feature based approach based on weight (component volume), component layout and manufacturing rules. Through this approach, the traditional weight based cost model has been expanded to one which directly takes into account assembly and detailed manufacturing cost. (See figure 1.)

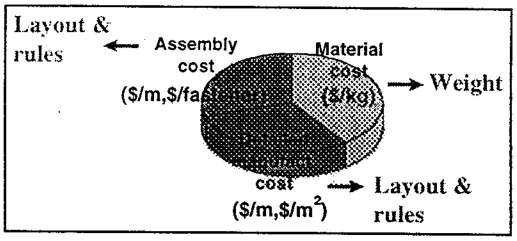

Figure 1: Recurrent cost breakdown

As already indicated, for simplicity, the model focuses on the P500 wing box. It calculates recurrent costs only and does not include non-recurrent cost such as engineering, testing and tooling.

The cost estimation process requires a definition of the product structure (bill of material) for the wing box. This is currently based on the A340 but the MDO software(4) allows for a definition of different product models. Once the whole product structure is defined, each of its components is analysed with respect to material, manufacturing and assembly processes. For each component, several features which drive the component cost are assigned. These features, or cost drivers, can be: geometrical such as length, area, weight; processes such as milling, drilling, assembly including joints, inserts; etc. (6)(7)(8)

The present application concentrates on geometric and assembly features. The feature information is obtained from the MDO software and is automatically being updated each time the wing design has been changed by the Multi-Model Generator (MMG(4)). After identification of the relevant features, cost factors (e.g. \$/m, \$/m^2,...) need to be defined. This is done using an estimation program or by directly assigning the values as described in the next section.

The primary aim of the model is to have a fast tool which can accurately predict and visualise the cost changes and cost trends, when going from one design to an other. The absolute accuracy of the cost predictions is of secondary importance.

MDO Cost models

Two recurrent cost models have been developed, one for metal the other for composites each based on the approach discussed above. For both models the cost analysis is done in two stages:

1. the calculation or assignment of cost factors for a reference wing is performed. (top-down cost approach)
2. the cost of an aircraft variant is performed using the reference cost factors. (bottom-up cost approach)

By employing the Multi-Model Generator, the manufacturing cost can be calculated for a change of both external wing geometry variants and internal wing layout. The Technical Data Modeller and Browser (TDMB) has been modified to store all cost data and results.

Metal cost model

The model building process began with a metal cost model using the current A340 wing box manufacturing and assembly methods as the reference. A simplified prototype model was developed first and expanded later.

Prototype. The prototype did not identify the different processes which are needed to produce and assemble a component. Three main cost categories; material, detailed manufacturing and assembly were defined. For each cost category, the following general geometry and assembly features were assumed:

- Material:
  - Component weight
- Detailed manufacturing:
  - Component area
  - Component length
- Assembly:
  - Component length

For rib assembly, for example, the component length is the sum of all the rib sides and for the spar assembly length the sum of the spar top and bottom length. Multiplying these features by their cost factors, the manufacturing cost can be calculated.

The estimation of the cost factors is based on a defined cost distribution(9)(10)(11) between the three main cost categories:

- Material cost = 40%
- Assembly cost = 30%
- Detailed Manufacturing cost = 30%

Using the optimised reference weight and material usage factors (MU), a reference cost breakdown can be estimated. An improved estimate of the detailed manufacturing cost for each component is obtained by distributing this cost in the same way as the component weight is distributed. The reference cost factors are obtained after dividing the reference cost by the cost driver value. (e.g.: reference cost = 500\$, cost driver = 50 m ⇒ reference cost factor = 10 \$/m)

Detailed model. A detailed metal cost model is currently under development. It has a similar level of detail as the composite wing model discussed below.

The three main cost categories are still used, but for each wing box component it now includes a detailed breakdown of the processes. Rib assembly, for example, now contains processes such as lift, drill, debur and fasten. In co-operation with BAe-Airbus the different processes, cost drivers and cost factors are being defined and evaluated. The model is still based on the current A340 manufacturing, but it is intended to use the model for cost assessment of new manufacturing and assembly methods.

