DEVELOPMENT OF A PREPROCESSOR FOR THE GENERATION OF STRUCTURAL BEAM MODELS FOR MULTIDICIPLINARY OPTIMISATION

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ABSTRACT

In this paper a structural preprocessor developed at the Department of Mechanics (LFM) of RWTH Aachen University and its application are presented. The preprocessor was implemented in the course of the cooperative research project MEGADESIGN and serves to automatically generate reduced structural models from geometrical information and user-suplied parameters. It forms one element in the effort to create a program environment for the multidisciplinary optimisation of the shape and structure of aircraft wings.
After detailing the motivation for this project the theoretical background to the structural preprocessor is outlined. The accuracy of its results is proven for a generic configuration. Finally, its application in a simplified process chain is presented.

1 INTRODUCTION

In designing an aircraft one strives to achieve an optimal result, taking into account technical and economical constraints. To this end the application of Finite-Element Methods for dimensioning the structure and the application of numerical flow solvers for aerodynamic analysis have become industrial standard. However, structural and aerodynamic properties of an aircraft are generally still determined and optimised independently, often even by different departments of the manufacturer. This approach does not duly consider the interaction between fluid and structure, which becomes more momentous with the increasing size and flexibility of modern transport aircraft wings[1].

For this reason the cooperative research project MEGADESIGN[2] was initiated and conducted under the lead-management of the German Aerospace Center (DLR). A primary goal was the creation of a multidisciplinary design environment for the simultaneous optimisation of shape and structure of wings. LFM acts as a technology supplier specialising in the development of tools and techniques for aero-structural analysis and the identification of reduced-order structural models. The contributions of LFM to MEGADESIGN comprise two major workpackages.

The first contribution consists of the Aeroelastic Coupling Module (ACM). In the partitioned approach for aeroelastic flow simulations pursued by LFM, this modular program carries out the consistent and conservative exchange of loads and deformations between the problem fields as are flow solution, elastic structural deformation and CFD volume grid deformation. The ACM has been extensively validated and successfully applied for transonic steady and unsteady aeroelastic simulations[3], [4], [5],[6]. For the MEGADESIGN project the DLR flow solvers FLOWer and TAU[7] were coupled through the ACM, whereas the in-house Finite-Element code FEAFA[8], [9] (Finite-Element Analysis for Aeroelasticity) was used for determining the structural deformation.

The second workpackage addresses the automatic generation of reduced structural models. These constitute Finite-Element models consisting of generalised Timoshenko beam elements which are multi-axial in the sense that the torsional axis, the mass axis and the flexural axis can be chosen independently of the geometrical beam reference axis. Beam models allow an accurate determination of the aeroelastic equilibrium configuration (AEC) with only small additional computational effort compared to flow computations about rigid

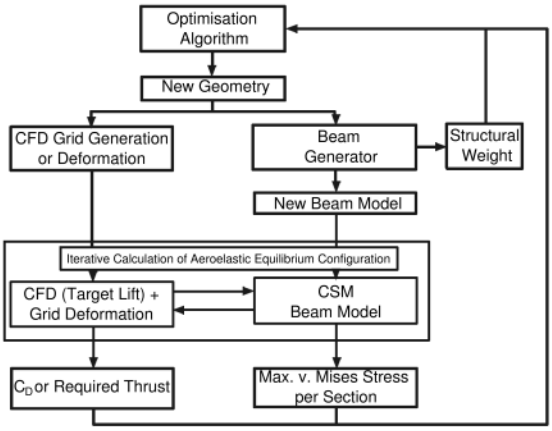

Figure 1: Optimisation scheme realised in MEGADESIGN. The Beam Generator encompasses the Beam Preprocessor and the FE-code FEAFA.

