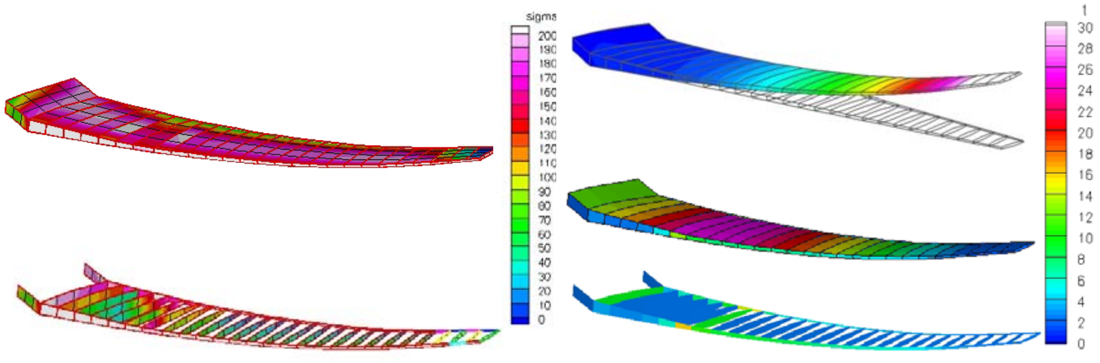
Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

Executive summary

Consistent models for integrated multidisciplinary aircraft wing design



Problem area

In wing design various disciplines are involved. Presently wing design involves a top-level design, which allocates design targets to each discipline. Subsequently these disciplines perform their designs independently, using discipline specific methods and tools resulting in non-harmonised wing design characteristics.

An objective of the described multidisciplinary design optimisation is to base the early wing design on a harmonised set of characteristics, commonly referred to as an integrated design model. The other objective is to create a flexible framework integrating the relevant design tools, taking the interaction between the disciplines into account.

Description of work

An automated framework has been realised which couples a number of disciplines tools into an integrated multidisciplinary design analysis system. The realised wing design framework prototype includes:

- geometry generation,
- engine sizing, based on a rubberised engine,
- weight bookkeeping,
- Finite Element Method based structural optimisation (for a single JAR/FAR 25 specified load case the +2.5 *g* pull-up manoeuvre),

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Author(s)
E. Kesseler
M. Laban
W. J. Vankan

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- high-fidelity Computational Fluid Dynamics (CFD) based aerodynamic analysis,
- mission analysis.

Some of these top-level disciplines, like structural optimisation, comprise interactions between their constituent lower-level discipline models, adding another layer of multidisciplinary analyses.

Results and conclusions

By integrating various design disciplines into one wing design facility, the design cycle is compressed. The design facility is adaptive as more discipline modules can be added or existing ones can be removed (or expanded) tailoring the tool suite to the design task at hand.

The computational requirements of the models used for the various disciplines are compatible with the wing MDO requirements to cover larger parts of the design space than possible with conventional non-automated methods.

Applicability

The framework demonstrates NLR's capability to couple and incorporate various existing tools into an integrated design facility. Such integrated analysis and design capabilities can support Dutch industry to move up in the supply chain, i.e. perform more integration activities.

NLR participates in the large European Union sponsored VIVACE (Value Improvement through a Virtual Aeronautical Collaborative Enterprise) project, which aims to reduce costs and time-to-market for aircraft and engine design.

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Summary

In aircraft wing design, various conflicting objectives are addressed by use of multidisciplinary analyses. The models used in each of these analyses must be consistent with one another, i.e. be based on the top-level design parameters. Each discipline has created its own models and tools. In this paper models of several disciplines are combined into an integrated wing design framework to evaluate the design objectives throughout the wing design space. Framework disciplines involved include geometry generation, engine sizing, weight calculation, structural optimisation and aerodynamics. Some of these top-level disciplines, like structural optimisation, comprise interactions between their constituent lower-level discipline models, adding another layer of multidisciplinary analyses. Other disciplines, like aerodynamics, produce results that are needed in several other top-level disciplines, like engine sizing and structural optimisation. The structure of the integrated wing design framework, and initial results of the integrated analyses related to application for civil aircraft are presented.

