Final report: EUDP 2010-I Light Rotor

1. Project details

Project title	Light Rotor
Project identification (program abbrev. and file)	Light Rotor
Name of the programme which has funded the project	Energy Technological Development and Demonstration Wind
Project managing company/institution (name and address)	Technical University of Denmark, Wind Energy Department Risø Campus, Frederiksborgvej 399, 4000 Roskilde
Project partners	DTU Wind Energy Vestas Wind Systems
CVR (central business register)	30 06 09 46
Date for submission	31 August 2014

2. Short description of project objective and results

2.1 English

The objective of the Light Rotor project was to develop the basis for design of wind turbine blades for use on the order of 10MW rotors with lower weight, tailored aeroelastic response and optimized aerodynamic efficiency.

The main results from the project are:

- the development of a tool, where integrated design can be carried out and where couplings to aerodynamic, aeroelastic and structural simulation tools are included.
- the design and test of aerodynamically and structurally efficient airfoils for use on +10MW wind turbines.
- the design of rotors to demonstrate that a multi-disciplinary design methodology is an advantage, and where it showed e.g. a simultaneous 2% increase in energy production and 12% reduction in blade mass.
- Establishment of a 10 MW reference wind turbine that is now used world-wide.
- Topology optimization of an entire blade showing the anticipated design, but also showing a ribbed structure near the root area.

2.2 Dansk

Formålet med Light Rotor projektet var at udvikle grundlaget for design af vindmøllevinger til brug på i størrelsesorden 10MW rotorer med lavere vægt, tilpasset aeroelastisk respons og optimeret aerodynamisk ydeevne.

De vigtigste resultater fra projektet er:

- Udvikling af et værktøj, hvor integreret design kan udføres, og hvor der kobles til aerodynamiske, aeroelastiske og strukturelle simuleringsværktøjer.
- Design og test af aerodynamisk og strukturelt effektive profiler til benyttelse på +10MW vindmøller.
- Design af rotorer som demonstrerer, at en multi-disciplinær designmetode er en fordel, og hvor der viste sig f.eks. en 2% forøgelse af energiproduktionen og samtidig en 12% reduktion af vingemassen.
- Etablering af en 10MW reference vindmølle, der nu benyttes i hele verden.
- Topologi-optimering af en hel vinge, der viser et forventet design, men som også viser en interessant spante-struktur tæt på vingeroden.

3. Executive summary

The objective of the Light Rotor project was to develop the basis for design of wind turbine blades for use on the order of 10MW rotors with lower weight, tailored aeroelastic response and optimized aerodynamic efficiency. Considering the great potential and the distance to the market, much of the work in this project was focused on research, which is necessary to push existing blade designs towards significantly lower cost. Despite of the main focus on research, the work in the project created not only much new knowledge, but also several products that can be applied as a result of the project.

The activities in the project were:

- WP1: Administration and project management
- WP2: Airfoil design with development of tools and airfoils and investigation of aerodynamic devices.
- WP3: Aero-servo-elastic blade design with development of a multi-disciplinary optimization tool and design of a reference blade and optimized designs to demonstrate the multi-disciplinary tool.
- WP4: Structural blade design with 3D topology optimization of the structural layout and design of the reference blade.

The main outputs and their application are listed below.

