MULTIDISCIPLINARY DESIGN CHAIN FOR MODEL ROTOR BLADES

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Abstract

This paper presents a rotor blade design chain with multidisciplinary approach resulting in a full 3D-CAD model of the geometry, a structural and a dynamic description of the rotor blade. It further contains steps and challenges in this process. Also a brief overview over the manufacturing is given. The design chain is shown, using the example of a model rotor blade with a modern geometry. Focus lays on the structural characterization part and its integration in the process together with existing tools for structural modeling and analysis and a comprehensive rotor dynamics code. The example is just a passive model rotor blade, but also some considerations for active purpose are made in this paper.

1 Introduction and Motivation

Due to its functional principle, the aerodynamic interaction of rotorcrafts with their environment is highly unsteady and dynamic. The aerodynamic conditions on rotor blades change rapidly depending on their azimuthal position. Also the blades affect each other by creating vortexes. This induces a high vibration and noise level which is transferred to the fuselage, causing stress for all people aboard, including the pilot, and reduces thereby the maximum mission time for the helicopter [1]. The most common use of helicopters is for professional purposes, be it civil or military and mission time has direct impact on the economic efficiency. Therefore reducing these stress factors becomes important. As for all other transportation there is also interest in increasing the profitability and environmental friendliness by increasing the fuel efficiency of the rotorcraft.

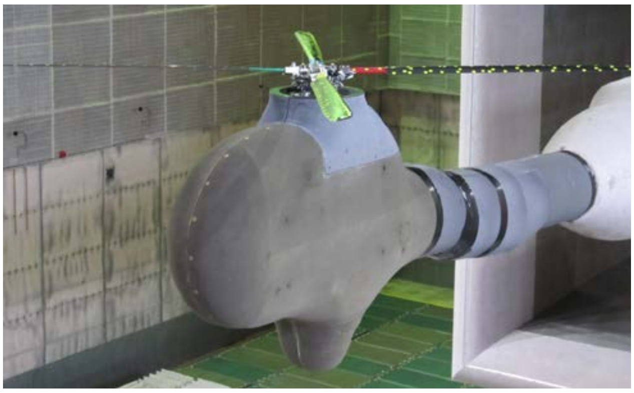

Figure 1: DLR's rotor test rig with FTK blades at DNW-LLF

This leads to the need for research on new rotor blades and rotor associated technologies. For experimental testing of these technologies wind tunnel tests are the best option. The effort on strength calculations and prove of reliability for flight test certification would be much higher. Also the environmental conditions in the wind tunnel can be controlled. Still most aerodynamic and aeroelastic effects can be evaluated.

Even though requirements for model rotor blades are not as high as for flight tests, the design process is challenging. Models for wind tunnel tests are often scaled, due to limited wind tunnel diameters and manufacturing costs. The small size of scaled model rotor blades, the complex geometry, a variety of boundary conditions and interacting parameters make this task so difficult. The designing boundary conditions have their origins in different disciplines, like manufacturing, aerodynamics, aeroelastics, structures, acoustics and structural properties, static and dynamic. This causes the need for multidisciplinary optimization to meet all these demands. Rotor blades boundary conditions are very different depending on its purpose. This applies to industrial rotor blades, but all the more for model rotor blades in research, for example active twist [2, 3] and other morphing rotor blades. Those blades are often highly instrumented with sensors and possibly actuators. New challenges involve new geometries, materials and so forth.

Not only at the DLR this topic is being researched for years, another optimization framework is for example described in [4].

2 Design Chain

This chapter will describe the design chain for model rotor blades. The flowchart in Figure 2 shows a schematic of the procedure. This chapter describes all included steps and their interaction. Direct *references* to Figure 2 will be emphasized with italic writing. Abbreviations are explained in the flowchart legend.

2.1 Rotor blades

The model rotor blades used as example to show the design chain were built for research on the Multiple Swashplate Control System for active rotor control in the frame of the nationally funded LuFo-V-1 joint research project FTK (engl. advanced swashplate concepts). The design, engineering and manufacturing [5] took place at the DLR with support from Airbus Helicopter Germany (AHD). The blades completed their first wind tunnel test successfully in the DNW’s Large Low-Speed Facility (LLF) [5, 6](see Figure 1).