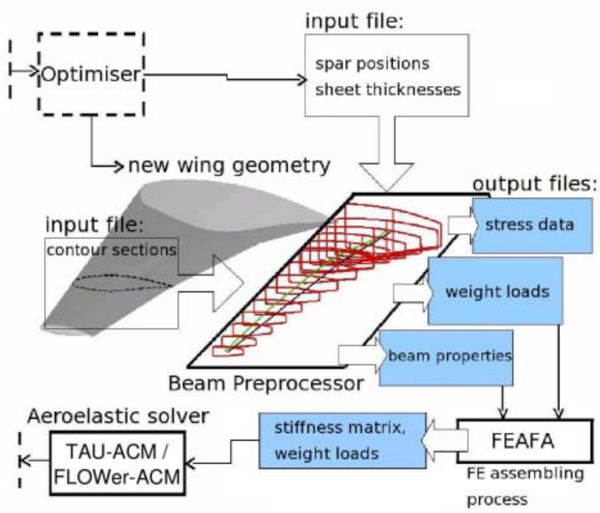

Figure 2: Closeup of the optimisation scheme in Figure 1 showing the Beam Generator process chain.

bodies disregarding deformation.
To this end a preprocessor tool was developed which is the subject of this paper and will henceforth be referred to as "Beam Preprocessor". It is an integral component of the scheme[10] realised in this project for the multidisciplinary optimisation of wing shapes and structures. Together with the FE-code FEAFA it represents the process instance denoted as "Beam Generator" in Figure 1.

2 METHOD

The Beam Preprocessor generates a multicellular, thin-walled spar box from sections of the wetted surface. The number of spars, their chordwise positions as well as the sheet thicknesses of the spars and of the upper and lower panels can be externally prescribed and thus represent potential optimisation parameters (see Figure 3).

The resulting beam properties are calculated analytically applying the formulas for multi-cell thin-walled hollow sections. The data is processed in a manner suitable for FEAFA, which in turn assembles the mass and stiffness matrices (see Figure 2). Latter constitute a reduced structural model of the wing box consisting of Timoshenko beam elements as is required by the structural side of the coupled aeroelastic solution process (see Figure 4).

Representing the structure as a beam is possible for wings with high aspect ratios, which are typical for transport aircraft. Also, material cross-sections perpendicular to the undeformed elastic axis have to remain plane even in the deformed configuration. This is the case if the ribs are oriented accordingly. Often, a mixed construction is chosen in which the inboard ribs are aligned parallel to the incoming flow whereas the outboard ribs are arranged orthogonally to the elastic axis. This type of configuration can also be modelled in the described manner as long as the wing stiffness strongly decreases along the wing span.

The geometry of the sections through the wetted surface is supplied to the Beam Preprocessor in the form of coordinate lists together with the corresponding connectivity data.
In a preparatory step the coordinates of a given section are first sorted to create a consecutive loop. Possible gaps in the contour connectivity are bridged with neighbourhood searches. As the structural properties of a section are determined by the centerline of the sheet and not by its outer surface, the nodes can be moved inwards along

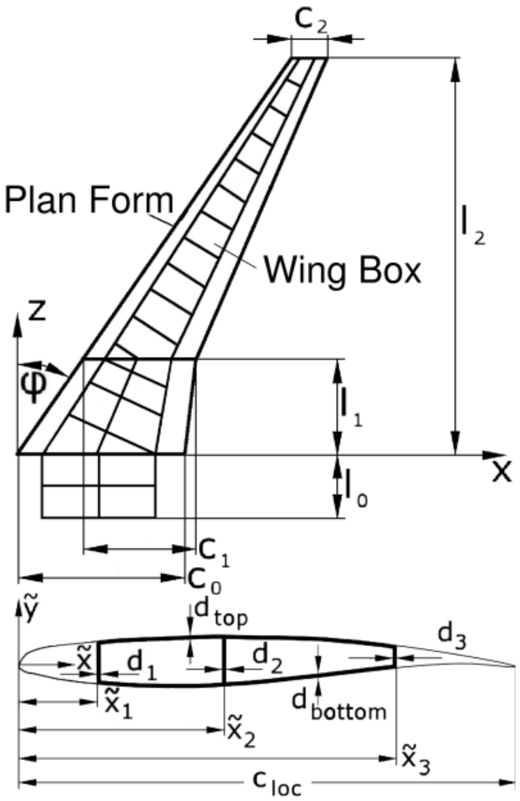

Figure 3: Generic wing box with spar positions and sheet thicknesses as parameters.

