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A. Van der Velden
Synaps, Inc.
Atlanta, GA

R. Kelm
Daimler-Chrysler Aerospace Airbus
Hamburg, Germany

D. Kokan
Synaps, Inc.
Atlanta, GA

J. Mertens
Daimler-Chrysler Aerospace Airbus
Hamburg, Germany

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Alexander Van der Velden  Synaps, Inc., velden@synaps-inc.com
president
Roland Kelm  Daimler-Chrysler Aerospace Airbus, Hamburg, Germany
head aeroelastic structures
David Kokan  Synaps, Inc.
head consultant
Josef Mertens  Daimler-Chrysler Aerospace Airbus, Bremen, Germany
RAWID project manager aerophysics division

Daimler-Chrysler Aerospace Airbus and Synaps developed a preliminary design tool to quickly trade-off wing planform, thickness and lift distribution on a large commercial passenger transport wing. Goal of this study was to minimize the weight of the wing structure + fuel at a constant maximum takeoff weight. The design study was performed with the Pointer™ MDO framework software. Pointer™ couples the required analysis codes and searched the design space for the best solution. The section drag was determined using a large database of swept airfoils that were shape optimized for specific design conditions. The wing loads and induced drag were determined with a vortex-lattice code. The weight of the wing was estimated using the Airbus FAME software which sizes the wing primary and secondary structure based on the wing loads with static aero-elastic effects. The present method used led to significant performance improvements (which were confirmed by later detailed studies) and a better understanding of what drives the design of very large transports. As compared to conventional design iterations performed by teams of experts, the present method requires only half the time per design cycle and a fraction of the number of design cycles to converge the design.

Introduction

The design of a new very large transport [Fig. 1, Ref. 13] poses several challenges to the conventional method. In the conventional approach, the preliminary design department proposes an initial description of the design to the aerodynamic design team. This team finishes a full aerodynamic design optimization for this configuration and then passes this detailed geometry to the structural design group who compute the required weights. However, in the case of very large aircraft, many detailed design cycle iterations (>10) were required to converge to an optimal design. One of the reasons for that is because the initial preliminary design does not include the right level of physical modeling to trade-off design decisions for a very large transonic aircraft.

Fig 1: Proposal for a new large aircraft (photo Airbus Industrie)

This problem is the most pressing for wing design. Therefore, in the past 6 years significant effort has been invested to create preliminary design tools that accurately predict the aerodynamic and structural potential of well designed transonic aircraft wings. With these
tools it is possible to make accurate tradeoff studies using multi-disciplinary optimization technology in the initial stage of aircraft definition. This tool is similar to the MIDAS tool [5] developed in the early ’90s to design the DASA & European supersonic transports. However because subsonic transports are much more mature, a much higher accuracy in the physical modeling is required to achieve (typically smaller) performance gains.

Present Method

In order to increase the accuracy of the initial preliminary design trade-off, we developed a new wing preliminary design tool. This is achieved by increasing the physical fidelity of the models and by using multi-disciplinary design optimization. This tool was comprised out of three parts:

a) Pointer MDO framework. The purpose of this tool is to execute computer simulations more efficiently, and to search the design space created with the outputs of these simulations for the best solution.

b) FAME-W weight and loads model developed by DASA-Airbus Hamburg. It determines the potentially best structural weight for a well designed aero-elastically deforming wing using only a preliminary description of the structure and aircraft mission.

c) Globair aerodynamics model developed by Synaps and DASA-Airbus Bremen. It determines the potentially lowest transonic drag for a well designed wing for a given mission point using only a preliminary description of the wing surface.

Pointer as a tool to perform design studies.

Pointer [6,9] is an MDO framework tool. MDO framework tools are explained in detail by Salas and Townsend in ref. [7]. The development of Pointer was driven by the following consideration:

_Pointer should give the expert user the ability to find a better answer to a wide class of complex design problems in less time than it would take him to solve the problem in a conventional way._

Therefore, the setup of the design problem should be as user-friendly as possible. In terms of the software architecture Pointer achieves this by using intuitive GUI’s [Fig 2], object oriented principles and the use of software standards. Pointer automatically parses the parameters defining the input to legacy and proprietary codes. Pointer also controls the running of these codes both in sequence and parallel.