2.2 Boundary Conditions and Input Data

In the beginning phase of designing a new model rotor blade it is important to define all mandatory boundary conditions. These boundary conditions will have influence on the approach to the multidisciplinary design process. Mandatory boundary conditions can be broken down into "sub"-boundary conditions.

- aerodynamic (outer) geometry and further demands to the outer geometry
  - inner geometry all subject to the outer geometry
- flutter and dynamic stability
  - center of gravity should be at the 25% of the chord length or slightly in front of it
  - eigenfrequencies of the rotor blade at nominal rotational speed must not be multiple of the nominal rotation frequency
- strength under static and dynamic loads with consideration of fatigue, directly depending on
  - materials, which must be light, strong and durable
  - inner geometry and structure, which in combination with materials provides stiffnesses
  - aeroelastic response of the blade, which must keep the loads in reasonable range
- integration of sensor and actuation concepts
  - sensors need installation space and mostly energy supply and data connections
  - actuation concepts need actuators, energy supply, data connections and additional structures
- scaling to model size
  - geometric scaling
  - aeroelastic scaling
- manufacturing limits

This list has no claim to completeness, but gives a good overview over the numerous boundary conditions which have to be taken into account. Also the type of boundary conditions can vary between different blades.

Since the design chain is set up sequentially not all demands are directly related to each discipline in the design chain. Nonetheless, the iterative design chain connects all models and thereby all those demands.