Composite cost model

The composite cost model is based on the current A340 horizontal CFRP tail plane manufacturing and assembly methods which are used by its manufacturer CASA. The model takes into account aspects relating to the manufacturing of large wings such as the A3XX. These include component size (e.g.: autoclave size), curing method, manufacturing method etc. Again three main cost categories are included; material, detailed manufacturing and assembly costs have been defined. For each component the cost category contains a breakdown of the required production processes. Examples of the detailed manufacturing processes which are currently considered include:

- Automatic tape lay-up (skins, stringers, spars and stiffeners)
- Hand lay-up (ribs)
- Hot forming: set-up, cure, extract (stringers, stiffeners, ribs)
- Curing: bagging, set-up, cure, debagging (stringer-skin, spar web, rib web)
- Co-bonding (rib and spar stiffeners)
- Cut and debur.

The selected geometric features which drive the component manufacturing cost are: weight, ply stacking and % fibre material per stack, length, area, number of components, number of cut-outs and lightening holes. Assembly cost includes processes such as part fit up, shimming, hole drilling, fastening, and sealing. The assembly cost drivers are geometric and assembly features, such as area and number of fasteners. Close co-operation with CASA allowed for cost feature and cost driver identification and for an intensive iterative process of model updating and refinement in order to make it more realistic.

Future work will be to expand the model and to incorporate more advanced composite manufacturing methods such as resin transfer moulding and composite stitching.

Integration of manufacturing cost into MDO

This section describes the integration of the manufacturing cost models into an MDO environment.

As indicated earlier the full DOC model was not used in this part of the MDO study but was replaced by a simplified Direct Operating Cost model. This takes into account changes of weight and drag, without direct coupling, being employed. This reduced form is given by:

$$\Delta DOC = \sum_{i=1}^{6} w_1 \times \frac{\Delta M}{\Delta p_i} \times \Delta p_i + \sum_{i=1}^{6} w_2 \times \frac{\Delta D}{\Delta p_i} \times \Delta p_i \qquad (1)$$

with i = *aircraft variant*
p_i = *parameter being varied*
wi= weighting factor

The integration of manufacturing cost into this DOC objective function is not so straightforward and a number of problems required solving. The first of these relates to the fact that one of the required inputs for the recurrent cost models, is a weight break down. Hence, there is a dependency between cost and weight. For this reason it would not be appropriate to include manufacturing cost in a DOC equation which already contains the optimised weight. Thus, the first approach contains manufacturing costs in the sub-level only. However, it was recognised that some attempt should be made to provide a contribution for cost in the top-level DOC and a number of options were explored which are described in the next section.

A second problem is associated with the fact that all optimisers are guided by gradient information to find an optimum solution. However, for manufacturing cost calculations one often does not have gradient information available as the changes of manufacturing parameters can be discrete e.g. tolerances, number of ribs. This leads to discrete cost changes and complicates the integration into the DOC optimiser. Assuming that only small changes are allowed, discrete cost changes are avoided by using a quadratic interpolation algorithm which approximates discrete points by a quadratic, continuous curve.

Although the DOC objective function sensitivity formula (1) involves the 6 major design parameters, the total MDO process has two sets of parameters which the multi-level optimisation process can manipulate. These are geometry and layout. The geometric parameters are the 6 wing parameters described in reference (4), e.g.: sweep, area, etc., whilst layout parameters are the wing internal design features, rib pitch, stringer pitch, etc.. The layout parameters are not employed in the top-level optimiser and, therefore, do not appear explicitly in the top-level objective function (1). We may note that in the absence of flexibility effects internal layout changes influence structural behaviour with aerodynamic behaviour being a function of the overall geometry of the wing.

To solve this problem using the multilevel approach the layout changes are always dealt with at a secondary level.

DOC formulations

Different DOC formulations, taking into account manufacturing cost are under investigation. The first set of investigations is based on equation (1). Three cases are currently studied: a DOC which only contains mass and drag, a DOC with only drag and cost, and a DOC which contains mass, drag and cost (see equation 2). These cases were taken to investigate the coupling of mass, drag and cost and how they influence the DOC optimisation process. The studies have been carried out for different values of the weighting factors.

$$\Delta DOC = \sum_{i=1}^{n} w_1 \times \frac{\Delta M}{\Delta p_i} \times \Delta p_i + \sum_{i=1}^{n} w_2 \times \frac{\Delta D}{\Delta p_i} \times \Delta p_i \qquad (2)$$

$$+ \sum_{i=1}^{n} w_3 \times \frac{\Delta C}{\Delta P_i} \times \Delta p_i$$

Drag (drag counts) optimisation is performed using response surfaces. Weight (tonnes) is optimised using response surfaces or the structural optimiser STARS, which has been developed by DERA (fully stressing and Newton based algorithms). Cost (million $) is calculated using the cost models or a response surface.