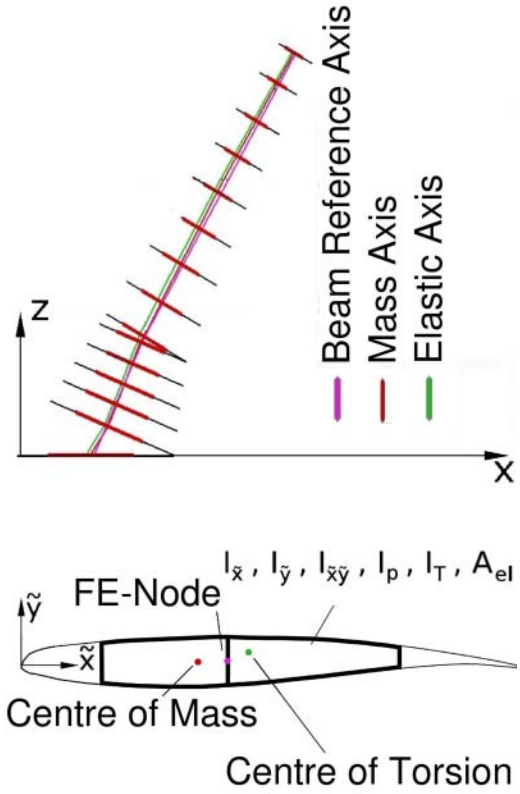

Figure 4: Equivalent beam model with corresponding beam properties.

the local contour normal by half the local sheet thickness.

To enable the ensuing computations to be performed in 2-D the coordinates defining the contour are then transformed into the section plane coordinate system. The actual multi-cell hollow section is created by inserting spars at the chordwise positions defined by the user. All coordinates in front of the foremost spar and behind the rearmost spar are discarded and the respective sheet thicknesses are assigned to each surface (see Figure 5).

For the calculation of the beam properties of a section the contour is idealised as a polygon. The data required in each section comprise

- the flexural and torsional stiffnesses,
- the torsional, flexural, and mass centres,
- the moments of inertia, as well as
- the structural mass.

The algorithms are based on the theory of thin-walled hollow cross-sections. It is assumed that across the thickness of the sheets the shear stress is constant and can be treated in terms of shear flow. This approach is valid for isotropic and homogeneous materials if the greatest sheet thickness does not exceed one-fifth of the smallest lateral dimension of the structure.
Also, warping stresses are neglected. These occur in regions where structural warping due to torsional loads is impeded or reduced, i.e. by the clamping at the wing root or at kinks and junctions. In slender structures, to which beam theory is limited, the majority of sections is not subject to warping stresses and this assumption should cause only a small error in flow and aerodynamic load computations.

The flexural stiffness, the total mass, and its centre can be obtained via straightforward summa-

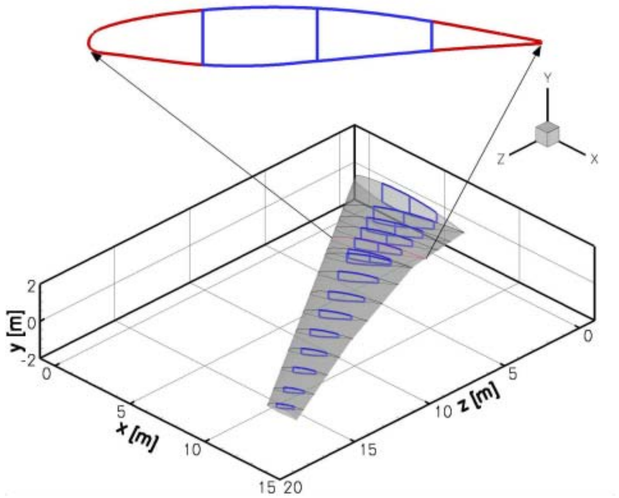

Figure 5: Schematic of the modelling of a wing box showing the introduction of spars in a read-in section.

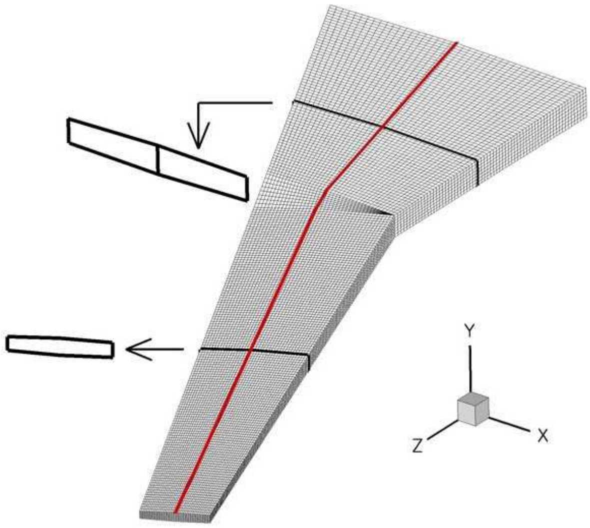

Figure 6: Shell model of the configuration used for the validation of the Beam Preprocessor. The line along which the comparison stresses were extracted is marked in red.