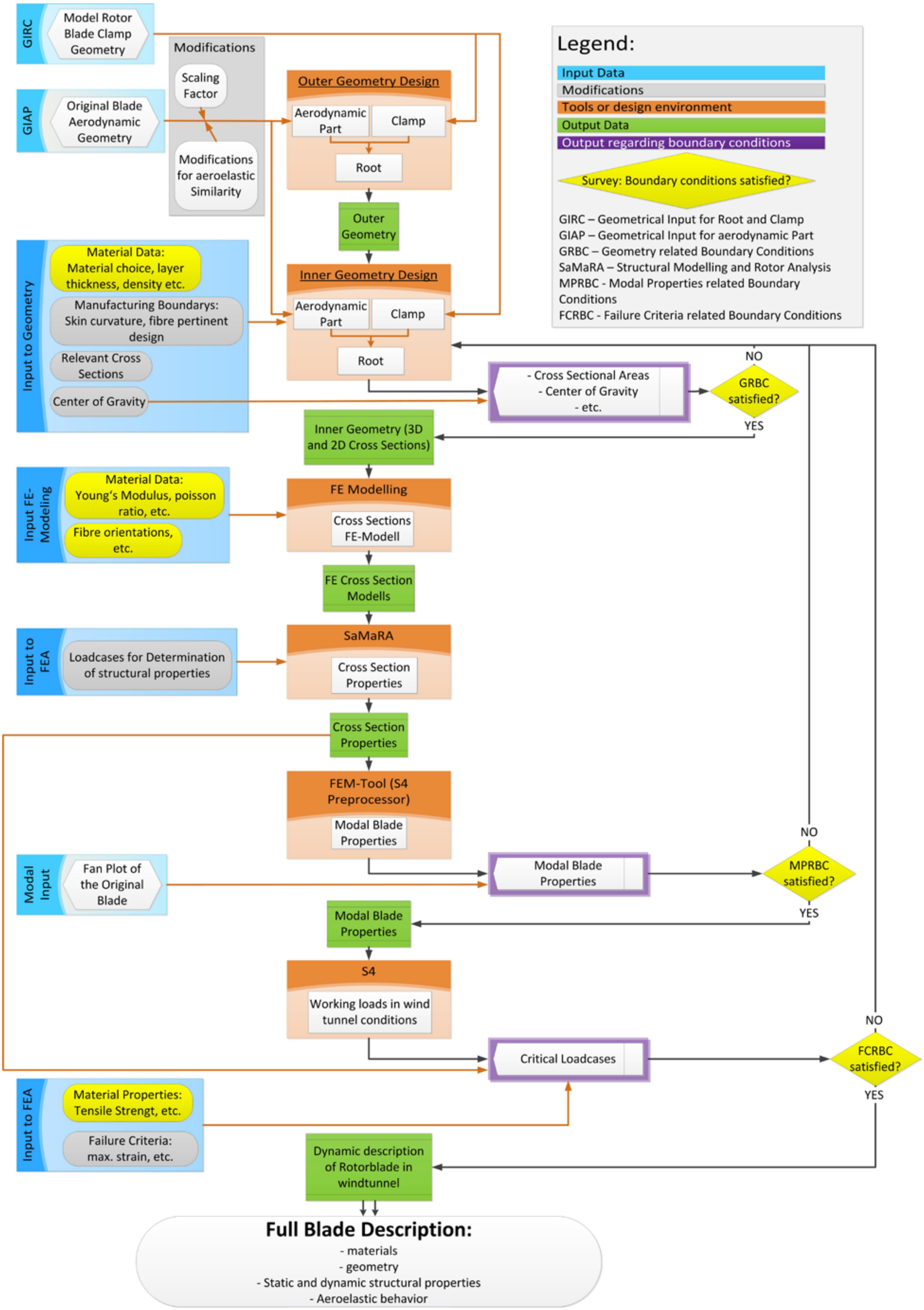

Figure 2: Design chain schematic

Because of the highly interactive design variables, boundary conditions should be defined, as far as possible, before starting the multidisciplinary design process.

Input data are the boundary conditions in a form which can be directly implemented to the design, this for example can be numerical values or rules for certain design parts. Some boundary conditions, like the aerodynamic shape (section wise) and the location of the center of gravity can already be described numerically, for others an implementable form has to be found and defined. Each step of the design chain has its own set of input data and generates a certain set of output data.

The FTK model rotor blade was designed with the premise of being a 1:2.75 Mach scaled version of the EC-145 C2 rotor blade regarding the aerodynamic shape and dynamic behavior, whereas the root and clamp area are derived from a BO-105 model rotor blade. This blade is hingeless and compatible to the rotor head, which is used on the META.

2.3 Design

The first model created for the FTK rotor blade was the *outer geometry*. Input data were for one the profile data for the aerodynamic part from the EC-145 C2 (*GIAP*). Secondly the clamp and root geometry from the BO-105 were used for the root area with a transition zone between those geometries on the non-aerodynamic part (*GIRC*). The geometry was designed section wise and then connected by tangentially constant surfaces, the resulting shapes had to be checked for unwanted bulges and dents. Positions and number of sections are determined by the change of the geometry, so that the transition zones between these cross sections can be constructed with reasonable effort. In this step also the geometric and aeroelastic scaling has been done (*Modifications*). The result is shown in Figure 3.

The *outer geometry* is the starting point for designing the inner part. This forces the construction principle outside-to-inside. That means each element, for example skin and spar, is constructed in this order and depends on the next outer element. Many challenges come up while

Figure 3: *Outer Geometry*

creating the *inner geometry*. To allow fast changes and multiple iteration loops it is important to build a parametric design (*Inner geometry design*). Also the stability to these varying parameters has to be considered, which can be difficult, especially when the design space is not clear in advance or because of limitations of the software. For example creating offset geometries causes difficulties for small radiuses, *material and layer thicknesses* cannot be scaled arbitrary, so the layer thicknesses get much thicker in relation to the overall section.

The inner part is constructed section wise, too. The number and positions of *relevant cross sections* can differ from the outer geometry, because of further details in the inner design changing the cross sections span wise and a needed set of cross sections for calculations within the following steps (chapter 2.5.1 - 2.5.3). The spanwise change of cross sections is mainly driven by the outer geometry profile and the *center of gravity* (masses and mass distribution are directly derived from the CAD data), but also details which only occur at certain spanwise positions.