Multilevel DOC optimisation

As mentioned earlier in this section, a multilevel approach is used to reduce the number of parameters being assessed in the DOC equation. For this case, layout changes are applied at a secondary level for weight optimisation only. The following process is now performed:

- Top level: minimisation of DOC by minimising weight and drag, subject to geometry changes.
- Secondary level: minimisation of cost for a given wing geometry, subject to layout changes.

Figure 2 gives an overview of the multilevel approach. For the top level DOC minimisation, RQPMIN or a Sequential Quadratic Programming algorithm are used. RQPMIN is a gradient based optimiser which uses a quadratic approximation, derived from finite difference evaluation of the objective function. It has been developed by DERA. Drag optimisation is performed using response surfaces which were provided by other MDO partners. At the secondary level, the model generator creates a new model for each change of the layout parameters e.g. rib pitch, stringer pitch. After a new model has been generated, DERA's STARS optimiser is used to minimise the weight.

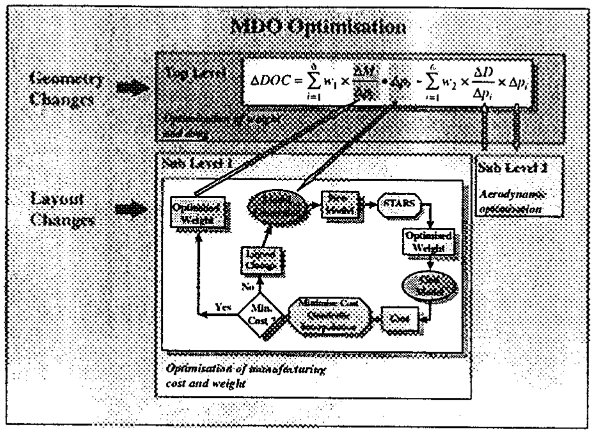

Figure 2: Multilevel optimisation

To improve computing efficiency, the fully stressing algorithm is used to generate the results given below. From the optimised weight breakdown and other cost inputs, the manufacturing cost is recalculated. The quadratic interpolation algorithm is then used to determine a new value for the layout parameter which gives an optimum manufacturing cost. As mentioned before this algorithm is used to avoid discrete cost changes. At the end of this optimisation cycle, the weight which is associated to the minimum cost layout is handed over to the top level.

Using this approach, cost and weight are not being optimised simultaneously at the same level. Future investigation will also include the reverse scheme, were manufacturing cost and drag are optimised at the top level and weight at the secondary level.

Results

The main aim of the cost models is to present clearly to a designer the cost changes with respect to design changes. All results have been calculated using cost factors which are obtained from the cost estimation program or literature(9)(10)(11). The accuracy of these factors is now being checked with company information. Some of the cost results below have been changed for reasons of company confidentiality.

Results metal cost model

The results shown here are obtained from the prototype model. Structural optimisation, combined with cost analysis has been performed on the six primary variants described in reference (4). The variants are subjected to a +3 % change. Figures 3 and 4 show the cost and weight changes of the variants with respect to those for the reference wing.