Contents

Abbreviations

AIAA	American Institute of Aeronautics and Astronautics
CFD	Computational Fluids Dynamics
COTS	Commercial-of-the-Shelf
FAR	(US) Federal Aviation Regulations
FEM	Finite Elements Methods
JAR	Joint Aviation Requirements
MDO	Multidisciplinary Design and Optimisation
VIVACE	Virtual Aeronautical Collaborative Enterprise

1 Introduction

Some background information to position the described work is provided in Figure 1. Based on some of the European Vision 2020 (Argüeles et al) [1] objectives, nearly 70 partners covering the whole spectrum of aeronautics stakeholders have decided to co-operate in the Virtual Aeronautical Collaborative Enterprise (VIVACE) project [2].

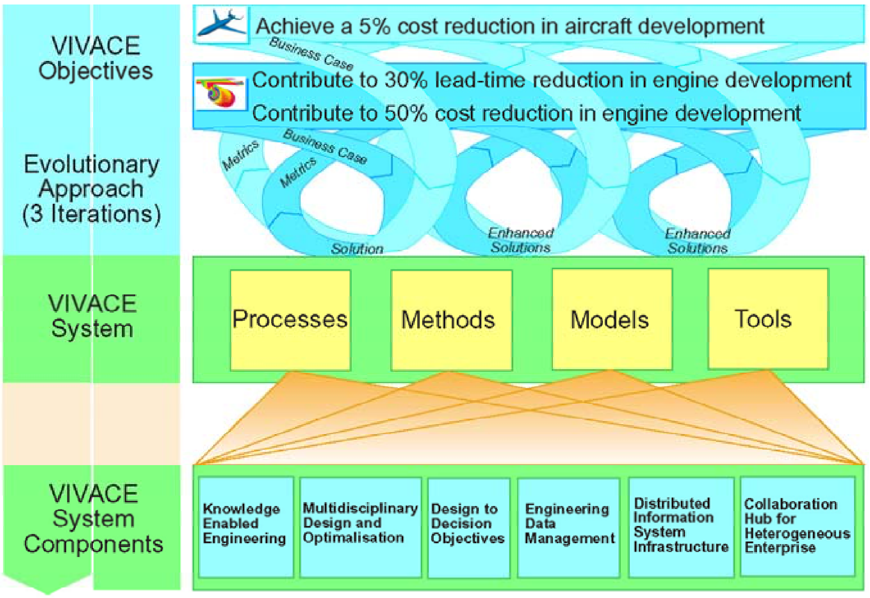

Figure 1 llustration of the global VIVACE process

This undertaking has opted for an evolutionary approach Gilb [3] in order to provide early benefits, to elicit user feedback and to accommodate requirements evolution. The latter is to be expected during the four-year realisation phase. For a European co-operation of this size this approach is innovative. This paper describes the results obtained for multidisciplinary wing design after the first of the three iterations. In line with the evolutionary approach, effort in this first iteration is concentrated on aircraft specific items, i.e. a wing multidisciplinary analysis capability has been realised. For the optimisation, Commercial-of-the-Shelf (COTS) optimisers can be used, at least for the first iteration. Connecting the various discipline analyses into a combined capability has been accomplished in a straight forward result-oriented way. For future iterations, use of more generic process integration tools, like Fiper [4], are envisaged.

2 Multidisciplinary design optimisation

Wing design is inherently a multidisciplinary activity that includes analyses in disciplines like aerodynamics, structures, flight control, manufacturing, etc. NASA [5] defines multidisciplinary design and optimisation (MDO) as a methodology for the design of complex engineering systems and subsystems that coherently exploits the synergism of mutually interacting phenomena. The American Institute of Aeronautics and Astronautics (AIAA) [6] more informal definition is "how to decide what to change, and to what extent to change it, when everything influences everything else." In the AIAA white paper by Giesing, Barthelemy [7], multidisciplinary design and optimisation is characterised as a human-centred environment that:

1. allows for the design of complex systems, where conflicting technical and economic requirements must be rationally balanced;
2. compresses the design cycle by enabling a concurrent engineering process where all the disciplines are considered early in the design process, while there remains much design freedom and key trade-offs can be effected for an overall system optimum;
3. is adaptive as various analysis/simulation capabilities can be inserted as the design progresses and the team of designers tailor their tools to the need of the moment;
4. contains a number of generic tools that permit the integration of the various analysis capabilities, together with their sensitivity analyses thereby supporting a number of decision-making problem formulations.

