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Interdisciplinary Wing Design – Structural Aspects

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ABSTRACT

The following paper describes a multidisciplinary approach to design a wing with almost optimal aerodynamic efficiency during the entire cruise flight. Therefore a tight collaboration between structural mechanics and aerodynamics is necessary. Aerodynamic aspects are described here to illustrate the interdisciplinary nature of the design process, but they are not explained very deeply. The paper focuses on structural aspects, e.g. description of the tasks of the wings structural members, their placement within the wing and the modeling of the actual wing structure.

INTRODUCTION

Large wing structures as they are used in modern passenger and transport airplanes can not be considered as rigid anymore. Due to their size and their limited stiffness they have a considerable deformation when air load is applied. Therefore, during the design phase special emphasis has to be placed on the *aeroelastic* behavior of such structures. Besides the prediction of the deflection and the influence of this deflection on the aerodynamic behavior and efficiency there is a great necessity to be able to control the deformation of the structure. This can be realized by a special distribution and orientation of the structural stiffness, the so-called *aeroelastic tailoring* [1], [3]. With the introduction of fiber reinforced polymers as a light and stiff material in aeronautical applications the opportunities of *aeroelastic tailoring* have increased enormously. Now it is possible to align the direction of the structural stiffness, using a certain fiber orientation, without the disadvantage of increasing weight due to additional structural parts [7].

In January 2002 the DLR Institutes of Structural Mechanics and Design Aerodynamics in collaboration with the Institute of Aeroelasticity of the University of Aachen started a project called AWiTech (Adaptive Wing Technologies). The goal of this project is to design a wing for a transport aircraft with an aerodynamically optimized flying shape for large parts of the cruise flight. Current transport aircraft have a certain design point, normally somewhere around the middle of their design envelope. This point is defined by a certain aircraft weight, mach number and altitude. At all other flight conditions the aircraft flies outside its optimum. With an advanced structural layout of the wing using *aeroelastic tailoring* and, if possible *aeroservoelastic tailoring* with integrated actuator system, it is possible to expand this optimal flight configuration to a large part of the cruise flight. Due to its sophisticated stiffness design the wing remains in an optimal shape, even with decreasing weight due to fuel consumption [6].
The structural design of the wing started from scratch with an empty aerodynamic shell, that had to be filled with all necessary structural members, like spars, ribs, stringers, skin and engine pylon attachments. After parametric studies of the optimal structural layout, e.g. number and positions of spars and ribs, direction of the ribs, etc. a finite element model of the wing was built and loaded with the lift forces and moments that were calculated with a CFD program, using a Navier-Stokes code. The resulting deformed geometry of the wing was then used as an input for a succeeding CFD calculation, resulting in a changed lift distribution. This new lift distribution provided a new structural deformation, input for a new CFD computation, etc.. The process of iterating the lift distribution and structural deformation to convergence is almost automated and a basic requirement for an optimization. A light weight wing design is obtained by decoupling the tension and shear bearing structural members. Additionally every configuration is checked for dynamic aeroelastic problems, like flutter.

THE F11 WING

For the whole design, structurally and aerodynamically, one certain wing has to be chosen, so that the aerodynamic engineers and their structural counterparts use an identical model. Due to a huge amount of wind tunnel and CFD results the F11 wing was chosen for this project [9]. This wing is an early design of a so-called megaliner wing, an aircraft with a wingspan of 80 meters and 400 to 500 tons maximum take off weight. The aerodynamic design point is at Ma=0,85 and c_A=0,5. The outside geometry is given by 33 airfoils, distributed from the root to the tip of the wing, as it can be seen in figure 1 (axes in mm).