tion over the contour elements. In contrast the calculation of the torsional stiffness and of the torsional centre of a multi-cell section are indeterminate problems. Each cell has to be cut open and additional shear flows have to be introduced to cancel any deformation at the cut edges. Both desired quantities have to be derived from the additional shear flows, which result from linear systems of equations[11], [12], [13]. The beam properties are calculated and stored separately for each read-in section.

Next the location of the beam axis is defined. It serves only as a geometrical reference for the description of the coordinates of the torsional, flexural, and mass centres. Thus it cannot be calculated but must be prescribed in some manner. Three different requirements should be fulfilled as well as possible: The beam axis should closely follow the elastic axis to make sure both possess the same bending lengths. To conform with beam theory the beam axis should lie perpendicular to the read-in sections. Finally, the beam axis should at least segment-wise be straight to enable an easier interpretation of results.
The simplest way of satisfiying these requirements is to specify coordinates defining the beam axis. This demands a rough *a priori* knowledge of the location of the elastic axis. Generally, the geometrical centreline of the wing plan form represents an appropriate first approximation.

For a good representation of a typical wing structure its beam discretisation should comprise at least 40 elements. To avoid having to read in this number of cross-sections the beam properties at intermediate positions can be interpolated from the calculated values.

The structural data characterising the beam model of the wing box is stored in a manner compatible with FEAFA, which in turn supplies the structural side of the aeroelastic solution process with the stiffness and mass matrices.

In the final steps of the analysis the additional information needed in an optimisation run is generated.

The wing structural weight enters the aircraft range as a typical objective function. Besides, the weight distribution along the wing span influ-

ences the bending and twist distributions of the AEC. The loads exerted by the structural weight can be immediately communicated to FEAFA as additional entries to the right hand side of the Finite-Element problem. Also, arbitrary additional loads may be specified by the user in the same manner, e.g. thrust forces.
The fuel loads generally have considerable impact on the AEC, but the fuel mass itself may depend on the formulation of the optimisation problem. To enable the calculation of the fuel loads the cross-sectional areas and the sections' geometric centres are stored separately from the beam structural data.

To limit the optimisation process to feasible designs boundary conditions must be imposed. A suitable formulation should confine the design space to structures in which the actual v. Mises stress does not exceed the material's yield stress. As no stress values can be derived from the beam model, the required information is obtained by analysing the geometrical information background to the beam discretisation. To this end normal and shear stresses per unit force or unit moment are calculated by the Beam Preprocessor.
Normal stresses as a consequence of longitudinal forces as well as bending moments are functions of the cross-sectional area of the load-bearing structure and the section modulus, respectively. The shear stresses due to transverse forces and torsional moments depend on the shear flows needed in the calculation of the torsional stiffness and of the torsional centre.

The estimation of the stresses in the wing is then carried out in a follow-up to the aeroelastic flow calculation: The loads acting upon the structural nodes in the AEC are added up to cut loads and the resulting shear and normal stresses in the read-in sections can be evaluated.

3 VALIDATION

For the validation of the Beam Preprocessor a generic multi-cell box beam was defined. Three aspects were considered:

- the accuracy of the deformation calculations based on the beam models,
- the accuracy of the stress approximation,
- and the accuracy of the weight estimate.

The first two points were investigated by using the commercial FE package MSC/MARC to create a thick shell model of the reference geometry. It is similar in plan view, size, and inner layout to the structure of a transport aircraft-type wing[10]. However, the configuration of the shell model was facilitated by specifying hexagonal cross-sections instead of curvilinear ones.
Inboards of the kink the structure has three spars, whereas outboards it only possesses two. Ribs are introduced at regular intervals to ensure the structural sections keep their profile during deformation and beam theory can be applied. The ribs are oriented in parallel to the x-axis inside the kink, while outside they are aligned perpendicularly to the geometrical centreline of the wing box (see Figure 6).