This succinctly describes the NLR's objectives in VIVACE and in particular those of the Wing MDO team. In general the various disciplines are not necessarily located in the same geographic site or even within the same company, as is reflected in the "CE" (Collaborative Enterprise) of the VIVACE acronym. As this paper deals with work performed during the first iteration, such multi-company, multi-site collaboration issues will not be elaborated. More information on these aspects in relation to NLR's VIVACE contribution can be found in Kesseler, Kos [8] and Kesseler et al [9].

Traditionally wing design and optimisation rely on the knowledge and experience of the human designers involved. It is common for a designer to focus on a single discipline. The interaction between the disciplines involved in wing optimisation, for example between aerodynamics and structures, is reflected in the interaction between the human experts. A typical sequence could be the aerodynamics expert designs a wing surface using dedicated computer-based models and tools. The aerodynamics forces are passed to the structures expert who subsequently designs a feasible structure for this wing geometry, using his own dedicated computer-based models and tools. This result can be transferred back to system level and the aerodynamics expert. Due to the human experts involved, a system level iteration typically takes a few weeks to a month to complete. The success of modern aircraft testifies to the effectiveness of this way of working. However the increasing requirements on aircraft performance and consequently on its design, as worded as part of the European Vision 2020 (Argüeles et al) [1], justify the investigation of a different, innovative optimisation option. The current work aims to couple the key disciplines involved by integrating the dedicated design tools used. Such an integrated analysis facility, coupled with a suitable optimiser, can explore many designs to find an optimum. The innovation of this work will be to compare the results of such mathematically oriented optimisation with traditional results. Also the current way of working is approaching its limits "to synergistically exploit these mutually interacting phenomena" NASA [5] as more disciplines get involved, e.g. by adding manufacturing concerns and hence costs, or environmental concerns like noise footprint.

For a single wing optimisation exercise, it is expected that the multidisciplinary analysis facility has to be executed hundreds or thousands of times. Consequently there is a strong requirement that the multidisciplinary wing analysis capability is computationally efficient. The analysis methods discussed in the subsequent sections are selected to comply with this requirement. Please note that fully automatic multidisciplinary analysis and optimisation (i.e. covering all disciplines involved for all relevant design criteria) is not yet considered feasible due to the complexity of the wing design and the many disciplines involved. Various discipline experts are still needed to initiate the optimisation, to provide limits for the parameterised design and to judge the feasibility of the generated results for the disciplines which are not (yet) taken into account. Automated MDO does provide the opportunity to assess a much larger part of the design space, compared with conventional approaches. This is reflected in the human-centred environment in the AIAA description cited above. Integration of the automated optimisation capability with the human-experts contribution is outside the scope of the current paper.

3 Top-level wing analysis

Figure 2 depicts the top-level view of the wing multidisciplinary analysis capability.