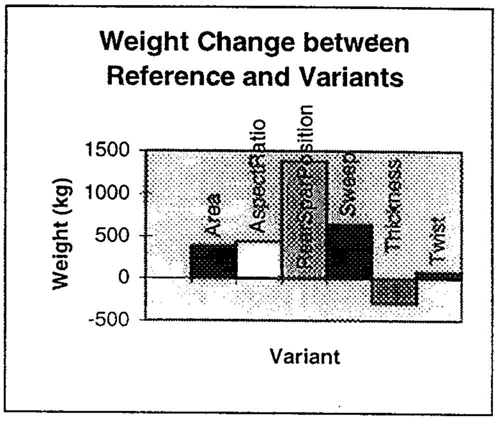

Figure 3: Weight change for 6 wing variants

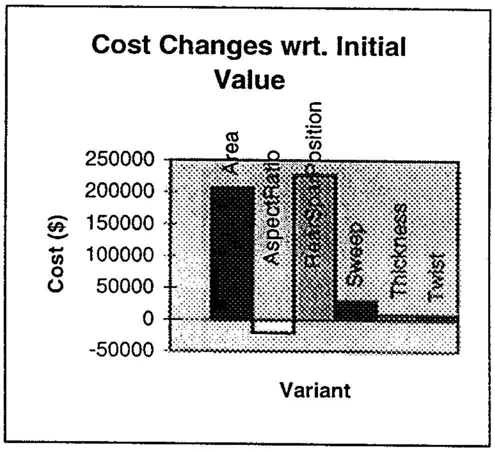

Figure 4: Cost changes for 6 wing variants

It can be noted from the figures that change in wing area and the rear spar position have the biggest effects on cost. With respect to the thickness variant, it is also clear that there is not a linear relation between weight and cost increase/decrease. An increase in wing depth reduces the weight (as the structure is more effective in bending) but increases the cost, as the rib area has increased (i.e. bigger component to manufacture and assemble). An overview of the cost contribution per component, for the 4 aircraft variants is given in figure 5. It can be seen from these results that it is mainly the ribs which influence the cost.

As mentioned in the previous section, it is also possible to perform layout optimisation, by changing the number of ribs and/or stringers. This optimisation is currently being performed. Figure 6 shows the change of cost with respect to 3 different numbers of ribs (57, 69 and 84) and 2 different stringer pitches (0.195 and 0.250).

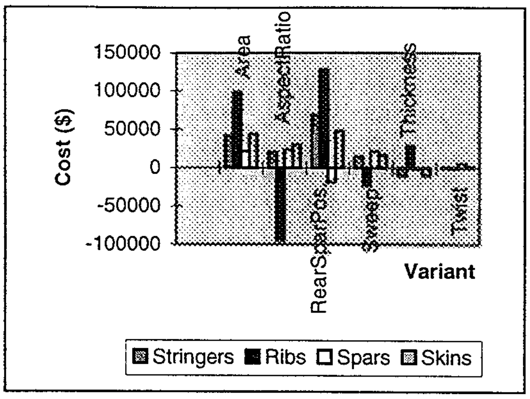

Figure 5: Cost changes per component for 6 wing variants

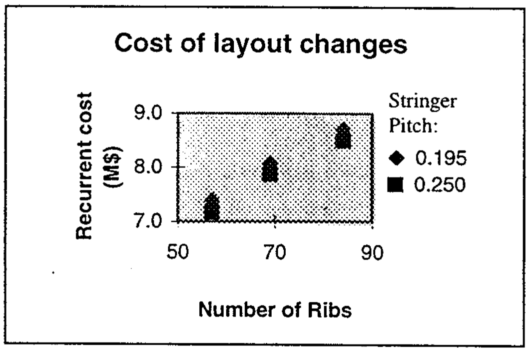

Figure 6: Cost effects of layout changes

Results composite cost model

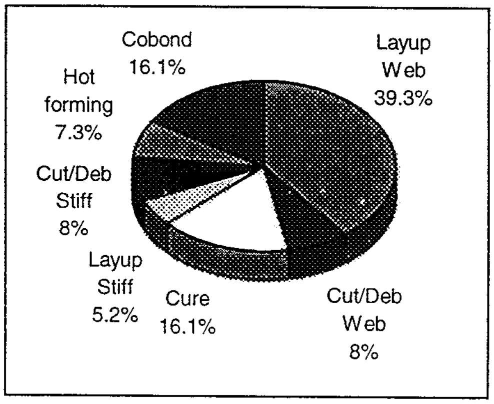

Figure 7: Cost distribution detailed manufacturing spar

Composite cost calculation has been initially performed on the full aircraft wing. This model is much more process oriented than the prototype cost model for metal wings. Figure 7 gives a breakdown of the processes involved in the detailed manufacturing of a composite spar. It assumed that the spar web and stiffeners were produced using automatic tape lay-up. The webs are cured, stiffeners are hot formed and co-bonded on the webs. Using the multi-model generator, it is possible to perform comparative studies between composite and metal designs. A comparison between composite and metal costs is shown in figure 8 for the three main cost categories.

Current work is now looking at the hybrid wing and at the cost effects of the position of the composite joint.