The model blade cross sections provide only very limited space and many boundary conditions (*Input to Geometry*) have to be taken into account. For example the *center of gravity*, designated to be at 25% chord length or slightly in front of it, affects the position of all structural elements and has thus very strong influence on the design. Structures have to be put as far to front of the blades as possible (see Figure 5). Even though the spar is the main carrying structure and its location is directly in the nose of the rotor blade, the position for the center of gravity cannot be reached without additional weights. With every change in the geometry, the center

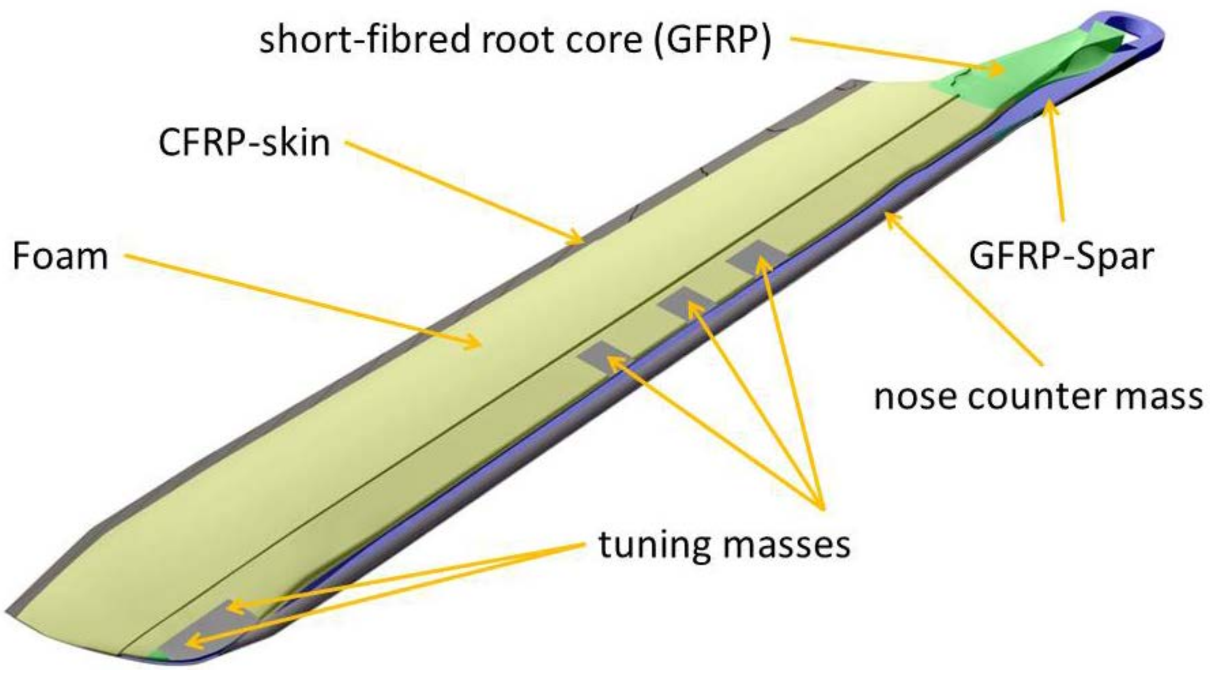

Figure 4: *Inner geometry* with tuning masses

of gravity moves and the weight sizing must be adjusted, as with the spar and all other depending geometry. So the construction is an iterative process by itself, which one has to work through, before going to the next steps in the design chain.

Further constraints at this step are material data, like layer thickness and *density*, manufacturing constraints, like skin curvature (*minimum radius)* and *fiber pertinent design* /fiber continuity.

The 3D-design of the inner part (Figure 4) is again mainly derived from the 2D-sections and its primary use is for manufacturing purposes but also further 2D-sections can easily be created at any spanwise positions. Nonetheless the 3D-construction holds further challenges, regarding 3D details. Major additional demands because of the dynamic requirements to the blade are additional tuning masses at several spanwise positions (see Figure 4). While most other geometry are more or less optimized on the 2D-sections, some the tuning masses suffer from very limited installation space not only in the section plane but also in spanwise direction and every in-plane change causes a spanwise change. So the 3D-design has its part in the iterative process at some points, too.

For every cross section and 3D-design it must be checked if all *geometry related boundary conditions* are satisfied. If not, further iterations in the *inner geometry design* are necessary; if they are the completed geometry can be used for the *FE-Modeling*. The geometric iteration process is parameterized but still manually on most parts.