After all the I/O is defined, the design problem is stated in the form of an objective, design variables and constraints. It is here that most users have problems and we consider this the major hurdle in the development of MDO technology.

In his paper “On making things best” [10] Holt Ashley said it all, when he stated the omission of the optimization algorithm description in a design study a “charming sign of maturity”. In Pointer a hybrid combination of the best current optimization algorithms [Linear Programming, Sequential Quadratic Programming, Gradient, Downhill-simplex and Genetic] are used to solve the problem. The program does not require any intervention from the user or specialist knowledge about optimization. In our experience, Pointer requires T hours to solve the problem:

\[ T = Z \times \#\text{variables} \times \text{Time-per-design-simulation} \]

\( Z \), the relative complexity of the problem, is typically 100, the first time a strongly non-linear engineering problem is solved. We see the initial investment of so many function calls as essential to understanding the problem posed by the topography of the objective function. In practice if the computer simulation takes more than 1 hour, parallel processing of the design simulation is required to avoid excessive run times.

In subsequent uses, Pointer learns from its experience and typically reduces \( Z \) to a number below 10. This saves a lot of time when optimizations are repeated, for instance when an optimal design database is created.
Weights & Loads Model FAME-W

The Airbus FAME-W preliminary weight model is described in detail in ref [1,2] The current description explains how this model was used in the present study. For the design of a real wing structure, the complete load case spectrum must be investigated, including gust, maneuver and landing in terms of both static and dynamic aeroelasticities. In this particular study, only the 2.5g maneuver case at sea level and maximum dynamic pressure with static aeroelastic deformations at cruise and maneuver were considered. Nevertheless, the current level of detail is sufficient to support the conclusions of this paper.

Fig. 3 shows the FAME-W structural wing design process. The cruise wing lift distribution is an input to the weight model FAME. Finding the twist distribution of the unloaded wing (jig shape) is not a trivial task, because there is already significant elastic deformation at the cruise condition. To solve this problem, initial values for the stiffness and the structural relief are estimated with a pre-dimensioning model. The accuracy of these values influences the speed of convergence of all following calculations.

After the first twist distribution of the jig shape has been found, the primary structural components can be dimensioned. In this process a new stiffness and mass distribution is found.

In the ‘loads loop’, the loads on the twisted wing are calculated using the Truckenbrodt vortex-lattice model [3]. The stiffness values are kept constant in this iteration loop. In the final step, the stiffness calculation, the stress distribution in the wing box and the required material cross-sections are determined iteratively for the given loads. If in this process the stiffness distribution changes significantly, the loads calculation must be repeated, because the deformation behavior, and thus the loads, change.

The converged stiffness distribution differs from the stiffness distribution used on the calculation of the jig shape. Therefore, a re-twist of the wing is performed and the loads loop is repeated.

Within the loads calculation the deformation through bending and torsion influences the zero moment coefficient of the wing. This in turn changes the trim state of the aircraft, specifically, the loads on the tail and wing. After these effects are taken into account and the whole solution is converged, the influence of static aeroelastic deformations on the aircraft performance can be estimated.

Globair Drag Model

In the preliminary design phase the wing is only described in terms of planform, thickness distribution, load distribution and mission description. This is adequate for the evaluation of the wing weight, but not adequate to determine the transonic drag. The transonic drag is dependent on the detailed (curvature) shape of the wing.

It would be beyond the scope of a preliminary design method to include the detailed curvature of the wing. The purpose of this model is to predict the wing drag which the detailed aerodynamic design will achieve but even before the detailed aerodynamic design is started.

We noticed that though transonic aerodynamic designs are designed with respect to many operating points, the wave drag at the principal cruise operating point is very close to the minimal achievable wave drag. This is easily understood since subsonic long range transports spend most of their time at this operating condition. We therefore created a model that predicted the minimal achievable transonic drag as a function of wing preliminary design parameters.