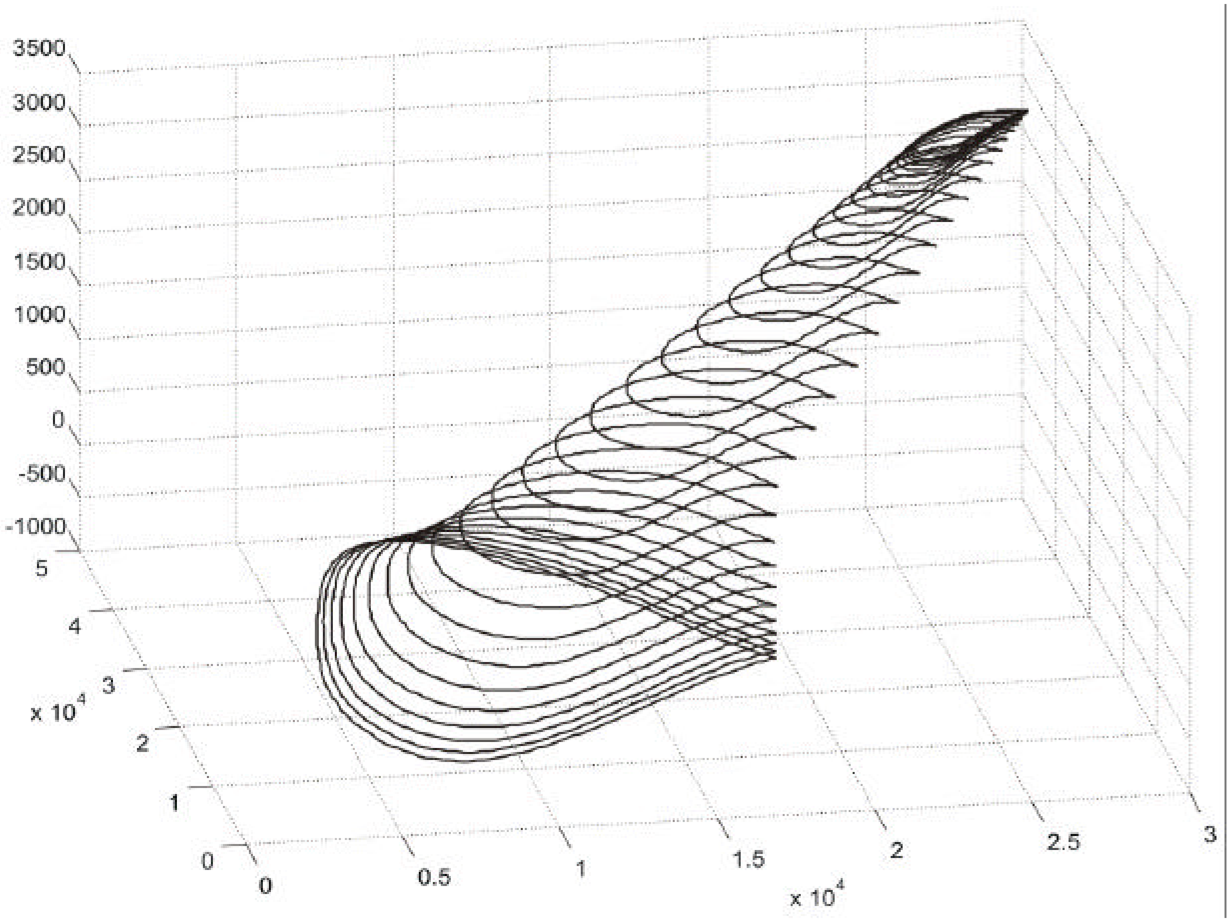

Figure 1: Airfoils of the F11-wing (no true scale)

The first task was to fill this aerodynamic hull with all necessary structural members, like spars, ribs, stringers, fittings, etc.. This had to be done with regard to the most efficient lightweight structure, meaning, that the volume of the wingbox, the actual load bearing part of the wing has to be maximized. Figure 2 shows the structural layout of the Airbus A340 wing, a wing with a similar geometry.

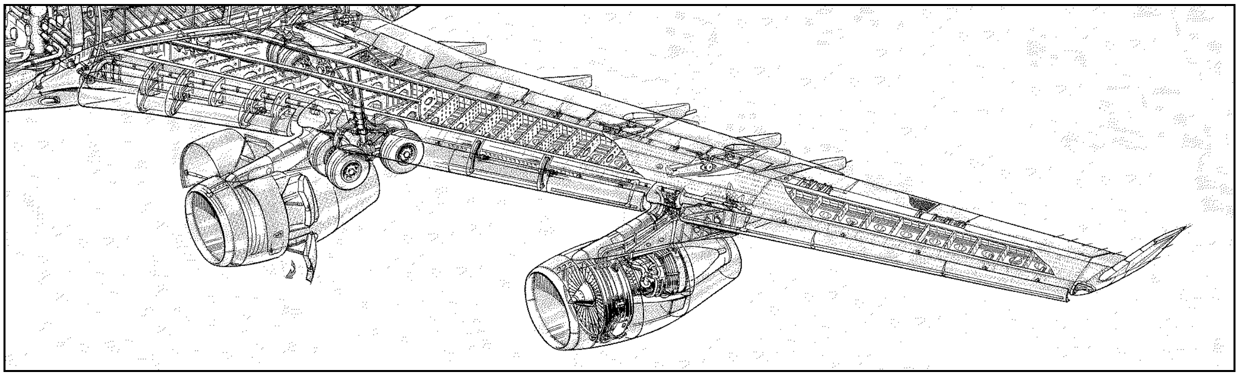

Figure 2: Structural layout of the Airbus A340 wing

The wingbox consists of front-, middle-, and rear spar, ribs, stringers, and the skin. In front of the actual wingbox is the slat, a high lift device that is used for take off and landing. Behind the wingbox is the location of the flap, a device with a similar purpose. For a sufficient high lift behavior the slat should have between 8% and 12% of the local wing depth, 10% are chosen in this case [10]. The outer flap begins at 70% of the local wing depth and runs to the wings trailing edge. The inner flap is parallel to the trailing edge of the wing and has a constant depth. Except for the necessary hinges, wire routings and fittings all space between the slat and the flap is used for the load bearing wingbox. The larger this box is, the less weight is necessary, because of the higher section modulus. Therefore the front spar is located at 15% of the wing depth and the rear spar is at 60%, outside the kink. Between the root and kink the rear spar is rotated rearward by 10° to increase the size of the wingbox – more rotation is not possible, due to the main landing gear. Between the front- and the rear spar is the location of the middle spar. It runs from the wing root to the kink and is exactly between the front- and the rear spar, as it can be seen on figure 3.