2.4 FE-Modeling

For calculation of the structural properties *FE models* are created for each relevant cross section. They are created with Ansys mainly composed from two parts. One part has all isotropic and unidirectional components, built in the mechanical workbench. The second part has the composite parts with surface and layer dependent *fiber orientations*, created with the help of Ansys ACP (Advanced Composite Prepost). Therefor additional auxiliary geometries have to be designed depending on the model creation

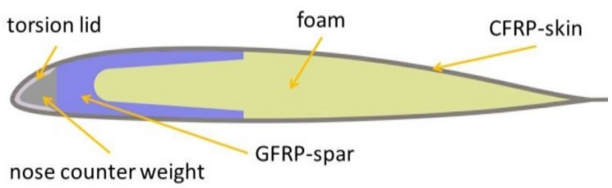

Figure 5: Cross section at 900mm spanwise position

method. Those geometries are based on the same detailed geometry which will later be used for manufacturing. The two components are then joined by contact elements with linear bonded contact. Thus fairly detailed *FE cross section models* are developed for each section with an extrusion length of 1 m (further details in chapter 2.5.1).

2.5 Existing DLR Tools

2.5.1 *SaMaRA - Structural Modeling and Rotor Analysis*

Rotor Blades, especially active twist blades, have been investigated by DLR (German Aerospace Center) for many years and the feasibility of this technology was shown in several projects [7, 2, 8]. However, many relevant features must be taken into account within the design process. For simulating the influence of such blade parameters in DLR Brunswick a tool called SaMaRA (Structural Modelling and Rotor Analysis) was developed. It consists of a parametric finite element model for passive or active twist rotor blades and a computation part of their structural properties.

SaMaRA is a tool for rotor blade simulation realized with the software ANSYS Classic, which is written by means of a script in Ansys Parametric Design Language (APDL). The simulation environment allows generating individual blade segments and computing their structural properties. At a first step it is necessary to create a finite element model for the respective rotor blade section. There are two basic methods. At the one hand, the model can be generated directly in ANSYS. For this purpose, the exact characterization of the respective cross-section is necessary, which can be done by the aid of about 50 parameters for the geometry and materials. Alternatively, it is possible to import an existing FE model, e.g. as an export of CATIA or ANSYS Workbench. Especially for the blade root this is required since a parametric generation in ANSYS has not been realized so far due to the high complexity. This second approach was chosen for the FTK rotor blade model as described in chapter 2.3 and2.4.

After generating the FE model, SaMaRA is starting the calculation process of the mechanical *cross section properties* for the respective section. For that it doesn't matter whether it is an aerodynamic blade section or a blade root profile. The extrusion of the cross-sectional profile a length of 1m represents a good compromise between accuracy of the respective results and calculation time. The blade segment is clamped at one side. At the other side a rigid area is created and a respective reference load will be applied.

Bending stiffness as well as torsional and tensile stiffness will be computed. Also very vital characteristics are the center of gravity, tension center and the shear center, because they are significant for the stability of the rotor blade flutter and the strain distribution at occurring loads of different flight conditions. Furthermore, the moments of inertia, the mass and the twist (for active twist blades) can be determined. Not all properties can be found in just one calculation, because different boundary conditions (*load cases for determination of structural properties*) have to be defined, therefore several individual calculations are necessary. This procedure must be repeated for different blade sections so that the results of each set of section properties can be combined to form a complete data set. After writing the obtained blade properties to an output file the data can be used for further post processing. For example these data is necessary for determining the eigenfrequencies of the blade. This is done in the Institute of Flight Systems with the tool called FEM (chapter 2.5.2). The determination of the occurring loads for different flight modes via S4 also requires the provision of data for the rotor blade properties.