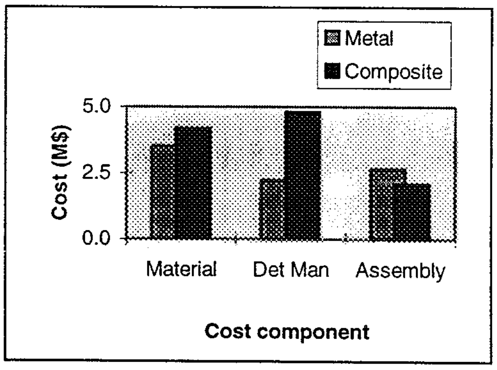

Figure 8: Comparison recurrent cost metal and composite wing

Results DOC optimisation

Several DOC formulations are under study to investigate the coupling of mass drag and cost. It was found that the resulting optima are relatively insensitive to variations in DOC formulation. This may be due to internal trade-offs taking place between mass, drag and cost.

The results shown here are for a DOC, based on weight, drag and cost (see equation 2), taking into account changes of wing sweep and area. Figures 9, 10 and 11 show these changes for weight, cost and drag respectively. The change in DOC is shown in figure 12 which indicates an optimal value for area = 690.21 m^2 and sweep = 34.98 degrees. A DOC improvement of 5.4 % was obtained in comparison with the Reference Wing. Table 1 gives an overview of some of the other cases that have been studied.

DOC formulation	% Difference in DOC
Mass + Drag + Cost	5.4
Mass + Drag	5.65
Drag + Cost	6.78
2xDrag + Cost	6.84
Drag + 2xCost	6.67
Mass + 2xDrag	6.24

Table 1: %DOC improvement for different DOC formulations

From the mass and cost response surfaces, it is clear that cost and mass do not necessarily behave in the same way. The assumption that with a minimum mass a minimum cost is obtained is not true.

Clearly further study is required to develop the multi-level optimisation process. In this way, the influence on the DOC when fully incorporating the interactive influences of weight, drag and manufacturing cost, can be evaluated.

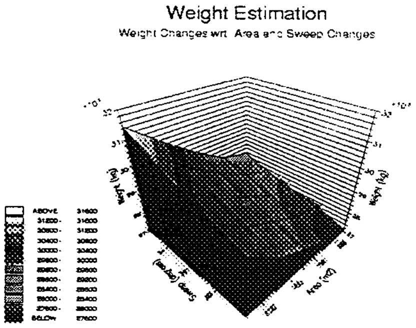

Figure 9: Weight response surface

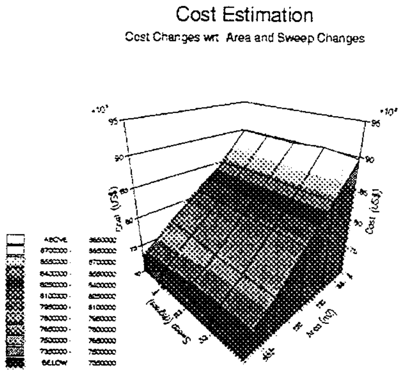

Figure 10: Cost response surface

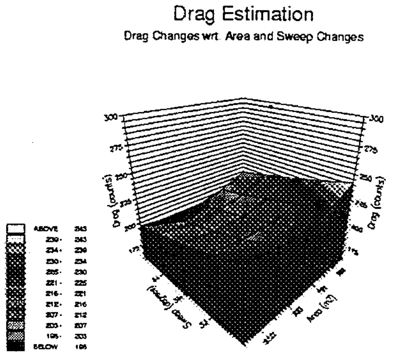

Figure 11: Drag response surface

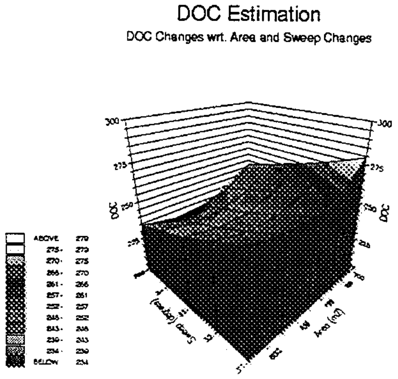

Figure 12: DOC response surface

Conclusions

A basic framework has been developed which allows the incorporation of manufacturing cost models into an MDO environment. Having proved its capability, the cost models can now be refined and expanded. Further work includes the incorporation of additional manufacturing processes and information for both the metal and composite model. It is intended to use the models for comparative studies of different manufacturing methods, for example, for composites: automatic tape lay-up versus resin transfer moulding.