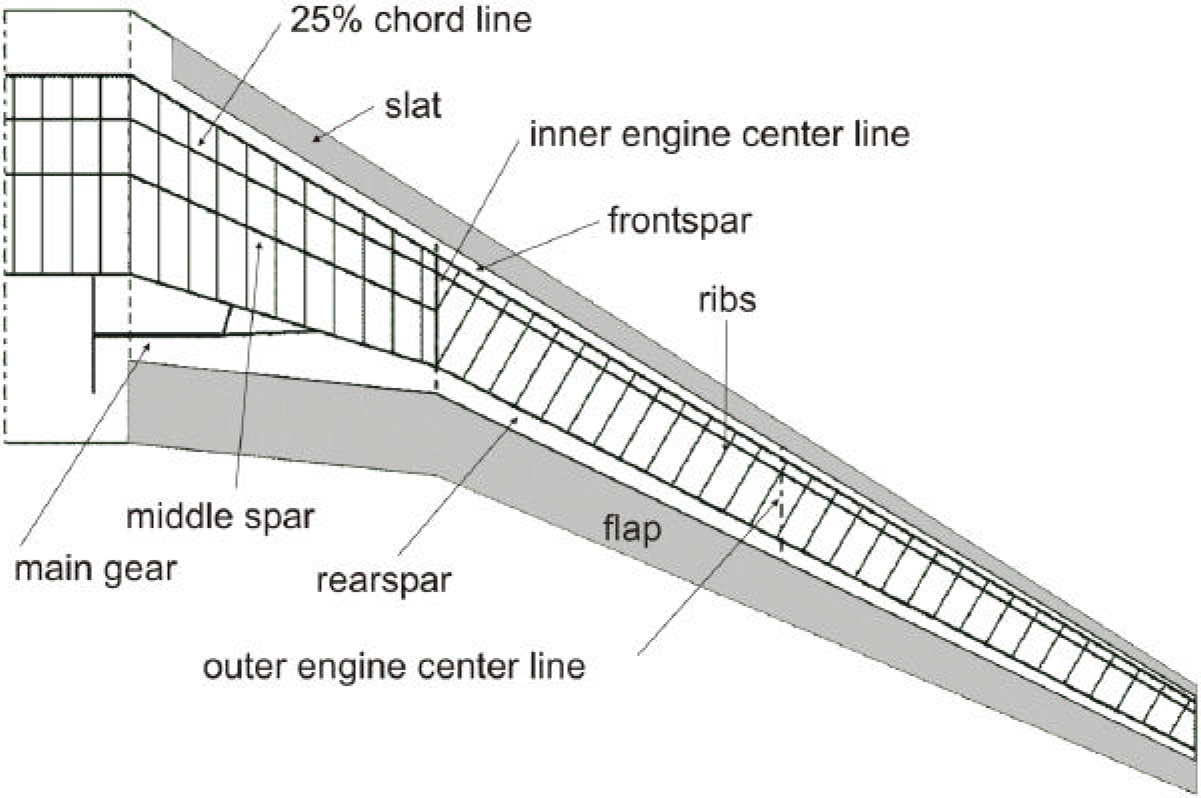

Figure 3: Structural layout of the F11 wing

The ribs are divided into two parts between the wing root and the kink, due to the continuous middle spar. In this part of the wing the ribs are aligned with the flight direction, whereas the undivided ribs outside the kink are perpendicular to the front spar. The main gear is attached to the rear spar, halfway between the root and the kink.

With this structural layout the modeling for the finite element calculations could begin. In order to be able to perform parametric geometry studies with slightly different structural layouts a software tool was programmed with MATLAB, that allows to generate a different geometry within minutes, including the export to the finite element program ANSYS. With this tool it is possible to define the number, the positions and the angle of the spars and the ribs. The program determines intersecting ribs automatically and shows all possible slicing options graphically, enabling the user to build such a geometry, as it can be seen in figure 3, within minutes. Although only the modeling of the actual wingbox is structurally necessary slat and flap are modeled, too. For the transfer between the structural and aerodynamic finite element mesh the whole geometry is required, otherwise a transfer of the pressure and deformation distribution would be impossible. Figure 4 shows one example of a geometry that is defined in MATLAB and can be transferred to ANSYS with one single command. It is not the same geometry as it can be seen in figure 3, but one of many examples that were used to test the program.

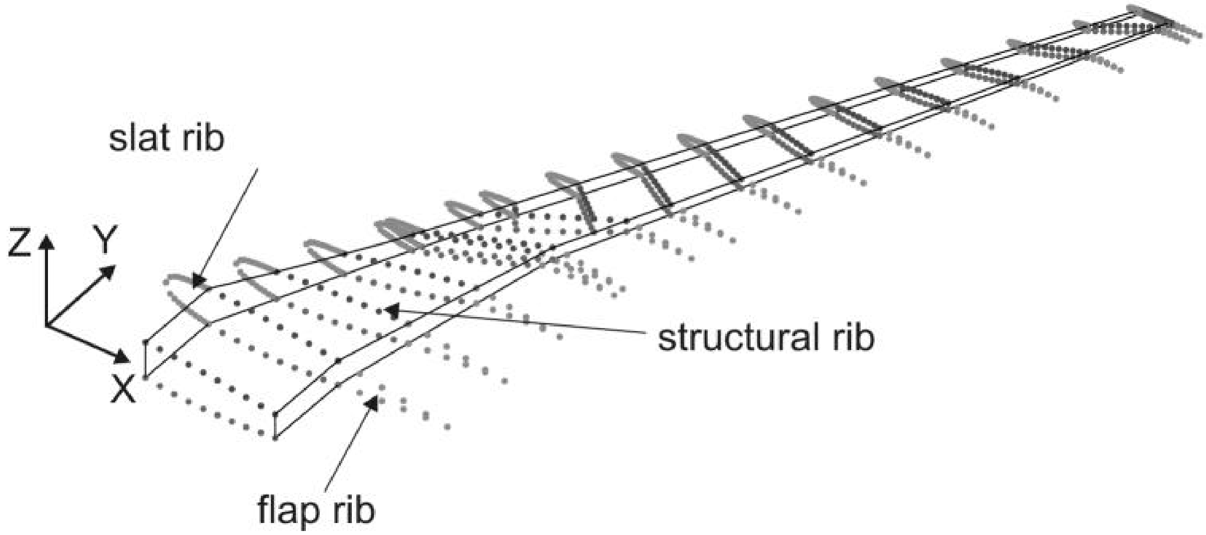

Figure 4: Example of an automatically generated wing structure

The geometry is not only exported as a geometry, but also automatically meshed within ANSYS. The result is a finite element model, where only the constraints and loads have to be applied to be ready for the solution process. In figure 5 the meshed geometry of the F11 wing (see figure 3) can be seen. The skin between front- and rear spar is removed in this figure to show the ribs and the middle spar underneath the skin.