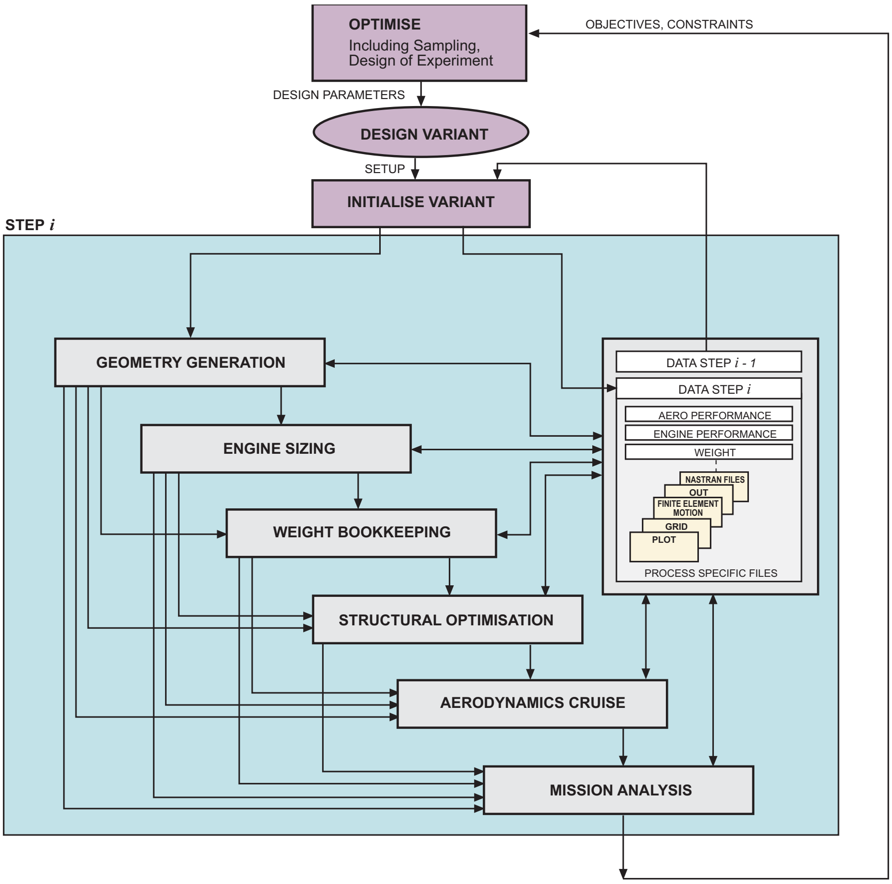

Figure 2 Top level wing multidisciplinary analysis capability

The wing optimisation is based on a multi-level optimisation, i.e. in addition to the top-level full-wing analysis and optimisation as shown in Figure 2, some lower-level analyses processes include optimisation processes at their own level. For example the engine-sizing process might optimise the thermodynamic cycles to arrive at minimum fuel consumption. Below some of the major top-level components are briefly described.

The *geometry generation* component (see box in Figure 2) uses a number of parameters to define a wing-geometry. These parameters are depicted in Figure 3. The generated geometry describes the external geometry, for aerodynamic purposes, and the internal geometry defines the internal wing structure, as needed for finite element analyses. In parallel with the work discussed, Cranfield University is working on a more generic version of the geometry generator, which is based on the industry standard CATIA software. Once their geometry generator becomes available it can replace the current geometry generator, illustrating the adaptive characteristic of MDO, as worded by the AIAA definition provided above.

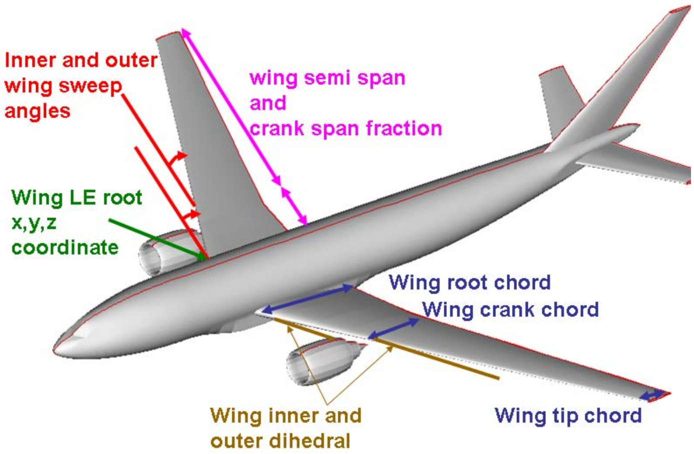

Figure 3 Parameters describing the wing geometry

For *engine sizing* (see box in Figure 2) a scalable engine data set is being used to determine the engine weight and the corresponding fuel flow. From the target range the total fuel weight and fuel volume can be determined. This is also referred to as a “rubberised engine”. The *structural optimisation* component (see box in Figure 2) determines the thickness of the wing’s primary structural elements like spars and ribs. For this component, standard desk-top computing equipment allows Finite Elements Methods (FEM) to be used. In the next section this component is explained in more detail. For the *aerodynamics cruise* component (see box in Figure 2), affordable standard computing equipment allows deployment of NLR’s proprietary simulation system MATRICS-V. MATRICS-V performs a full-potential boundary layer Computational Fluids Dynamics (CFD) calculation for the aerodynamics cruise component. Future, more advanced, multi-level evolutions of this component could take other relevant flight phases into account. The last component in Figure 2 is *mission analysis*. This component calculates some key characteristics of the wing design based on the information of the previous components. These characteristics are used by the optimiser to generate the design parameters of the wing variant for the next iteration.