The shell model and the equivalent beam model were both subjected to point loads at the wing tip. Special attention was paid to inhibiting local load transmission effects in the shell model. A comparison of the deformation distributions is shown in Figure 7 for a vertical force of $F_y = 80kN$ and in Figure 8 for a torsional moment of $\|\boldsymbol{M}_T\| = 300kNm$.
The depicted results were obtained with a thick shell discretisation of around 28000 linear quadrilateral elements, and a beam model of 56 Timoshenko beam elements. For visualisation purposes the deformations of the beam model were projected onto the shell surface. To this end the same algorithm was used as is implemented in the ACM for the deformation transfer.

The isolines of the bending deflection in Figure 7 prove that beam theory is indeed applicable to this configuration. The contour plots match well, with only minor differences visible at the root and around the kink. At the points denoted $\boldsymbol{x}_1$ the local error of the beam model relative to the shell model is $\triangle u_y/u_{y,MARC} = -0.23\%$, but it reaches nearly 10% close to the kink. In this region of load redirection beam theory is, strictly

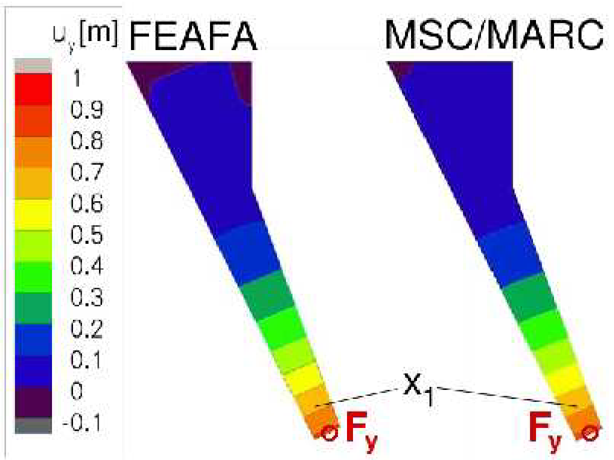

Figure 7: Contour plot of the deformation due to a tip load of $F_y = 80kN$.

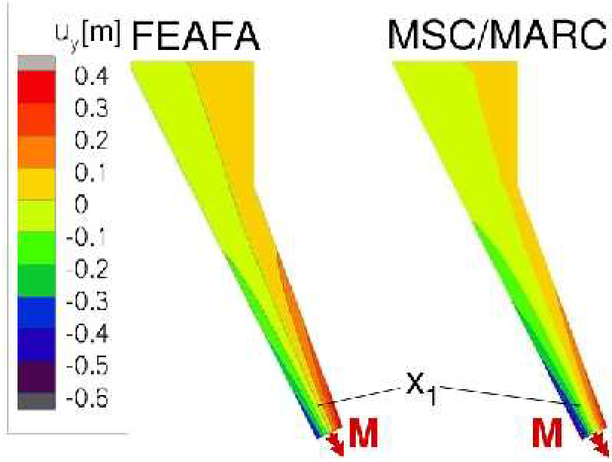

Figure 8: Contour plot of the deformation due to a tip load of $\|\boldsymbol{M}_T\| = 300kNm$.

speaking, not valid. Also the kinematic coupling of sections on both sides of the kink is not properly captured by the beam model.

The contour plots of the vertical deflection due to a torsional moment applied at the wing tip depicted in Figure 8 do not exhibit the same amount of agreement as for transverse force loading. Here the relative error in torsional angles at $\boldsymbol{x}_1$ is $\triangle\varphi_T/\varphi_{T,MARC} = -2.8\%$. As before, the discrepancies are concentrated around the kink. Apart from the reasons already given, for torsional loads the disregard of warping effects in the formulation of the beam model may play an additional role.

For the validation of the stress prediction generated with the data provided by the Beam Preprocessor, the v. Mises comparison stresses were extracted from the shell model along the red line plotted in Figure 6. The stress distributions due to torsion and bending are compared in Figure 9 and Figure 10.
In both cases the approximation from the geometrical information in the Beam Preprocessor is conservative and follows the distributions given by MSC/MARC, apart from the stress peak in the vicinity of the kink in Figure 9. Also the Beam Preprocessor strongly overestimates the comparison stress close to the root under torsional loads.