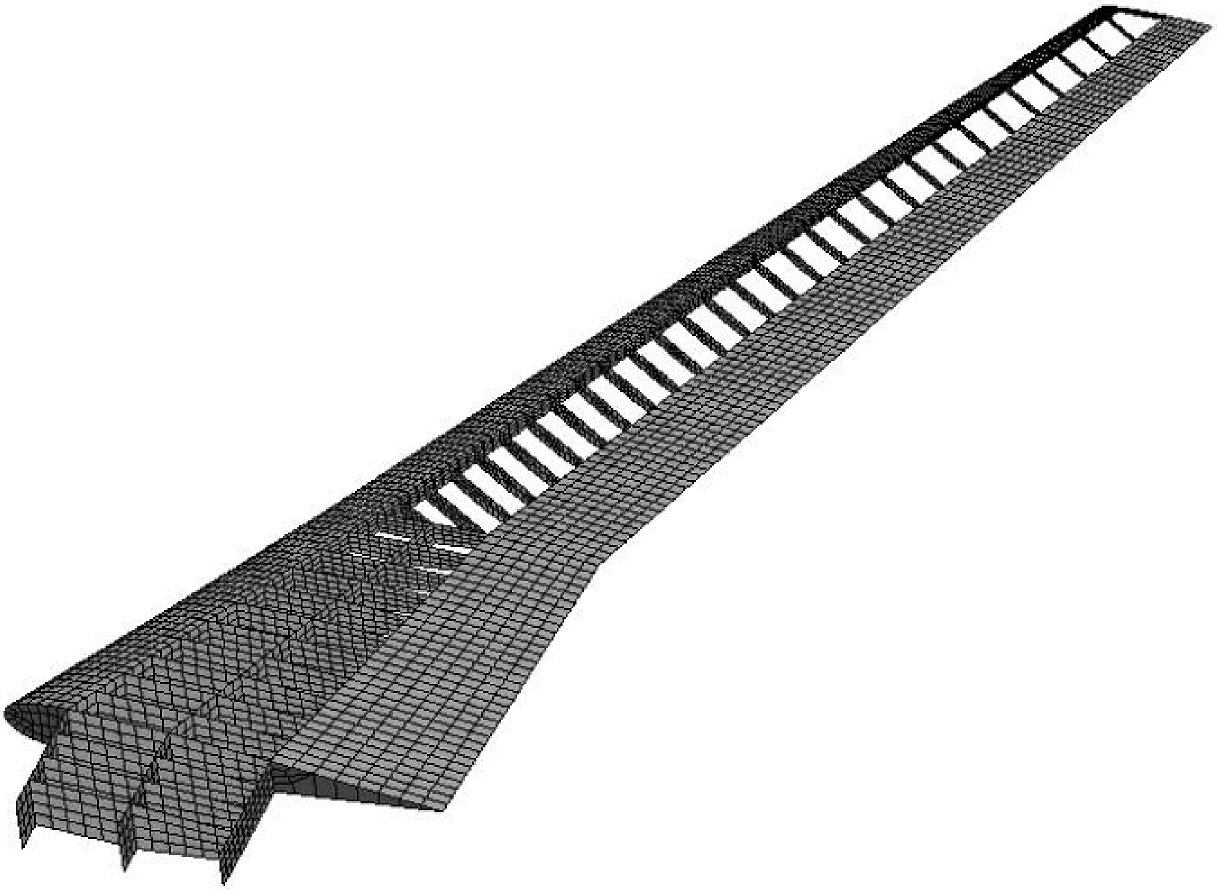

Figure 5: Finite element model of the F11 wing

The deformed wingbox is shown in Figure 6. The bending torsion coupling of the structure can be seen very clearly, by means of the different angles between root and tip.