In order to give an impression of the scope of the analyses within these top-level components, the next section elaborates the *structural optimisation* component as an example.

4 Structural optimisation

The Structural Optimisation component performs the sizing of the wing primary structural elements like spars, ribs and covers, based on certain representative load cases. Ideally, all load cases required to certify the aircraft structure according to the US Federal Aviation Regulation (FAR 25) rules [10] or its European Joint Aviation Requirements (JAR 25) equivalent should be considered. However, in order to simplify the analyses and to comply with the strict computing time demands, as stated in section 2 above, only a single representative load case consisting of a +2.5 *g* pull-up manoeuvre is analysed. Moreover, this load case is configured such that the wing structure experiences maximum bending moments, i.e. maximum payload, full stabilizer trim tank, and full wing tanks.

Figure 4 shows how the structural optimisation is embedded in the multidisciplinary analysis, and how this local-level optimisation loop interacts with the various analysis modules from the other disciplines. An iterative scheme arises as the, a-priori unknown, wing structural weight is fed back via the *total weight* module to the *prelude manoeuvre aerodynamic loads* module where the aerodynamic loads are updated for the new aircraft weight.

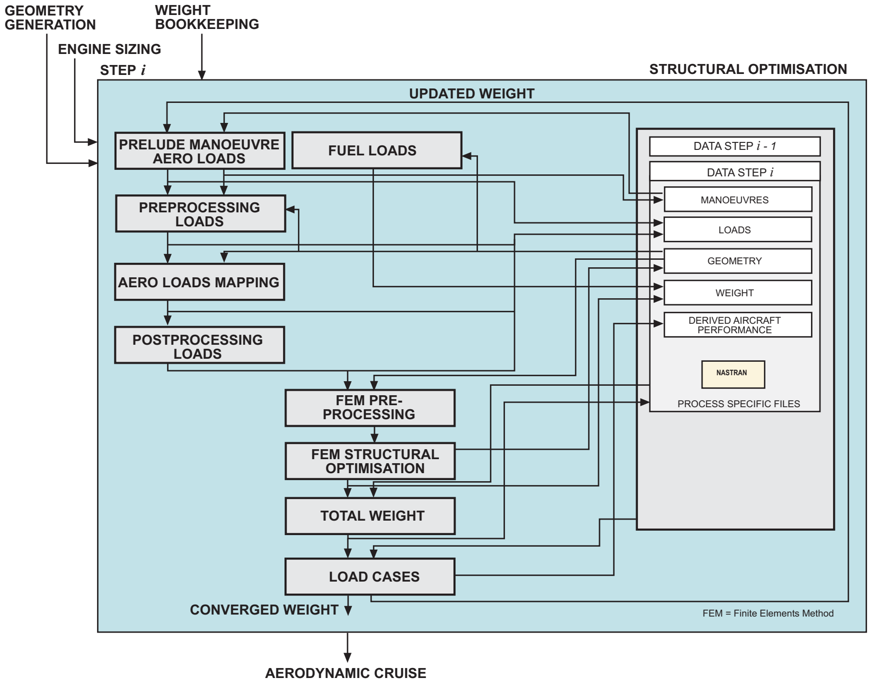

Figure 4 Top level breakdown of structural optimisation component

The *prelude manoeuvre aero loads* module (see box in Figure 4) provides the aerodynamic loads by calculation of the flow solution according to an extension of the non-linear lifting line method Weissinger [11].This calculation consists of a superposition of aerodynamic forces due to bound/trailing vortices, predicted according to vortex theory, and aerodynamic forces due to viscous effects and shock waves, predicted according to 2-Dimensional (2D) airfoil theory, see Figure 5.