Nonetheless, the accuracy of the stress prediction obtained with the Beam Preprocessor is sufficient for defining a boundary condition to the optimisation problem. Once the optimisation process will have delivered a structural design, this would have to be discretised with higher-order models. With the loads acting in the AEC a more detailed investigation of the comparison stresses would have to be carried out, paying special attention to kinks and corners.

In the stress distributions of the shell model downward-directed peaks occurred in regular intervals at the intersections of the upper surface and the ribs. These peaks are spurious, though, and their representation in the diagrams was suppressed. The stress distributions in such regions are three-dimensional and cannot be captured correctly with shell models.

For the validation of the structural weight estimation a different procedure was chosen. Because MSC/MARC does not offer the possibility to calculate the mass or volume, the surface model of another configuration was given a sheet thickness in the CAD program CATIA V5. The resulting mass was compared to the value provided by the Beam Preprocessor, resulting in a relative error of $\triangle m_{wing}/m_{wing,CATIA} = +1.4\%$.

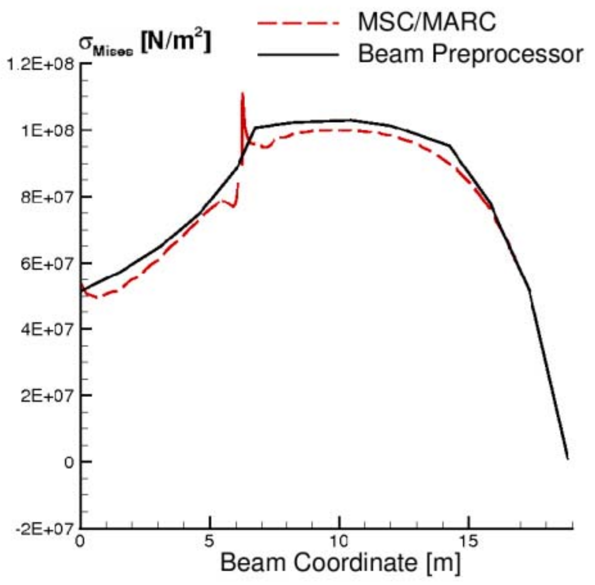

Figure 9: Comparison of the v. Mises stress distributions due to a vertical tip force of $F_y = 80kN$ obtained from MSC/MARC and from the geometrical information in the Beam Preprocessor.

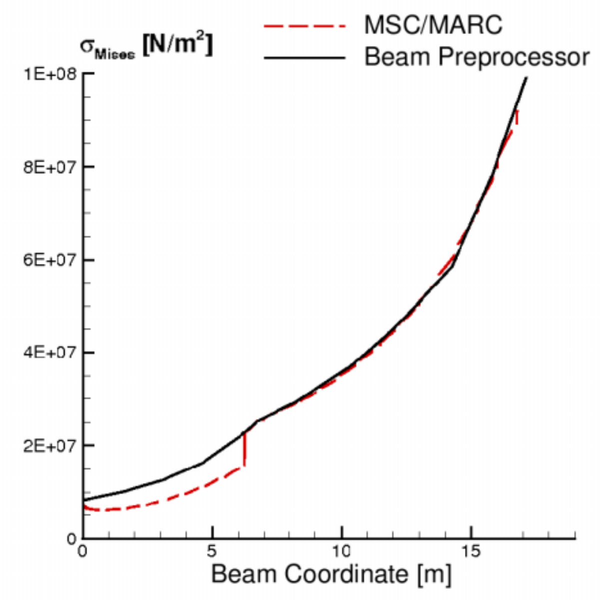

Figure 10: Comparison of the v. Mises stress distributions due to a vertical tip torsional moment of $\|\boldsymbol{M}_T\| = 300kNm$ obtained from MSC/MARC and from the geometrical information in the Beam Preprocessor.

4 APPLICATION

After the completion of the Beam Preprocessor and its associated modules, a process chain comparable to the MEGADESIGN optimisation scheme was set up in a command line script. Apart from proving the suitability of the Beam Preprocessor for its intended application, the process chain was built to evaluate the influence of different design parameters taking into consideration fluid-structure interaction.

Because LFM had no optimisation tools at hand and no prior experience in multidisciplinary optimisation, sweeps over the parameter space were performed instead. The script controlled the calculations necessary to obtain the value of the objective function at discrete combinations of design parameters and thus created a hyperplane of the objective function. This method obviously limited the number of free parameters to three which could be investigated simultaneously, as more parameters cannot be visualised in a simple manner.