- The FFA-W3 airfoil measurements have created new specific knowledge about the performance of the commonly used airfoils. Also, more knowledge and guidelines about the installation of vortex generators and Gurney flaps has been created.
- The LRP airfoil family with high aerodynamic and structural performance that was designed exclusively for Vestas. These airfoils are now in the Vestas portfolio of airfoils adding to the potential in future blade design projects internally in Vestas. The blade design work in this project has demonstrated the advantage of these airfoils. The airfoil design is of vital importance to Vestas and the plan is to adopt the outcomes of the project, airfoil designs as well as design techniques, in its future product range. This will enable both up-scaling to the rotor sizes beyond the current technology limits for offshore blades, as well as development of longer and more slender blades for low wind onshore sites - both markets with a strong growth potential.
- The project has also carried out an important research on aerodynamic devices such as Gurney flaps and Vortex generators, which can further enhance the blade performance. The project developed both simulation techniques as well as experimental data, and the outcome of the project feed directly into a Vestas program of aerodynamic enhancements of its current product fleet, bringing additional value to its customers and new revenue stream into Vestas.
- The multi-disciplinary design framework, OpenMDAO that is now dedicated airfoil design and blade design, including aerodynamics, structure and aeroelastic degrees of freedom. This framework is open source, but the simulation codes coupling to this framework, like aerodynamic, structural or aeroelastic tools are not part of the framework and therefore gives DTU the possibility to license more design tools such as Becas, Hawc2, HawcStab2 and EllipSys. Also, the OpenMDAO optimization framework could potentially become an 'industry standard' and Vestas is looking into adopting this framework for development of its future products. This would also further enhance its collaboration with DTU and accelerate adoption of outcome of future research projects, since implementation of new simulation methods could become significantly more cost effective when developed within a common software framework.
- The *DTU 10MW Reference Wind Turbine* (*DTU 10MW RWT*) has been designed and is used by more than 260 persons Worldwide till now. Users are mainly located in Europe, but also China, India, US etc. are represented. Users are both from the research society, but also from manufacturers, where development engineers need an example of large wind turbines to study different trends. The *DTU 10MW RWT* is used in several national and international research projects and has ensured several contacts, and ensured that DTU is part of networks, where they did not participate before the *Light Rotor* project was carried out. Further to this, the *DTU 10MW RWT* is now used in the education of PhD and

Master students for them to learn about loads, aerodynamics and control of wind turbines.

- The BECAS structural tool has been developed so that it is not only an excellent analysis tool, but also can be used in a blade design process. Is has been developed so that it is part of a traditional sequential design sequence or part of an automated setup like OpenMDAO.
- Topology optimization of the entire *DTU 10MW RWT* blade showed that the traditional structural layout is close to optimal. However, the investigation showed that ribs at the root part at the leading edge in an angle of 45° could be part of the design and save mass.
- The project demonstrated that multi-disciplinary procedures can create designs that are both more light weight and generate more energy. Even though designs using the new procedure cannot be created with just a “push at a button” it reflects some design directions that can be investigated in specific future blade designs. Thus, the work demonstrated that the many disciplines included in the blade design loop with advantage can be included simultaneously in contrast to the common way of designing, where the design is sequential considering each discipline at a time.
- With the demonstration of the aeroelastic rotor design showing e.g. 2% increase in energy production and 12% decrease in rotor mass, future blade designs has the option to become more cost effective. Furthermore, this will clearly contribute to the realization of the energy policy objectives.

4. Project objectives and activities

The objective of the Light Rotor project was to develop the basis for design of blades with lower weight, tailored aeroelastic response and optimised aerodynamic efficiency. This basis includes design and validation of an airfoil family with high relative thickness maintaining the aerodynamic efficiency as well as the design of a blade with tailored aeroelastic characteristics for use on a 10MW wind turbine and demonstration of the potentials with respect to performance and load alleviation.

These objectives were planned to be obtained by carrying out several work packages as shown below. The work packages should be carried out in parallel, in order to facilitate a necessary mutual interaction between the activities.

- WP1: Administration: Project management, meetings, reporting and dissemination is carried out in this work package
- WP2: Airfoil design: Development of tools for the optimization of airfoils with high lift devices and design of the airfoil family using AIRFOILOPT including evaluation using CFD. The performance of the airfoil family is demonstrated in a wind tunnel, e.g. the Stuttgart Laminar Windkanal
- WP3: Aero-servo-elastic blade design: Development of the coupling of the aero-servo-elastic tools to the numerical optimization tool HAWTOPT and design of reference blade and new blade using HAWTOPT and CFD. The designs are refined and demonstrated using aero-servo-elastic tools
- WP4: Structural blade design: Development of the 3D topology optimization of the structural layout and design of reference blade and new blade using topology optimization and FEM. The designs are refined and demonstrated using structural design tools, e.g. FEM

The project followed the original plan to a great extent, but some deviations from the plan appeared. These deviations were caused by unexpected appearance of new technology/tools or challenges in the development phase.