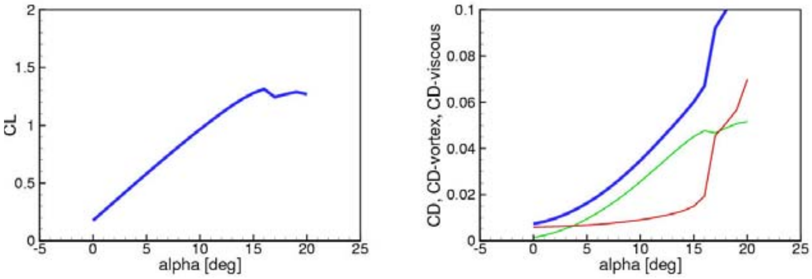

Figure 5 Illustration of the aerodynamic loads calculation considered in the structural optimization process Blue represents total drag (CD), green represents CD-vortex and red represents CD-viscous

The aerodynamic loads are translated by the *aerodynamics loads mapping* module into elementary force vectors on the aerodynamic wing surface grid. These force vectors are then mapped, using spline interpolation techniques, to the structural grid points of the aerodynamics/structures interface. The result is a load map representing the external surface pressure loads. The wing geometry, as considered in the aero loads calculation, and the resulting aero loads map are illustrated in Figure 6.

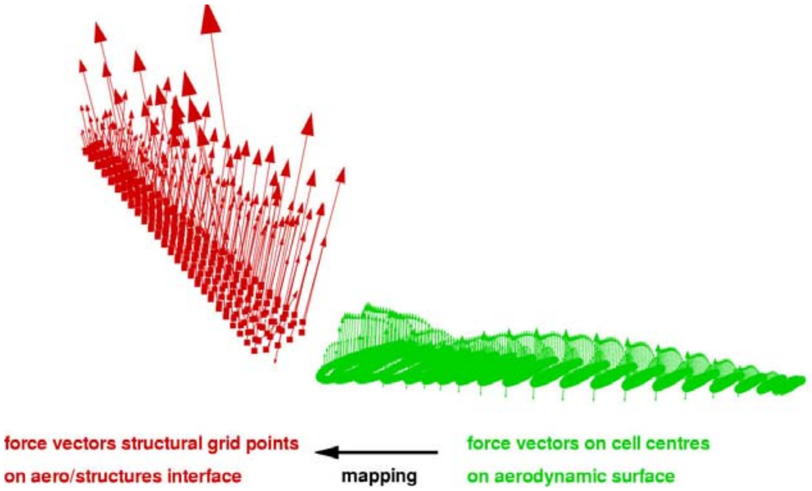

Figure 6 Illustration of the aerodynamic loads calculation considered in the structural optimization process: the mapping of aerodynamic loads (green) to force vectors (red) in structural grid points

Wing fuel loads during the +2.5 *g* load case are computed as hydrostatic loads on the wing-box lower-skin. In this load case, the various wing tanks are filled to equi-potential levels to reach the maximum take-off weight. The wing structural layout, as provided by the geometry module, is read into a special purpose *FEM-pre-processing* module. This module meshes the structural geometry using quadrilateral elements (covers, spars, ribs) and bar elements (stringers), groups structural elements into design areas and connects the mass items (landing gear and engines) to the primary structure. Next the module reads the externally provided (aerodynamic and fuel) loads and returns a bulk data set for the subsequent structural analysis step. For the engines, data including weight and thrust forces from the engine-sizing module are used, see Figure 7.

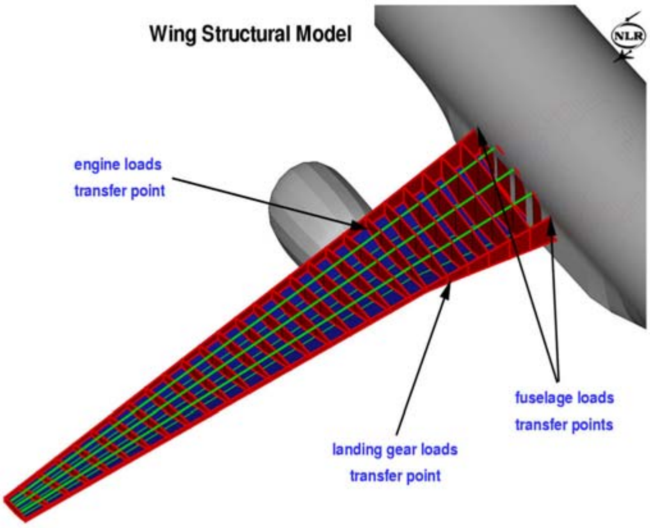

Figure 7 Illustration of the wing structural model, incorporating the loads due to weight and thrust from engines, and fuel weight.