The formulation of the problem was adapted from the goals of the MEGADESIGN project[10]: With a scaled version of the HIRENASD wing[4] as an exemplary geometry it was aimed to maximise the achievable range R[14],

$$R = \frac{2}{b_f}\sqrt{\frac{2\,g}{\varrho_\infty A}}\frac{\sqrt{c_L}}{C_D}\left(\sqrt{m_0}-\sqrt{m_1}\right). \tag{1}$$

The total mass m_0 was defined as constant, the structural weight influencing the amount of fuel available and thus the zero-fuel mass m_1. The lift was accordingly required to remain constant. Furthermore the yield stress boundary condition was taken into account:

$$\begin{aligned} c_L - \frac{mg}{q_\infty A} &= 0\,, \\ 1 - \frac{S\sigma_{Mises}}{\sigma_F} &\geq 0\,. \end{aligned} \tag{2}$$

The yield stress σ_F was reduced here by a suitable safety factor S[15].

In all hyperplane investigations two of the above three parameters were chosen in common: The

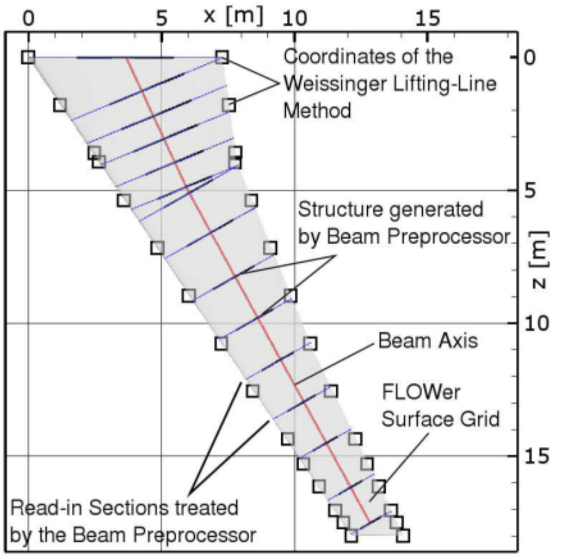

Figure 11: Scaled HIRENASD wing used in the hyperplane investigations. The structural model generated by the Beam Preprocessor and the coordinates forming the Weissinger model are included.

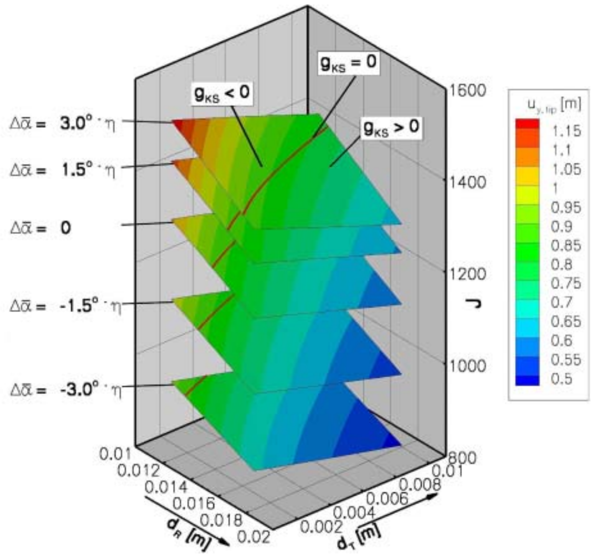

Figure 12: Reduced range $J\,(d_R,\, d_T,\, \triangle\overline{\alpha}(\eta))$. The valid design space $g_{KS} \geq 0$ is limited by the red line.

sheet thicknesses of the wing structure were varied at the root and the tip, with values at the intermediate sections being linearly interpolated. Moreover, the geometrical spanwise twist distribution, the percentage of the chord length considered in the structural modelling and the chordwise position of the middle spar were individually varied in three separate analyses. For the first two investigations a structure with three spars inboards of the kink and two spars outboards was defined, whereas for the third investigation three spars were introduced over the complete span.