- WP2: Airfoil design
    - It was at the start of the project the intention to further develop the in-house DTU design tool AIRFOILOPT, but new possibilities occurred, when NASA (US) developed the tool OpenMDAO, which is open-source and allowing for many different simulation tools to be coupled in a system and thereby more flexible. Therefore, it was chosen to base the further development on OpenMDAO.
- WP3: Aero-servo-elastic blade design
    - As was the case for the airfoil design work package, it was at the start of the project the intention to further develop the in-house DTU design tool HAWTOPT, but in this case it was also chosen to base the further development on OpenMDAO.
    - The design of the reference wind turbine blade turned out to be a bigger effort than anticipated. One of the reasons for this was the more intense cooperation between persons with competences within aerodynamics, aeroelastics and structure. Another reason was the many aspects that appeared in the design process, such as interpretation of load cases according to certification standards. Since definitions, simulation tools and formats are different within the different subjects, a big effort was needed to streamline the communication at DTU.
    - What was intended to be the Light Rotor 10MW Reference Wind Turbine turned out to be the DTU 10MW Reference Wind Turbine, because many projects happened to need a detailed description of a 10 MW wind turbine. Among those were the big EU project InnWind, that is now basing all innovative designs on the Light Rotor design.
    - It was the plan to optimize a rotor using 3D Computational Fluid Dynamics (CFD). Attempts were carried out, but because the optimization problem proved to be complex, it was decided to focus on the aero-servo-elastic optimizations based on tools with lower fidelity.
- WP4: Structural blade design
    - It was at the start of the project the intention that full Finite Element Modeling (FEM) of the blade should be used, but new possibilities oc-

curred, when the wing section structural tool BECAS was developed and could with some development replace the full FEM in many processes.

There were several risks in the project. Some of those were:

- The change of development of AIRFOILOPT/HAWTOPT to OpenMDAO. OpenMDAO was very new in the start of the project and not in a final and mature stage. Therefore, there was a risk that development of the tool would stop. However, since NASA was the main driver it was considered as a minor risk. Several years have passed by since the start of OpenMDAO and the interest is significant and therefore this risk is now very small.
- The use of the common aeroelastic simulation tools in the time domain to design rotors aero-servo-elastically, can be very time consuming, but can also cause convergence problems because of its stochastic nature. This could cause unacceptable long response times in the design process. However, this risk is to some extent eliminated because the aeroelastic calculations are based on a much faster simulation tool that predicts the wind turbine response in the frequency domain, and therefore both long response times and the stochastic character is eliminated. However, load calculations still need to be carried out using a time domain simulation code.
- In connection to the above item, there was a risk that rotors could not be optimized significantly compared to existing blades or that the rotors designed with the new framework were too far from realistic and manufacturable designs and therefore needed much more development.
- Both DTU and Vestas experienced organizational changes during the 3.5 years, which in itself introduce a risk of losing focus. Despite of these changes the project kept the momentum and important results were a result of the project.

Even though many activities in the project were of generic nature and long term R&D, both Vestas and DTU kept the activities at a high level through the project. Because of the long term development connected to the rotor design procedure Vestas focused most on the activities concerning airfoil design. DTU kept focus on both airfoil design and rotor design through the entire project.

5. Project results and dissemination of results

Considering the great potential of increase in annual energy production and the decrease in blade mass, much of the work in this project was focused on research, which was necessary to push the existing blade design towards significantly lower cost. Thus, the *Light Rotor* project was regarded as a phase one of several phases, where phase one was the part, where tools were established and fundamental investigations of concepts were carried out and the following phases will include further refinement, investigations of materials and manufacturability, specific design and test before a blade can be realized at the market. In this connection it is important to be aware that the blades to be manufactured will have lengths of +90m, which makes the blades themselves and the decisions connected to them very expensive. These decisions include not only the specific design, but also e.g. the methods used in the design process.