The structural analysis is based on the finite element method implemented in MSC-NASTRAN. The response of the structure (local stresses and strains) to the applied loads (aerodynamic, weights, thrust) is evaluated by NASTRAN's linear static analysis of the wing. For the sub-sonic aircraft wing as shown in Figures 8a – 8e this involves 748 elements and 1800 degrees of freedom. The optimisation is performed using NASTRAN's gradient based SOL200 optimiser, which directly controls the linear static FEM analysis. The optimisation problem considered is a constrained minimisation of the structural weight of the wing:

$$\min_{x_i} f(x_i)$$

$$\textit{subject to: } g_j(x_i) = \sigma_j(x_i) - \sigma_{\max} \le 0 \quad \forall i, j \quad ; \quad l \le x_i \quad \forall i \qquad (1)$$

Here the objective function *f* represents the wing's structural weight, which depends on the design parameters x_i (plate thicknesses of spars, ribs and covers, defined for each design area *i*). The wing structural weight is minimised by variation of these design parameters that are bound by a minimum value *l*, for which a value of 2 mm is chosen. Furthermore the optimisation is constrained by the non-linear function g_j, which represents the local value of the Von Mises stress σ_j in each of the FEM element centres *j* and which is bound to $\sigma_{max,}$ the maximum level of 200 N/mm^2 (isotropic aluminium). The Von Mises stresses in the constraint function *g* result from the linear static structural analysis of the wing for the *+2.5 g* manoeuvre concerned. The optimisation analysis converges in approximately 20 iterations. Some of the results of the optimised wing structure are given in Figure 8 below.

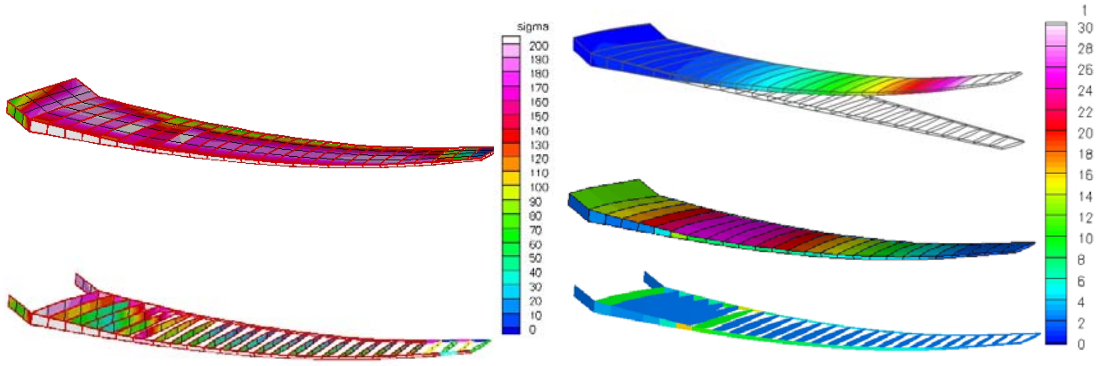

Figure 8 Von Mises stresses at +2.5 g manoeuvre for wing internal structures (bottom left), and wing skin (top left). Wing thickness optimisation results at +2.5 g manoeuvre for internal structures (bottom right) and wing thickness (middle right).
Top right, maximum wing deformation at +2.5 g manoeuvre.

The thicker rib in the inner wing (and the adjacent beam sections) is where the engine weight and thrust are transferred, see also Figure 7. Towards the wing tip all ribs have the minimum thickness (Figure 8 bottom right) whereas the maximum Von Mises stress is not reached. This indicates that, for the outer wing, the wing design does not utilise the full capabilities of the used material for the +2.5 *g* manoeuvre analysed. Only the outermost design areas experience a Von Mises stress below the maximum, see Figure 8 bottom left. Figure 8 middle right, shows that for these design areas the wing skin reaches the minimum level. Figure 8 top right depicts the significant wing deformation for the +2.5 *g* manoeuvre. It should be noted that this local level structural optimisation involves only the structural elements' thicknesses. Incorporation of also the wing planform design parameters in this structural optimisation, i.e. aero elastic tailoring, is achieved via the higher level optimisation loop but is currently not specifically considered.