2.5.2 *FEM*

Target of a successful scaling of rotor blades to model scale is to match the dynamic characteristics of the full-scale blades, which means the *fan plot of the original blade* are boundary conditions for this step. So, the FTK-blades were aeroelastically scaled in a way such that the natural frequencies in terms of their non-dimensional values in n/rev are matching the full-scale behavior for the first three flapping modes, the first two lead-lag modes and the first torsion mode of the EC145 C-2 blades. This was

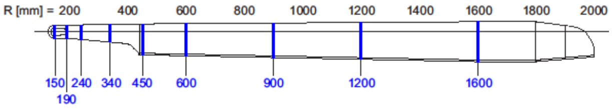

Figure 6: 2D-sections for dynamic design

done by building a data set for an equivalent beam model for the blade for the calculation by an in-house finite element program (FEM). Starting point for the dynamic design was a rough assessment of the structural properties at a small number of 2D-sections of the blade along its radius (see Figure 6).

Thereon *modal* model blade *properties related boundary conditions* (*MPRBC*) had to be fulfilled. At this point the second iterative loop between design environments is closed. The loops feedback is again to the inner geometry design and all steps from there on must be repeated. This iterative process between analysis and modification of the data set, with consistent refinement of the 2D-sections and improvement of the results in terms of the objected target frequencies was carried out. Table 1 shows the final result of the frequency analysis for the FTK-blades as percentage deviation to the values of the original series blades. Deviations in the flapping and torsional frequencies of all modes don't exceed 2%, while especially the first lead-lag frequency is clearly increased but as far as possible acceptable.

Rotor radius R	2m
Equivalent blade chord c	0.124m
Airfoil	OA Series
Rotor system	hingeless
Deviation in flapping mode frequency 1st 2nd 3rd 4th	 +2.0% +0.8% -1.5% ±0%
Deviation in lead-lag mode frequency 1st 2nd	 +16,4% +2,8
Deviation in torsion mode frequency 1st	 ±0%

Table 1: Data of Mach scaled FTK-blades

2.5.3 Comprehensive rotor dynamics code S4 - Dynamic load calculation

For the calculation of the *working loads* of the blades *in wind tunnel conditions*, DLR operates its own comprehensive rotor code S4. S4 is based on blade element and momentum theory and has integrated analytical and semi-empirical models to allow for fast calculation of the rotor dynamics and loads. The calculation of the dynamics of elastic rotor blades is based on the *modal* blade *properties* from the pre-processor code FEM and a modal synthesis in S4.

For the design of the blades the *critical loads* and fatigue limits have to be known. For the evaluation of the maximum blade loads a worst case load scenario had to be defined. After intense search for high load cases from all previous wind tunnel tests, it turned out that high speed level flights with high thrust at the power limit of the hydraulic unit driving the rotor of the rotor test rig define the worst load cases. The loading condition (mean values and dynamic loads) of the FTK-blades for this worst case scenario calculated by S4 is given in the Figures 7-10.

As can be seen, the highest loads in flap, lead-lag, torsion and centrifugal loads increase towards the blade root, so this part of the blades has to be investigated carefully for the proof of endurance limit.

2.6 Strength Calculation

With data from the FE model and the calculated loads, the strength analysis is done section wise. The chosen failure criterion is maximum strain compared to the Goodman diagram for the relevant materials for all loads causing strain in the blade. Also shear forces have to be considered, resulting from torsion and forces perpendicular to the blades axis. Both cases have to be regarded with the aspect of fatigue strength. Spar and skin are the primary load carrying structures and are thus mainly in focus for strength calculations.

Since the tuning masses of the blades are high density masses at an outboard position, they suffer very high centrifugal forces and their connection with the blades is another very critical load path. If the *failure criteria related* *boundary conditions* (*FCRBC*) are not satisfied the third iteration loop will like the loops before, feed back to the inner geometry design; if they are satisfied the blade design is completed and a *full blade description* has been created.