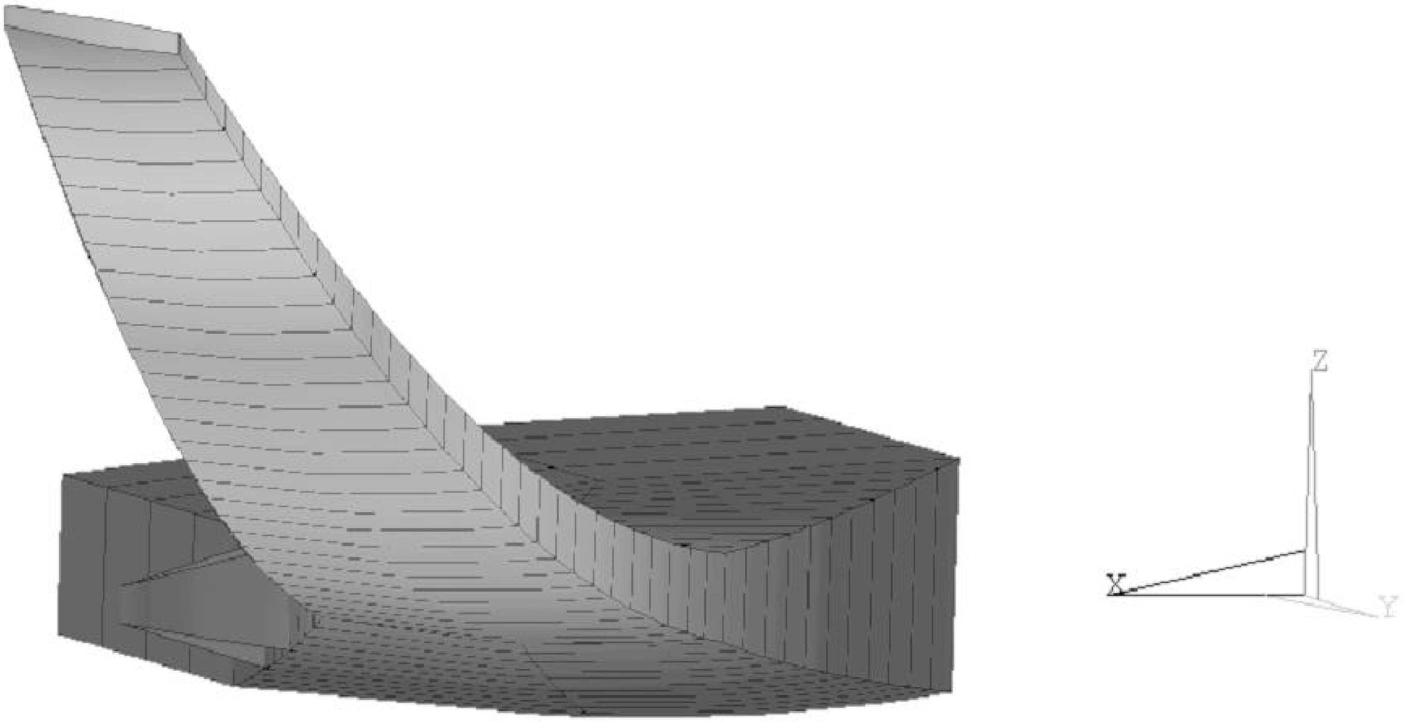

Figure 6: Deformed wingbox

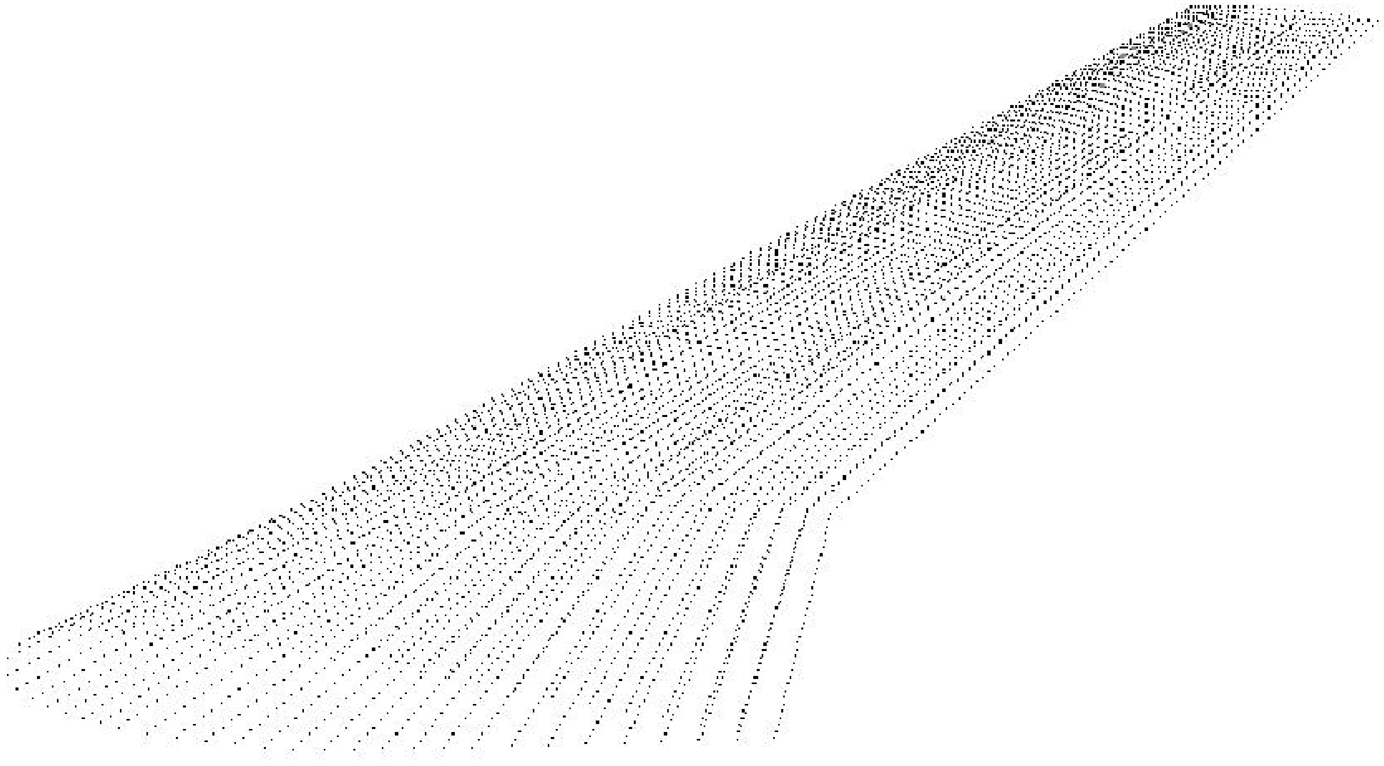

Figure 7: Surface nodes for data transfer between the models

The transfer between the structural and CFD model is done with the surface nodes of both models, because the surface of the wing is the part both models have in common. In figure 7 the nodes of the structural model are to be seen, and figure 8 shows the comparison between the structural and the aerodynamic surface mesh.

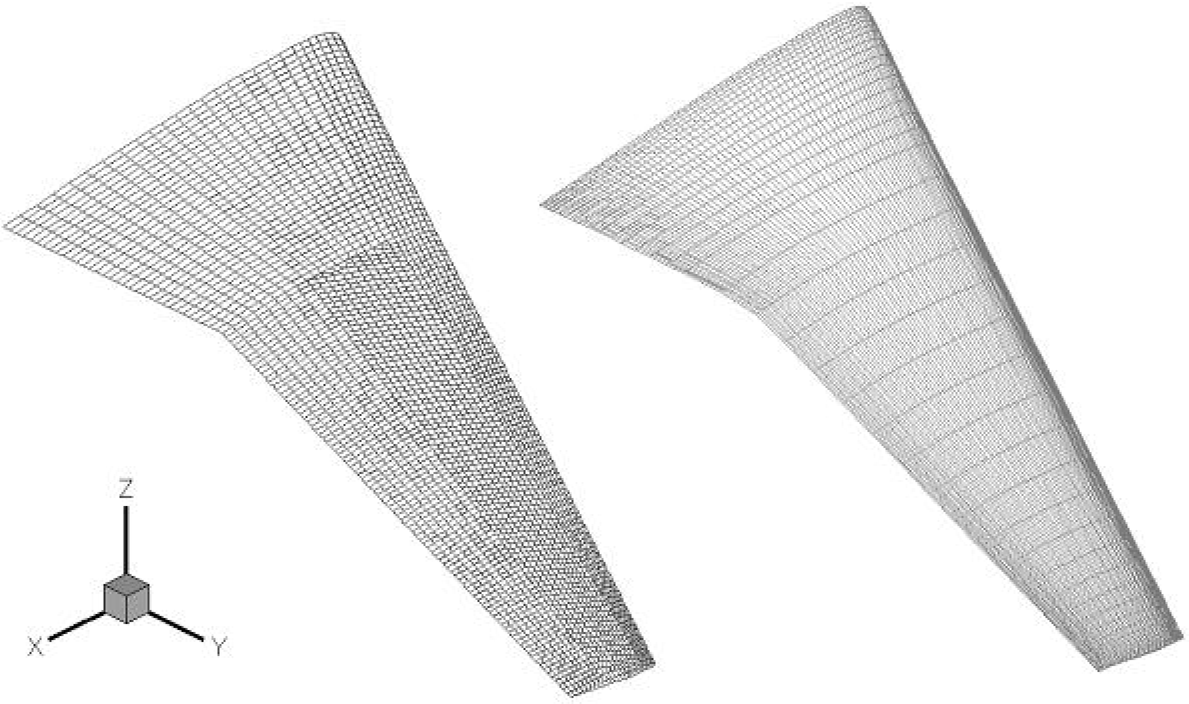

Figure 8: Comparison between the structural (left) and aerodynamic (right) surface mesh

For the transfer an interface was written, that is able to transfer node loads and deformations between different meshes with a conservative interpolation. The sum and distribution of the forces and moments is constantly checked during this interpolation process, in order to transfer the proper loads and deformations. This process is highly automated. With the node coordinates of the structural and the aerodynamic mesh and the deformations at the structural nodes the interpolation of these deformation to the aerodynamic mesh is done with a simple mouse click.