Because the main part of the work in the Light Rotor project focused on research, the products developed in the project are software and airfoil shapes. These products can be used in future design of blades and therefore the impact of the project results is not yet directly measurable on the turnover, the export or number of employees.

The *Light Rotor* project focused on increasing the generation capacity of larger wind turbines, which is perfectly in line with international and Danish policy objectives put in place to meet the increasing need for renewable energy. Also, the Danish Megavind strategy on research was supported by the *Light Rotor* project, where issues like *wind turbine design* and *Blades - aerodynamics, structural design and materials* were supported.

There are many results from the *Light Rotor* project and the project is considered very successful. Despite of many challenges, all objectives were met and on top of this unexpected spin-offs were obtained. Also, almost all planned activities were implemented; some activities became more intense such as the development of the open source framework OpenMDAO and the 10MW reference wind turbine, and other activities became less intense such as optimization using 3D computational fluid dynamics. However, the result of the project was an operational multi-disciplinary design and optimization framework that can be used by e.g. Vestas in their design of new airfoils and blades. Also, the framework was used to demonstrate that the multi-disciplinary design method is advantageous, where both an increase in energy production and a reduction of mass seem possible. Such designs would be difficult to obtain without the integrated optimization framework. Furthermore, an unexpected spin-off from this project was the global interest in the DTU 10MW Reference Wind Turbine that led to inclusion of DTU in several networks/projects and enquiries from manufacturers world-wide, and also the cooperation with NREL (US) on the integrated design complex OpenMDAO, where a MoU is now signed. Furthermore, some of the challenges that were seen in the Light Rotor project, such as the uncertainty of the aerodynamics for very large wind turbine rotors, are now part of e.g. the EU project AVATAR, where solutions to this challenge is investigated.

The results in the project were presented at conferences, in journal articles and in magazines. A list of the published results is seen in Chapter 8.

The key results from the project are described below, but are described in more detail by Bak and Zahle[1].

[1] Christian Bak and Frederik Zahle, " The Light Rotor project, EUDP-2010-I: Final report", DTU Wind Energy E-0056, August 2014, Denmark

5.1 Integrated design: OpenMDAO

Design of wind turbine rotors is an inherently multi-disciplinary process, since the designer on the one hand strives to maximize the annual energy production of the rotor, while on the other hand also needs to minimize mass, loads and noise, with the final aim of minimizing cost of energy (CoE). These individual objectives and constraints are to a great extent conflicting with each other, since, for example, a purely aerodynamic design would drive the relative thickness of the airfoils along the span down in order to increase efficiency, while a structurally biased design would tend towards the exact opposite. The designer thus has to choose a compromise that to the greatest possible extent meets both objectives. Such a design problem has hundreds of possible design variables describing the outer shape of the blade as well as the distribution of material in the blade, as well as a large number of constraints related to both the aerodynamic and aeroelastic performance of the rotor to manufacturability. If the design team relies on a manual design process to setup models for the different simulation codes, the exploration of the design space will be quite limited. Since it is not humanly possible to evaluate the trade-offs between this many design variables and constraints, the design problem is often simplified and based on incremental changes of previous proven designs, which will likely result is conservative, sub-optimal designs. The above described approach can be characterized as a *sequential* design approach, since the design of the turbine is often divided by discipline-oriented boundaries in which the aerodynamic design is passed to a structural design team, followed by tuning of the controller and load simulations of the design based on a given set of load cases.

The *DTU 10MW RWT* designed in this project, which will be briefly described in Chapter 5.3.1, was in fact designed using a sequential approach, in which the aerodynamic design of the rotor only to a limited extent considered the aeroelastic and structural characteristics of the rotor. The structural design was thus carried out based on a planform design that was aerodynamically optimal, and only through a manual iterative process was the necessary structural constraints imposed on the aerodynamic design. Since this sequential iteration of the design was a manual process, only a limited number of major design iterations were possible.