Figure 8 illustrates the obtained material thickness distribution of the wing covers and wing ribs, as well as their resulting von Mises stresses and the resulting deformation of the optimised wing. The finite element analysis does not yet include details of the structure which arise from manufacturability or maintainability constraints. Due to the modular approach of the design capability, modules addressing such items can be either included in the lower-level loop of Figure 4, or in case the interaction is considered less direct in the top-level loop of Figure 2. Several studies suggest a factor of 1.5 between the FEM-optimised structural weight and the actual real-life aircraft structural weight. This additional 50 percent is designated as "secondary" structural items and included in the weight breakdown. Again, as more disciplines are included in the analysis capability, actual data could replace such significant additional engineering weight factors and take them into account when optimising the wing.

During the *global-level* wing planform optimisation (Figure 2), subsequent aircraft variants inherit their initial material thickness distribution from the baseline aircraft. These material thicknesses are adapted to the +2.5 *g* manoeuvre loads in the *structural optimisation* loop, and then updated in the global level wing data base. After this update the manoeuvre loads can be recalculated and the structural optimisation can be run again taking these updated loads into account. With each such pass through the structural optimisation loop of Figure 4, the wing weight is observed converging about one order of magnitude. Initial experiments indicate that executing a sequence of two structural optimisation loops was found to provide sufficiently well converged wing weight data.

5 Conclusion and future work

This work addresses all four AIAA multidisciplinary design optimisation characteristics mentioned above. Clearly the optimisation has to balance conflicting technical and economic requirements, demonstrating the first AIAA MDO characteristic. By integrating various design disciplines into one facility, the design cycle is compressed, illustrating the second AIAA MDO characteristic. The facility is adaptive as more discipline modules can be added or existing ones can be removed (or expanded) tailoring the tool suite to the design task, as stated in the third characteristic. Especially for the collaboration aspects, generic tools can, and indeed are planned to be deployed, as worded in the fourth characteristic.

The current status of the multidisciplinary wing optimisation is integrating some main disciplines into a single tool suite. Once this activity is completed, the first optimisations can be performed. The experience up-to-date is that the models used for the various disciplines have computational requirements that are compatible with the requirement of the wing MDO, i.e. allow a sufficient part of the design space to be covered as needed by the automatic optimisation proposed.

Based on the experience with those first optimisations the next steps will be defined, which is compliant with the evolutionary approach, and which is an improvement of the waterfall approach as typically used in previous large European collaborations.

Acknowledgement

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References

[1] P. Argüeles, et al, Report of the group of personalities, European aeronautics: a vision for 2020, 2001, europa.eu.int/comm/research/growth/aeronautics2020/en/index.html, accessed March 2006

[2] VIVACE project website, www.vivaceproject.com, accessed March 2006

[3] Tom Gilb, June 2003, Competitive engineering, Chapter 10, page 1-26, www.gilb.com, accessed July 2005

[4] Anonymous, Fiper Engineering Enterprise Infrastructure, www.engineous.com/index.htm, accessed March 2006

[5] Anonymous, NASA Multidisciplinary Design and Optimisation branch http://mdob.larc.nasa.gov/index.html, accessed March 2006

[6] Anonymous, AIAA MDO technical committee, www.aiaa.org, accessed March 2006

[7] J.P. Giesing, J.F.M. Barthelemy, A summary of industry MDO applications and needs, 1998, AIAA, http://endo.sandia.gov/AIAA_MDOTC/sponsored/mao98_whitepaper.html, accessed March 2006

[8] E. Kesseler, J. Kos, The next step in collaborative aerospace engineering, RIVF'05 conference proceedings, February 2005

[9] Ernst Kesseler, W. Jos Vankan, Taking collaborative engineering to the sky, EUCASS conference proceedings, July 2005, also available as NLR-TP-2005-312

[10] Anonymous , FAR 25 Airworthiness Standards: Transport Category Airplanes, http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?&c=ecfr&tpl=/ecfrbrowse/Title14/14tab_02.tpl, accessed August 2005

[11] J. Weissinger, The lift distribution of swept back wings; NACA TM 1120, 1947