PERFORMED CALCULATIONS AND FIRST RESULTS

The goal of the first calculations was to determine the influence of the wing deflection and the tip rotation on the lift- and drag distribution. Therefore wing tip deflections of 3, 4, 5, 6, 7, and 8 meters and different wing tip rotations were used to get a parameter field. Figure 9 shows these wing tip deflections.

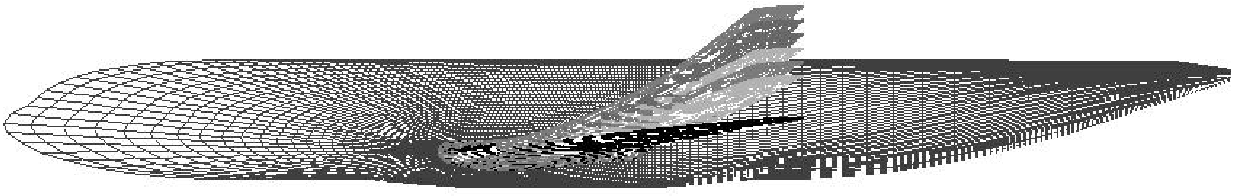

Figure 9: Deflections of the F11 wing

The results were a little bit surprising. With increasing deflection also the drag increased, just as it was expected. Surprisingly the lift increased, too, although the horizontal wing area decreased. With increasing mach numbers this lift enlargement grew. Below mach 0,6 this effect disappeared suddenly. Further investigations showed, that the increasing lift is caused by transonic effects at the wing root. There, the deflected wing decreased the angle between the wings upper surface and the fuselage, as it can be seen in figure 10. Due to this nozzle effect the airflow in this area is accelerated, leading to a lower pressure and therefore to a higher lift (see figure 11). Although this nozzle effect is not very strong, it is distinctly perceptible. Slowing down to airspeeds without transonic effects shows the expected decrease in lift, due to the decreasing horizontal wing area.