The procedure described above involved a large number of simulations, making the use of a Navier-Stokes flow solver for the determination of the AEC for each parameter combination impractical. Rather, a simplified aerodynamic model was implemented in the stand-alone version of the ACM. It is based on the Weissinger subsonic lifting-line theory[16], which was expanded by 2-D polar data to approximately consider viscous profile drag (see Figure 11). The method was validated against rigid and aeroelastic simulations using the FLOWer code.

For the investigation of the design space the Weissinger-ACM was embedded in a target-lift loop to fulfill the first condition of equation (2). The values of the yield-stress boundary condition were determined with the data supplied by the Beam Preprocessor in all read-in sections of the wing. To gain a single value g_{KS} of all boundary conditions the Kreisselmeier-Steinhauser-function[1], [17] was employed. It represents a continuously differentiable conservative envelope to a set of boundary conditions.

The hyperplane investigations resulted in diagrams of the type exemplified in Figure 12. The sheet thicknesses at the wing root d_R and at the tip d_T – common values were prescribed for the spars as well as the upper and lower surface in each section – form the abscissas.
Compared to equation (1) the objective function J plotted on the ordinate is modified:

(3) $$J = \frac{\sqrt{m_0} - \sqrt{m_1}}{c_D}.$$

All constant factors are omitted, which does not affect the position of the optimum in the parameter space. The variation of the third design parameter is visualised by plotting a group of planes.

According to equation (3), an improvement in range can be achieved by two mechanisms: reducing drag and reducing the wing structural weight. Latter is a linear function of the sheet thicknesses.
As Weissinger's method is limited to subsonic flow, for the flight conditions investigated here the most susceptible drag component was the induced drag. It depends on the spanwise circulation distribution which should approach the ideal elliptic distribution. The wing bending deformation introduces an aeroelastic twist, so that the induced drag also depends on the stiffness of the wing and thus on the sheet thicknesses.
An optimal configuration is a trade-off between the structural and aerodynamic requirements: The spanwise aerodynamic centre is moved slightly inboards compared to the elliptic circulation distribution in order to reduce the root bending moment and thus to allow a lighter wing structure[1].

In the shown hyperplane plot the geometrical twist was varied as the third design parameter. Linear distributions were prescribed over the half-span s in the form of $\triangle\overline{\alpha}(z) = \triangle\overline{\alpha}_{max}\, s\, \eta$.
As this design parameter does not affect the structure, the wing weight is not influenced either. Accordingly, the higher range caused by a positive spanwise geometrical twist can be attributed purely to the reduction of drag. For the wing geometry investigated, a geometrical twist distribution which counters the aeroelastic twist has a beneficial effect on the circulation distribution.

The design space is limited by the Kreisselmeier-Steinhauser function $g_{KS} = 0$, leading to a boundary optimum in terms of sheet thicknesses at wing root and tip. With increasing spanwise geometrical twist the boundary is shifted to greater sheet thicknesses. This is a consequence of the spanwise lift center being moved outboards, amplifying root bending moments.

Upon each plane a contour plot of the vertical tip deflection is superimposed. The relative orientation of the deflection isolines to the line $g_{KS} = 0$ reveals that the often used deformation boundary conditions are not suited so well for this kind of optimisation problem and might indeed lead to structural layouts in which the yield stress is exceeded.

5 SUMMARY AND OUTLOOK

In the MEGADESIGN project a Beam Preprocessor was developed at LFM. Its purpose is to automatically create beam models of wing structures intended for multidisciplinary optimisation of wing shapes and structures. The program creates a multi-cellular, thin-walled spar box from cross-sections through the wing's wetted surface with prescribed sheet thicknesses, numbers and positions of spars. The calculated beam properties are stored in a manner suitable for the assembly of the stiffness and mass matrices by an already existing Finite-Element code. Also, weight information and data needed for the estimation of stresses in the sections are determined.
The accuracy of the resulting beam model was validated against a shell model created with the commercial Finite-Element code MSC/MARC, resulting in sufficient accuracy for the intended application.
The Beam Preprocessor was included in a simple process chain built with a command line script. This was used to prove the suitability of the Beam Preprocessor and to investigate the influence of different design parameters.

Meanwhile, the MEGADESIGN project has been successfully concluded and the Beam Preprocessor has been delivered to the project partners. Several possible extensions to the program are being considered. These include improvements to the stress estimation method and the inclusion of hybrid structural models of beams and shell elements for a better representation of root and kink regions.

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