Further work is also being carried out on the DOC integration of manufacturing cost. It is intended to expand the current recurrent cost to a manufacturing cost which also includes non-recurrent and life cycle costs. All this work will be carried out in close co-operation with industry.

The European MDO project, has provided the Cranfield College of Aeronautics with a foundation from which further MDO research for preliminary design can be performed. This gives a broad based capability which does not only include the cost module, but also a suit of optimisation tools and aircraft design software. It has also created closer co-operation between research teams from aerospace industry and institutes. This co-operation will be further pursued to expand not only the manufacturing cost aspects, mentioned above, but also other MDO issues such as top level MDO methodologies, MDO of fuselage structures, etc.

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References

1. Rais-Rohani, M., and Dean, E. B., *"Toward manufacturing and cost considerations in multidisciplinary aircraft design."*, 37th AIAA/ASME/ASCE/AHS/ASC Structures, structural dynamics and materials conference and exhibit, Salt Lake City, April 15-17, 1996, AIAA-96-1620-CP, pp. 2602-2612.
2. Borland, C. J., Benton, J. R., Frank, P. D., Kao, T. J., Mastro, R. A., and Barthelemy, J-F. M., *"Multidisciplinary design optimisation of a commercial aircraft wing - An exploratory study."*, 5th AIAA/USAF/NASA/ISSMO Symposium on multidisciplinary analysis and optimization, Panama City Beach, September 1994, AIAA 94-4305-CP, Part 1, pp. 505-519.
3. Boothroyd, G., Dewhurst, P., and Knight, W., *"Product design for manufacture and assembly."*, Marcel Dekker, 1994.
4. Morris, A. J., and Gantois, K., *"Multidisciplinary Design and Optimisation of a large scale civil aircraft wing."*, 21st Congress of the International Council of the Aeronautical Sciences, Melbourne Australia, September 13-18, 1998, ICAS-98-6.4.2.
5. Giesing, J. P., and Wakayama, S., *"A simple cost related objective function for MDO of transport aircraft."*, 35th Aerospace Sciences Meeting & Exhibit, Reno, January 6-10, 1997, AIAA 97-0356.
6. Noton, B. R., *"Optimizing aerospace structures for manufacturing cost."*, 13th Congress of the International Council of the Aeronautical Sciences, September 1982, ICAS-82-3.8.1.
7. Noton, B. R., *"Cost Drivers and design methodology for automated airframe assembly."*, 31st International SAMPE symposium and exhibition, Los Angeles, April 7-10, 1986,pp. 1441-1455.
8. Taylor, I. M., *"Cost Engineering - A feature based approach."*, AGARD workshop on Virtual Manufacturing, Allborg, Denmark, October 13-15, 1997.
9. Scott, P. W., *"The cost effectiveness of weight reduction by advanced material substitution."*, SAE Transactions Aerospace, Volume 95, Society of Automotive Engineers, Warrendale, 1986, SAE-86/1850.
10. Davis, J. G., Starnes, J. H., and Johnston, N. J., *"Advanced composites research and development for transport aircraft."*, 17th Congress of the International Council of the Aeronautical Sciences, Stockholm, Sweden, September 9-14, 1990, ICAS-90-0.3.
11. Resetar, S. A., Rogers, J. C., and Hess, R. W., *"Advanced airframe structural materials. A primer and cost estimating methodology."*, RAND, Santa Monica, 1991, R-4016-AF.

12. Allwright, S., *"MDO Process and specification for the primary sensitivity stud.y"*, Technical Report D2.4.S, British Aerospace, 30th April 1996, MDO/SPEC/BAE/SA960430

13. Allwright, S., *"MDO Reference aircraft performance and primary sensitivity study report"*,D3.12.R., British Aerospace, 30th May 1997, MDO/TR/BAE/SA970530/1.

14. Grihon, S., "MDO Planform shape optimisation.", Technical Report D4.21.R, Aerospatiale, 21st January 1998, MDO/TR/AS/SG980121.

15. Gould, A., *"MDO Surface Shape Optimisation."*, Technical Report D5.21.R, British Aerospace, 5th January 1998, MDO/TR/BAE/AG980105.

16. Allwright, S., *"Technical data management for collaborative multi-discipline optimisation."*, 6th AIAA/UASF/NASA/ISSMO Symposium on Multidisciplinary Analysis and Optimisation, Seattle, September 1996, AIAA-69-4160-CP.