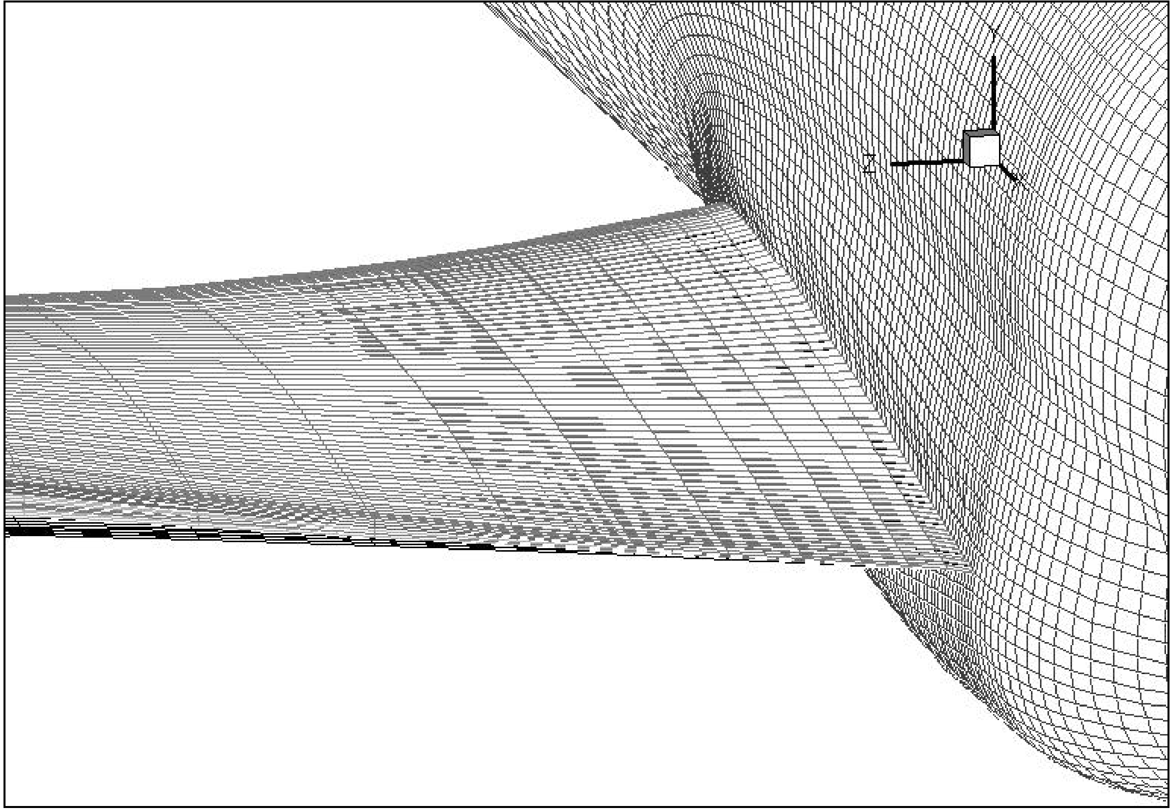

Figure 10: Wing deflections at the wing root

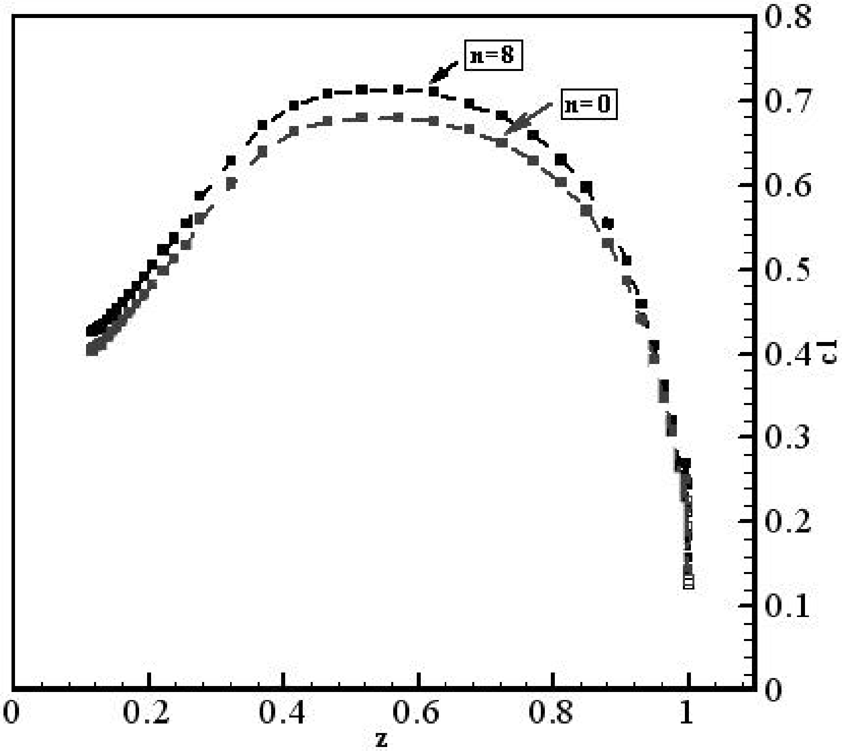

Figure 11: Increased lift, due to the nozzle effect (n=8: 8 meters tip deflection)

For the F11 wing an optimal twist between root and tip is –4,3°, that means, that the angle of attack (AOA) at the tip is 4,3° lower than the AOA at the root position. During flight a backward swept wing decreases the AOA at the wing tip, due to geometrical reasons (see figure 6). Therefore the unloaded shape (jig shape) of the wing must differ from the flight shape (higher angle of attack at the wing-tip), in order to provide the optimum twist when airload is applied. To find the proper jig shape the wing tip was rotated between 0° and 6°, meaning, that the AOA was increased at the wingtip between 0° and 6°. The actual twisting of the wingtip when airload is applied depends on the structural stiffness of the wing and therefore it is not possible to simply re-twist the wingtip by 4,3°.

After numerous iterations between the aerodynamic and the structural model the computations converged, leading to a wing with the required tip rotation and a tip deflection of 2,8 meters, as it can be seen in figure 12. A lower deflection would have been possible, but for the price of a much higher weight. The mass of this wing is 43,2 tons (without landing gear and engines), much more than the mass of the A380 wing, because of the lower depth and thickness. Due to the low thickness of the wing the section modulus is very small, requiring a thick and therefore heavy skin, if a small wing tip deflection is needed [2]. Aerodynamic computations showed, that a deflection below three meters is not necessary.