In a multidisciplinary optimization (MDO) design process, multiple disciplines are included and evaluated simultaneously, and the trade-offs between different objectives and constraints are evaluated by a numerical optimization algorithm that will drive the design towards a numerically optimal point, according to the user-defined merit function, bounded by the constraints defined. A key strength of MDO is that exploration of the design space can be carried out much more systematically and comprehensively than a manual process, since the execution of the different simulation codes is automatized and fully coupled such that sensitivities relative a certain design variable is evaluated by all participating disciplines.

5.2 Airfoil design

5.2.1 FFA airfoils

In this chapter wind tunnel measurements of the FFA-W3-301 and FFA-W3-360 are described. These airfoils were designed in 1990. The reason to test these airfoils is that they have been used extensively by the Danish wind turbine manufacturers and they are still being used. Also, they are known for their good structural performance and rather good aerodynamic performance. Furthermore, the airfoils have a high relative thickness, which is needed to design stiff and light weight blades and finally, these airfoils are open source and only a few open source airfoils with high relative thickness exist. That is the reason for choosing these airfoils as reference to new airfoils and blades in the *Light Rotor* project.

The measurements were carried out in the *Stuttgart Laminar Wind Kanal*. Measurements on these two airfoils have also been carried out earlier in the *VELUX wind tunnel*, but these measurements were at a somewhat lower Reynolds number and at higher turbulence intensity.

Many tests were carried out: 20 tests on the FFA-W3-301 and 23 tests on the FFA-W3-360. Some of these tests were confidential, but in the following, tests on the airfoils with clean surface and some tests with vortex generators and Gurney flaps will be shown.

In Figure 1 polars for the FFA-W3-301 with clean surface are seen and compared to measurements with leading edge roughness (LER). It is seen that $c_{l,max}$ is approximately 1.8 for $Re=3.0*10^6$ and 1.75 for $Re=1.6*10^6$ in the clean case, but also that $c_{l,max}$ drops to approximately 1.2 and 1.0, respectively, when LER is assumed. The corresponding maximum lift-drag ratio is approximately 100 and 90 for $Re=3.0*10^6$ and $1.6*10^6$, respectively, for the clean case, and dropping to 45 and 40 with simulated LER.