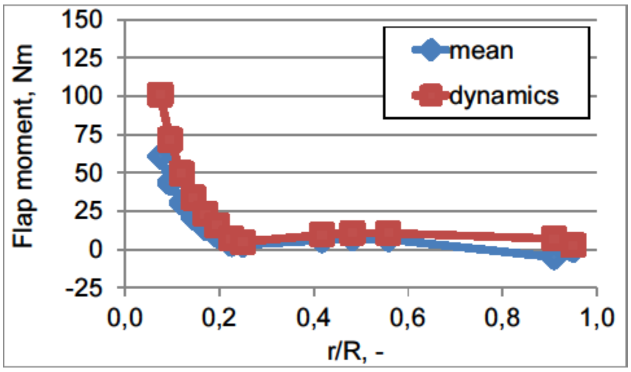

Figure 7: Worst case scenario flap moment

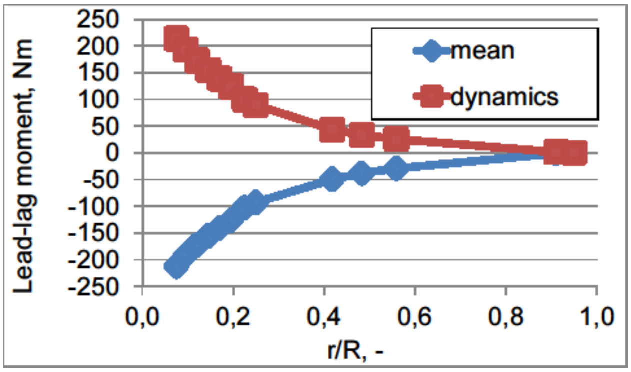

Figure 8: Worst case scenario lead-lag moment

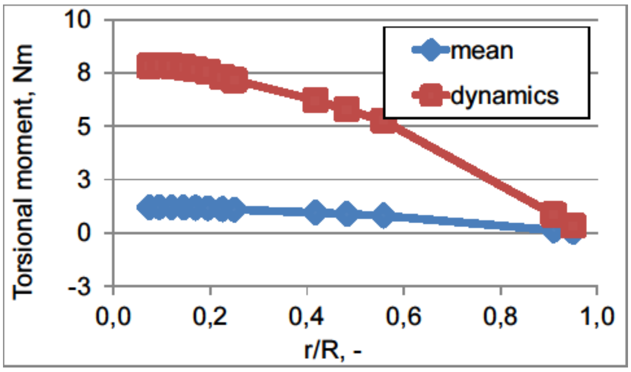

Figure 9: Worst case scenario torsional moment

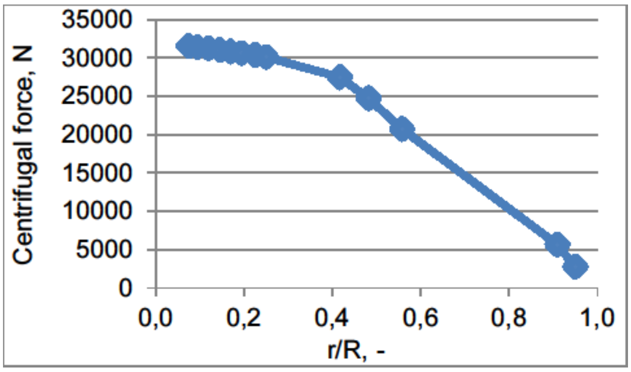

Figure 10: Centrifugal force distribution

3 Manufacturing

As a result of all simulations and calculations the inner structure of the FTK composite blades appeared. The following step was to develop a manufacturing method which provides aerodynamically, dynamically and optically accurate blades.

3.1 Boundary Conditions

The FTK blades consist of carbon fiber skins, a glass fiber spar, and a blade nose counter mass. Five additional weights (tuning masses) are required to reach the calculated dynamic blade behavior. The inner space is filled up with milled foam.

Only five blades have to be manufactured. Thus it is about a small batch series. This fact has a big influence on the choice of the manufacturing technique.

Aluminum molds were used due to good past experiences at DLR.

Originally it was planned to manufacture the blades in almost the same manner as professional blade manufacturers do. They mostly use prepregs as fiber material and build the blades in one shot using heated metal molds. Prepregs are fiber mats which are already impregnated with resin. The big advantages of prepregs are the high quality in terms of fiber orientation, the high fiber volume content and due to a slight stick effect the drapability. On the other hand prepregs need a curing temperature around 120°C. The latter fact leads to a lot of troubles with different thermal expansions of glass and carbon fibers and aluminum (mold) in case the blades are not manufactured in one shot. A carbon blade skin (thermal expansion coefficient roughly 0/K) made of prepregs would not stay in an aluminum mold (thermal expansion coefficient roughly 23*10^-6/K) after the mold is cooled down. In order to avoid by thermal expansion caused troubles it was decided to use a cold process for blade manufacturing.