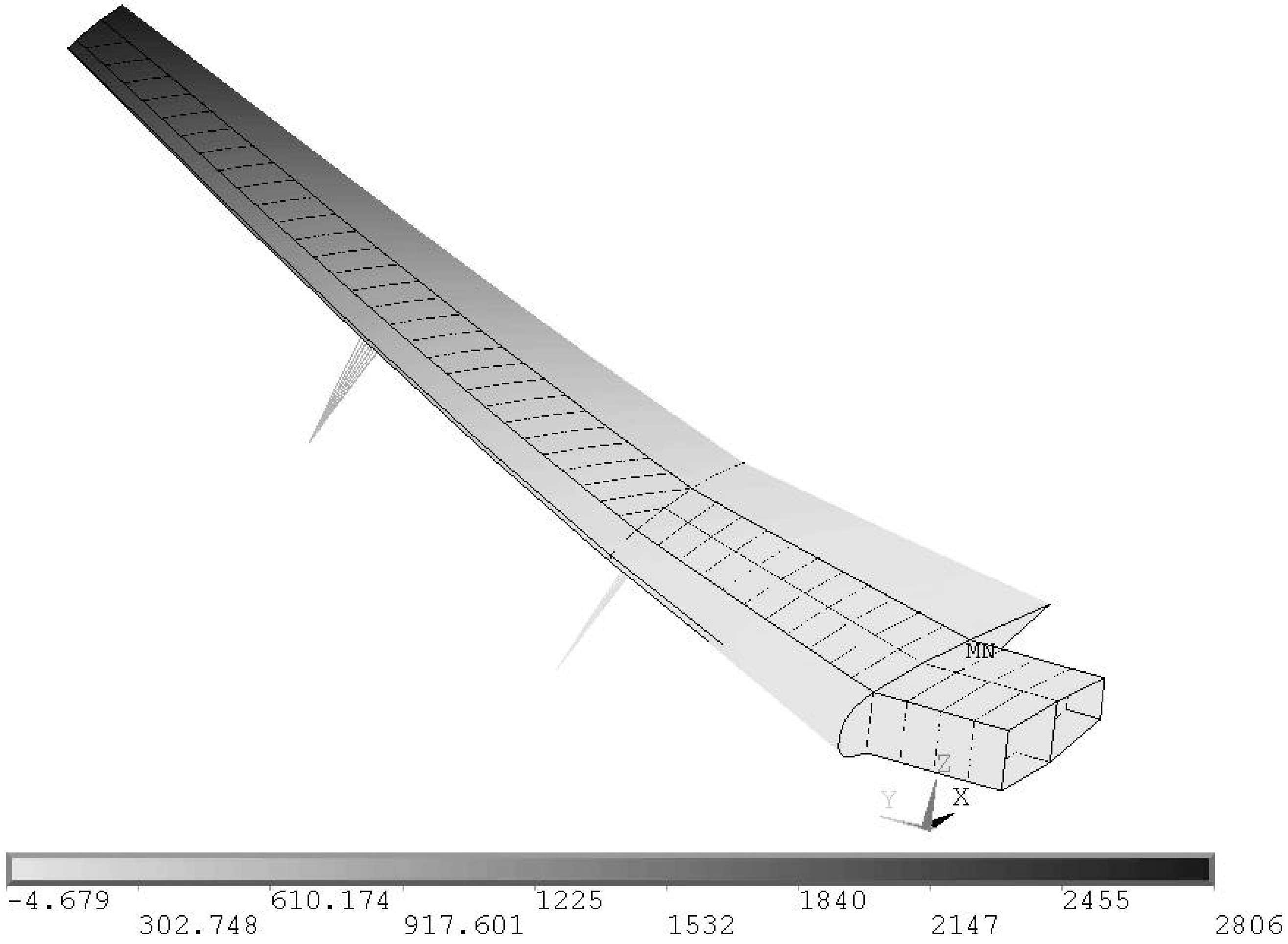

Figure 12: Deformation of the F11 wing

NEXT STEPS

After the optimization of the deflection behavior with regard to an increased aerodynamic efficiency of the deformed wing in the next step a weight optimization will be performed. Therefore two measures are necessary – the usage of carbon fiber reinforced plastics (CFRP) and a new structural concept for the use of this material. It is not reasonable to substitute Aluminum structures with similar CFRP components, using a quasi-isotropic layering. In such a case the real weigh potential of this material can not be used. Instead of this a consequent anisotropic build-up of the laminate with a utilization of the high strength and stiffness in fiber direction should be preferred [4], [5], [8].

To use the outstanding anisotropic properties of CFRP a consequent separation of the load carrying properties should be achieved. Therefore bundles of longitudinal fibers in spanwise direction are used to carry the longitudinal forces of bending. Layers of 45°-fiber orientation are wrapped around these bundles to carry the shear forces, necessary to provide the required torsion stiffness. In contrast to the current isotropic build-up of CFRP laminates this concept has a lot of advantages:

- optimal usage of the fiber properties (unidirectional stresses, no disturbance of the fibers and therefore of the carried stresses)
- no unfavorable loads in load carrying cross-sections
- no undesired additional strains and stresses (no additional constraints, due to a prevention of strains)
- stiffness and loads are in the same direction
- no damage expansion to adjacent structural parts (independent bundles, fail safe principle)
- physically clearly defined optimization possible (direct correlation between stiffness direction and loads)
- simple optimization models (reduced number of optimization variables, analytical description for the structural design possible, use of structural couplings possible)

Figure 13 shows the described concept in a principal sketch.

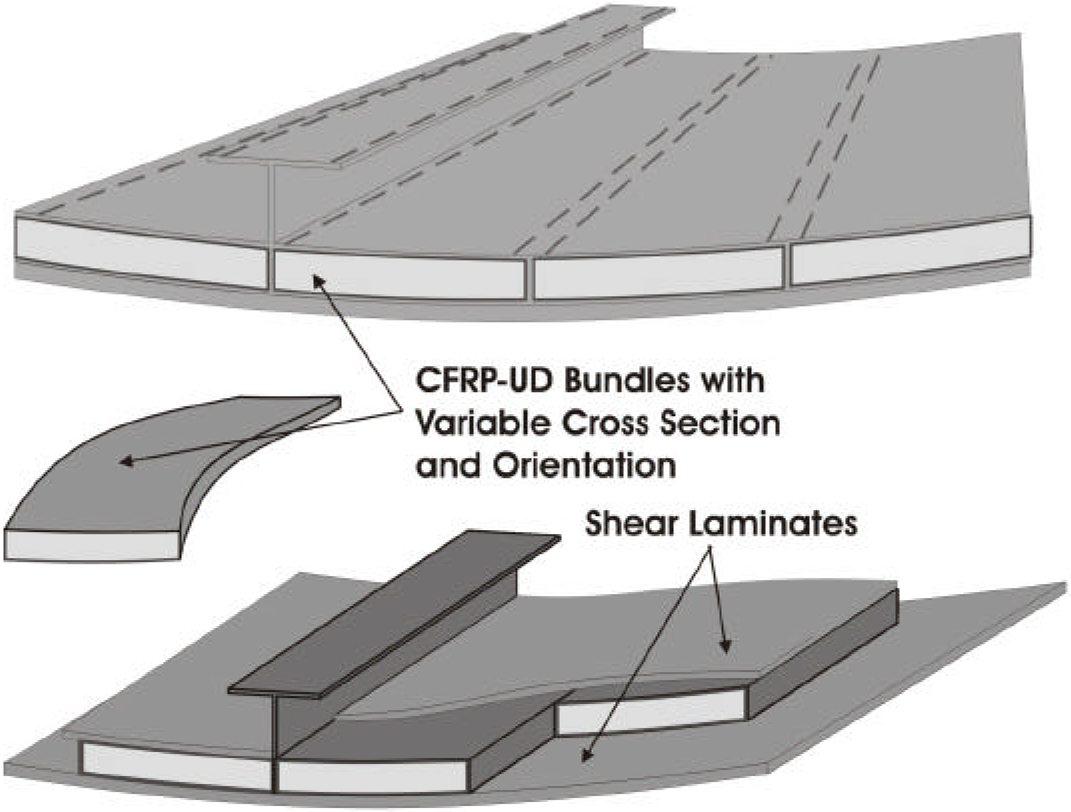

Figure 13: New structural concept for laminate structures

The finite element modeling of such a structure is done by using anisotropic shell elements, where the properties in the three coordinate directions are adapted to the load carrying properties of the real structure (e.g. no shear stiffness in the longitudinal fiber bundles). The weight optimization computations with the described structural concept are on their way and the first results are very promising. A lower weight than at the conventional structure and a more efficient aeroelastic tailoring are achievable.

After the optimization process with this new structural concept an aeroelastic analysis will be performed to make sure, that no dynamic aeroelastic problems will occur during flight.

CONCLUSION

The paper describes the structural aspects of a multidisciplinary wing design. It is shown, how the iterative design process between structural mechanics and aerodynamics is performed and why it is necessary to work closely together. The structural layout of the wing, starting from scratch, is shown and it is described, why it is done in the performed way. Aerodynamic aspects are mentioned only to give a better understanding of the interdisciplinary approach, a closer description of the aerodynamics will be published later.

The result of the entire design process is a light-weight wing with an almost ideal aerodynamic shape for large parts of the cruise flight and new opportunities for aeroelastic tailoring. Dynamic aeroelastic problems are not to be expected within the planned flight envelope, due to parallel aeroelastic computations (not described in this paper).
This interdisciplinary approach in the early design phase is the best prerequisite for an optimized structure without expensive negative surprises in a later stage.

ACKNOWLEDGMENTS

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