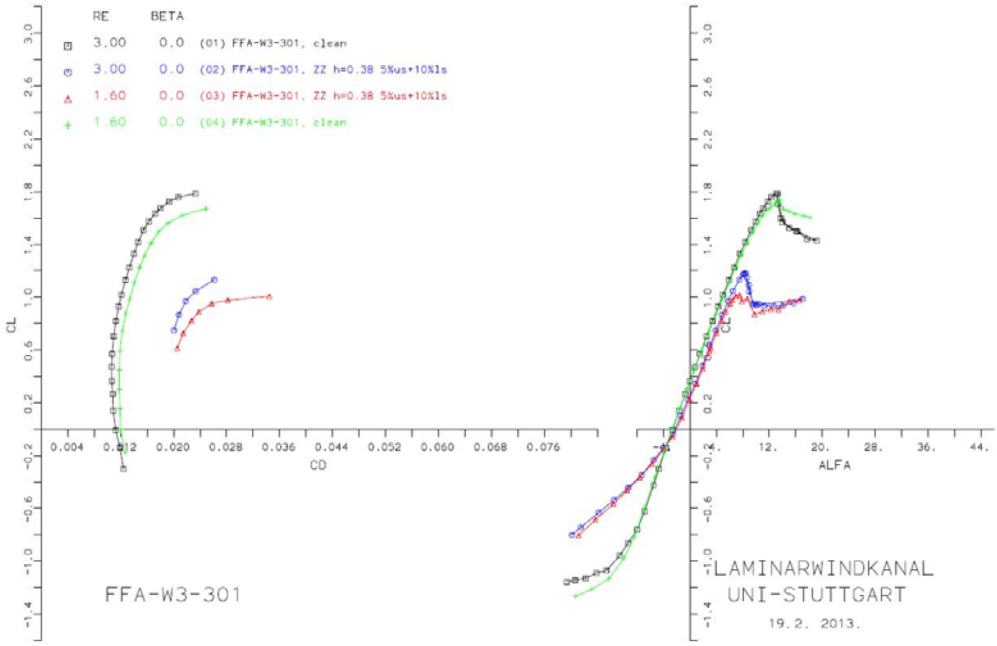

Figure 1 Polars for the FFA-W3-301 airfoil with clean surface and with simulated leading edge roughnes, LER.

Also, polars with VG's mounted at the upper side at different chordwise positions are seen in Figure 2. It is seen that the maximum lift coefficient is between $c_{l,max}$ between 2.3 and 2.5 depending on the position of the vortex generators and the corresponding maximum lift-drag ratio has dropped slightly to between 75 and 95.

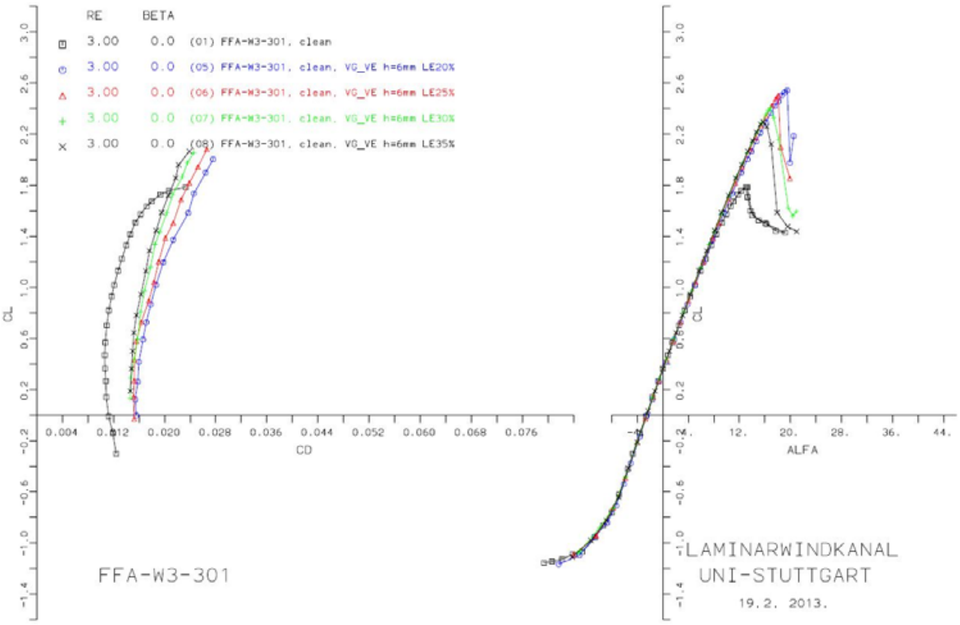

Figure 2 Polars for the FFA-W3-301 airfoil with clean surface and vortex generators.

In Figure 3 polars for the FFA-W3-360 with clean surface are seen and compared to measurements with LER. It is seen that $c_{l,max}$ is approximately 1.65 for *Re*=3.0*10^6 and 1.60 for *Re*=1.6*10^6 in the clean case, but also that $c_{l,max}$ drops to approximately 0.80 and 0.65, respectively, when assuming LER. The corresponding maximum lift-drag ratio is approximately 80 and 65 for *Re*=3.0*10^6 and 1.6*10^6, respectively, for the clean case. No data for drag exists for the airfoil with leading edge roughness.