The model was created with a database of 240 airfoils. Each airfoil had been automatically designed for minimum drag under representative specific operating condition [CL, M, Re] and geometric constraints [t/c, flap spar heights]. The creation of such a large database was possible through the use of the automatic aerodynamic shape optimization with Pointer as described in ref. [4, 8].

This database also clearly showed that the type of optimal pressure distribution is very dependent on the operating condition and that attempts to design this database using ‘perceived good’
pressure distributions is probably impossible. The individual design solutions were compared to DASA experience.

The 2D database was then approximated with a suitable response surface. For a given planform, thickness and load distribution, the equivalent 2D flow conditions on a straight tapered section of the wing can be determined using the sweep angle of the shock. Since we know the location of the shock on the chord for each airfoil in the database, its shock sweep can be determined iteratively for each combination of a straight taper section and airfoil.

The 2D airfoil wave drag of this wing section is known from the response surface model and this can be converted into a 3D value using a modified version of R.T. Jones's and Boppe's [11] sweep-taper theory and the value of the shock sweep. The friction drag was determined based on the 2D strip friction drag coefficient predicted by the response surface model.

The induced drag is calculated using the Truckenbrodt [3] vortex lattice induced drag model which includes the effect of the tail.

Fig. 2 Pointer MDO framework
Application to a Large Transport

Problem description

To demonstrate the use of this tool we posed the following test-problem.

What preliminary design of the wing produces the minimum weight of the wing + fuel to perform the harmonic mission (maximum payload) of a 550 pax very large transport? The maximum payload (in fuselage) mission is the most critical for the wing structure. We also wanted to know the sensitivity of this design to errors made in the prediction of wing weight and drag.

The wings own structural weight plus the weight of the fuel it carries represents half the maximum takeoff weight of the aircraft. It is therefore clear that the wing represents the most critical component of the aircraft.

The reference configuration we used was the current status (1998) of the design shown in Fig. 1 [13].

The following parameters were picked to describe the preliminary wing design of the type of Fig. 1.
a) Load distribution parameter $p$. This allowed the wing load distribution to vary from over-elliptic to under elliptic.

b) Wing planform parameters: Aspect ratio, Root chord, outboard taper ratio and sweep. Planform changes were performed such that the wing area remained constant.

c) Thickness parameters: Root thickness-to-chord ratio, Kink thickness-to-chord ratio. The thickness was assumed to vary in a fixed parametric way from the root to the kink and the kink to the tip.

Execution of the study

With our present method we first analyzed the performance of the reference configuration. The predicted weight and drag were very good. Cruise drag and weight were predicted with an error of around 2% as compared to the best available numbers for the reference configuration. The numbers were calibrated to correspond exactly to the reference aircraft performance.

Next, parametric scans were performed of the design parameters. The results were quite surprising. Fig. 4 showed that for the reference aircraft the aspect ratio had to be reduced from 8 to 6 to achieve the minimum objective function values (wing weight + fuel weight). In this case, the objective function was only reduced by 5 tons in absolute terms. After performing an optimization of the design parameters the scan of the aspect ratio showed that the original aspect ratio was indeed the best one, but only in combination with other values for the other design parameters. This exercise again shows the dangers of relying on 1-D parametric scans to drive such non-linear designs.

Next a matrix of 9 scenarios, each with 9 sub-scenarios (81 cases) was investigated. The scenarios covered expected uncertainties in both the wing structural mass (as predicted by FAME) and the cruise fuel mass due to aerodynamic performance (as predicted by Globair). The combination of all these scenarios covered all expected analysis errors.

Fig. 5 shows the result. All optimal wings showed significant improvements with respect to the reference wing. This was true even if it was assumed (in the extreme case) that both the aerodynamic and structural benefits predicted by the analysis were 20% lower in each case than computed. The (analysis = true) point shows the performance of the optimized wing assuming that the analyses were correct.

The solutions that get most of their benefit out of the reduction of the wing structural mass are called "structures solutions". The solutions that get most of their benefit (in terms of the objective function) out of the reduction of the fuel weight are called "aero solutions".