3.2 Manufacturing process

Figure 4 shows the general inner buildup of the blade. The manufacturing of the blades was executed in the following way:

1. Manufacturing of the carbon fiber skins using the vacuum infusion technique. By means of this method qualitatively high grade skins are reached.
2. Gluing the nose mass
3. Fabrication of impregnated glass fiber rovings (pultrusion with resin)
4. Lay-up of rovings in each blade half to build the spar
5. Installation of the foam in one half.
6. Installation of the five tuning masses
7. Final assembly of the two blade halves.
8. Curing of the blade.

4 Blade tests

The multidisciplinary design chain established at DLR for the whole design process has to satisfy all boundary conditions. Since the goal of the dynamic design was to manufacture new blades and not only to get data for simulation applications, the output of this design chain was a full 3D-model of the blade containing all information about the composite lay-up and the material properties needed. The process of manufacturing the FTK-blades is described in [3]. Upon completion, the blades were first CT scanned at AHD to find out possible weak points in the structure like cavities or kinks in the rovings and so on. After that, the blades were equipped with strain gauges on the blade root for measuring the blade loadings and then single tested on a whirl tower at DLR. The strain gauges were also used to determine the natural frequencies in flap, lead-lag and torsion of the finished blades. In Figure 11 the frequencies of the lower Eigenmodes of the FTK-blades are plotted over the rotational speed of the rotor.

The measured non-rotating frequencies of all four blades used in the wind tunnel test are also plotted in the same figure. As can be seen, the results of these measurements are almost congruent with the target values at 0 rpm. The blade-to-blade differences of the bending modes are virtually neglectable. Only in torsion small variations are visible. So, all in all the blades built satisfy the target design and should therefore have an identical dynamic behavior like the original series blades.

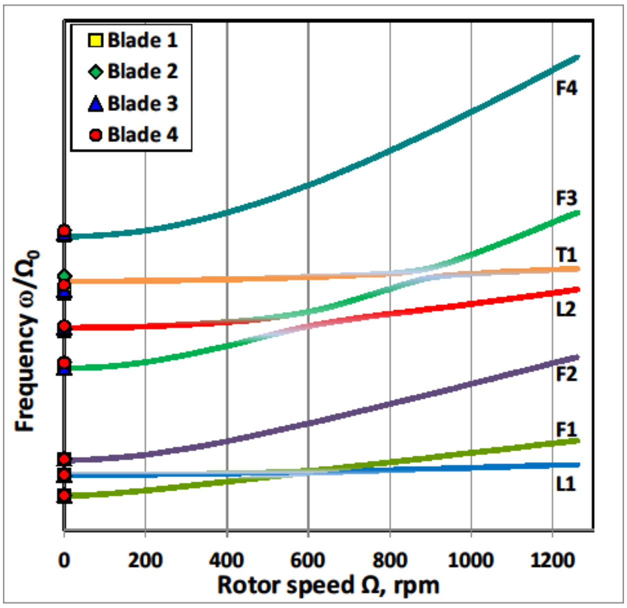

Figure 11: Rotor frequency diagram

5 Discussion and future outlook

Since boundary conditions determine the starting point of the design chain, different conditions will have influence on the designing procedure. Thus for other rotor blades than the FTK blade the design chain has to be adapted. In most cases the design steps and their order will remain. But the iterative process may change regarding its loops, input and output. For example the outer geometry may be part of the iterative process and the loops will be fed back to this design step.

All iterations are controlled manually, so the to speed up the process, there is need for automatization in, for example in form of optimization tools or automatic geometry updates while respecting the given boundary conditions.

Also at the moment there are only roughly defined interfaces between the design environments. A standardization of those interfaces would simplify data exchange and extend the potential use of the design chain in cooperation with other parties. The modular setup would also allow to easily substituting design environments.

6 Acknowledgment

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