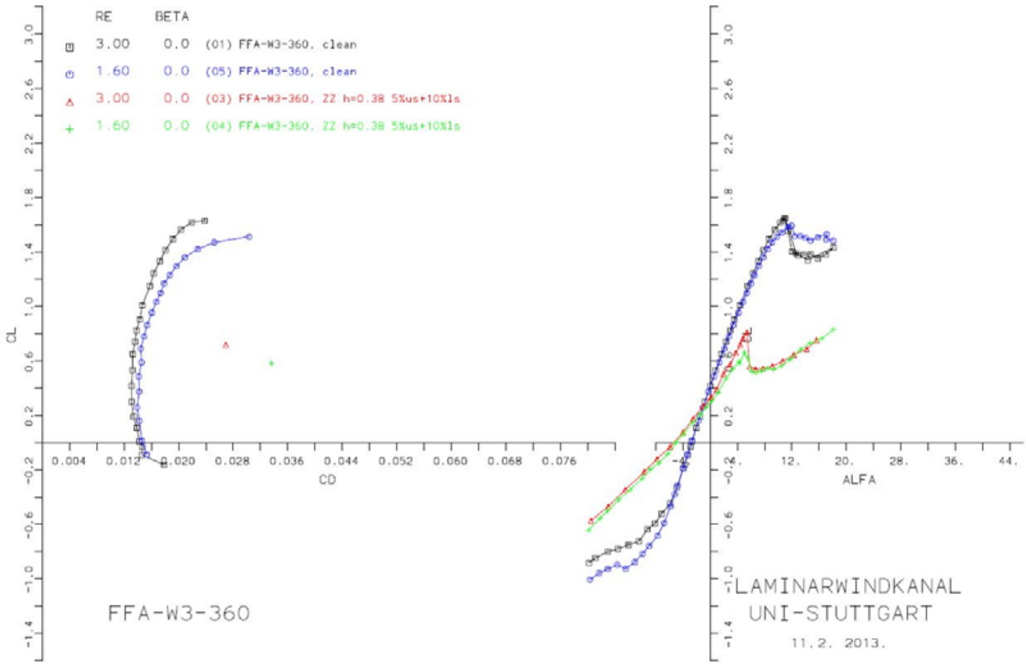

Figure 3 Polars for the FFA-W3-360 airfoil with clean surface and with simulated leading edge roughnes, LER.

Polars with VG's mounted at the upper side at different chordwise positions are seen in Figure 4. It is seen that the maximum lift coefficient $c_{l,max}$ is between 2.2 and 2.5 depending on the position of the vortex generators and the corresponding maximum lift-drag ratio has dropped slightly to between 55 and 80.