Selection of the best design

Since we felt that all scenarios were equally likely to be true, we were interested in whether we could find a design that was most likely to produce good performance. We did this by identifying the range of optimal design parameters for the different scenarios. Fig. 6 shows the result.

This showed that for three design parameters the direction of change was irrespective of the scenario. The load parameter was changed the most. The optimal design very likely had more load on the inboard wing than the reference design. Also the sweep was increased and the root chord decreased for all designs.

Fig. 7 shows why it is so important to have an inboard shifted load distribution for this type of aircraft. First of all, moving the load from the outboard wing to the inboard wing reduces the wing bending moments and decreases wing weight. Secondly, the nose-up pitching moment causes a reduction in the tail down loads and therefore reduces the load on the wing required to pull 2.5 g's. Thirdly, induced drag of an inboard loaded wing + downloaded tail is not very different from the ideal induced drag. This can be easily understood by applying Munk's theorem [12].

A year before this study was completed (1997) the second author had already proposed this design modification. This was not adopted at that time because shifting the load inboard caused significant additional wave drag.
The present study however, suggested modifying the wing load distribution, the wing sweep and the root chord simultaneously. This new planform design is shown in Fig. 8. The kink region was not very noticeable in the planform view any more and the wing sweep is increased a few degrees. The wing thickness ratio was not changed much. If we analyzed these design changes with our preliminary code we would get a performance gain of not less than 10,000 kg for every scenario.

**Verification of the design performance**

At this point the new preliminary design was finished. It was however hard to predict whether the large performance improvements were real. For that purpose a detailed design needed to be made. So we needed a detailed aerodynamic design based on the same specifications (multipoints) as the original reference design and analyzed with the same codes as the reference design. We used the Pointer-Aeropt code (as described in ref. 8) to design the detailed aerodynamic shape of the wing using 130 shape variables and 3 critical operating conditions. The start configuration for the detailed aerodynamic design loop used scaled A340 type airfoil sections. The drag of that wing was 30% higher than the reference configuration. After 2 cycles (1 month) the design had converged to a shape that produced a drag that was 5% lower than the drag predicted for the reference configuration with the same (Navier Stokes) code. This configuration is shown in Fig 9. Since we now also had the detailed section shapes we could repeat the application of the structural design and weight estimation tool FAME with more accuracy.

The overall performance gain was slightly higher than the 10 tons predicted. The improvement came equally from the drag and the weight. The reason for this can be found in the detailed design. Fig. 8 shows the location of the thickness maxima on the reference and the new wing. The reference wing puts the thickness maxima on an almost straight line. The optimal detailed wing sweeps the location of the inboard maximum thickness a lot more as compared to the outboard wing. We suspect that this (and the overall sweep increase) enables the higher inboard wing load without drag penalty.

Fig. 4 1-D scan of the aspect ratio before and after the optimization.
Fig. 5 Performance improvement over reference of wings optimized under various scenarios.

Fig. 6 Range of value of optimal design variables for all scenarios.
Fig. 7 Impact of an under-elliptic lift distribution

Fig. 8 Modified planform and thickness distribution.
Conclusion

We have presented a new wing preliminary design method that:

a) allows for estimation of transonic aerodynamic performance even in the early sizing procedure

b) accounts for the aeroelastic deformations of the wing in cruise and in load defining cases

c) enables significant performance improvements by interdisciplinary balancing the most significant design parameters.

This was only possible by extracting the significant physical properties and casting them into new, dedicated models for the preliminary design process. These models were calibrated using higher accuracy data from other sources.

Furthermore, the most significant design parameters were identified and included in the optimizer's variations. Future applications in the aircraft development have to include realistic constraints, such as landing gear housing, planform limitations by ground procedures, etc.

Additionally, a more accurate cost function should be developed which represents the essential project targets of the manufacturer.

Today, optimization within the individual disciplines is mature, but allows only for small improvements. On top of that, an improvement in one discipline can cause a penalty in another discipline.

In this paper, we presented a method whereby the minimum design modification was identified that produced the maximum total benefit for the design. These design modifications consisted out of the simultaneous modification of multiple design parameters. We showed that this result was not and (likely) cannot be achieved by conventional trade studies.
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References


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