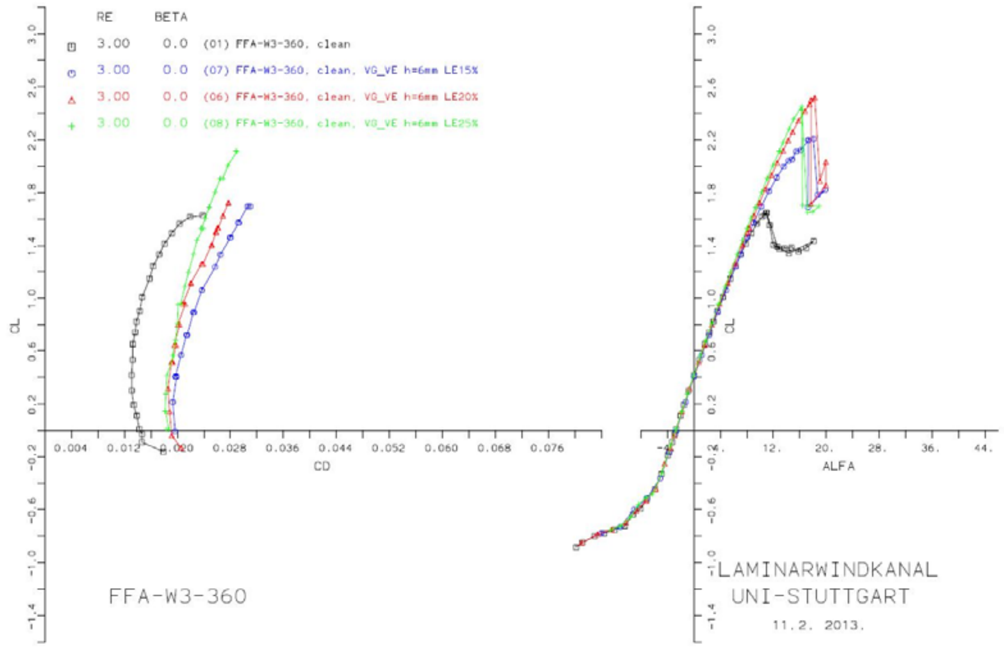

Figure 4 Polars for the FFA-W3-360 airfoil with clean surface and vortex generators.

5.2.2 The balance between structural and aerodynamic performance

This section contains an investigation of three existing airfoil families, where the aerodynamic performance and the structural stiffness are analyzed to find possible relations between aerodynamic performance and stiffness. This study could reveal whether a low or a high maximum design lift is beneficial for the structural performance.

When upscaling wind turbine blades there is an increasing need for high levels of structural efficiency to control blade mass and limit deflection. Using thick airfoils will stiffen the blade, but this will in general reduce the aerodynamic efficiency. On the other hand the use of thinner airfoils will in general increase the aerodynamic efficiency, but the stiffness will be low. When investigating wind turbine blade shapes, they vary in general from manufacturer to manufacturer: some blades are rather wide and others are very slender. These differences depend on the choice of both design lift and design tip speed ratio.

This investigation shows the relationship between design lift, lift-drag ratio and structural stiffness. These relations indicate the tradeoff between achieving structural stiffness through the use of a larger internal space in the airfoil or by a larger relative thickness. In this study an internal box with a height of $0.85*t_{max}/c$ should be fitted into the airfoil, typically with the box side closest to the leading edge at approximately x/c=0.15 and the box side closest to the trailing edge, positioned so that the box length or box size varies between 28 and 36% depending on camber of the airfoil. Three airfoil families are investigated and compared:

- Risø-C2 with relatively high camber and corresponding small box size (28-31%),
- DU with a camber less than the Risø-C2 airfoil family and corresponding larger box size (30-36%), especially for the smaller relative thicknesses and
- FFA also with a camber less than the Risø-C2 airfoil family and corresponding larger box size (31-35%).

The airfoil shapes of the above airfoils are in general very different, but many other shapes could potentially be possible to obtain similar performance. Therefore, the current study should be considered as a trend study rather than a search for the exact design lift coefficient and corresponding stiffness.

The aerodynamic characteristics are based on fully turbulent flow around the airfoil and with Reynolds number $Re=9\text{x}10^6$. The design lift, $c_{l,design}$, is defined as $c_{l,max}$-0.45 and the lift-drag ratio, c_l/c_d, is evaluated at $c_{l,design}$.

The key parameters are plotted in Figure 5. The points at the very left in the plots show the characteristics of the 18% airfoils, whereas the points at the very right are from the 36% airfoils. The left hand plot shows that the Risø-C2 airfoils with shorter box length, can obtain higher design lift for a given flapwise stiffness for the thinner airfoils. It also shows that the flapwise stiffness for a certain relative thickness is reduced if higher design lift is required; however, a certain stiffness can be obtained if a higher relative thickness is selected. The right hand plot shows that the lift-drag ratio is relatively independent of whether increased stiffness is obtained by either increased box length (e.g. the DU airfoils) or increased relative thickness (e.g. the Risø-C2 airfoils).

The analysis showed that the lift-drag ratio as function of flapwise stiffness was the same for the three airfoil families. However, the trend for the design lift as a function of flapwise stiffness was less clear, where especially the thinnest DU and FFA airfoils show significantly lower design lift than the Risø-C2 airfoil. This deviation was possibly intended, since the DU and FFA airfoils with relatively low lift could have been the target in the design of the airfoil families in contrast to the Risø-C2-18 to -24. It should also be noted that the 24% Risø-C2 airfoil had approximately the same flapwise stiffness as the 18% DU airfoil and 21% FFA-W3 airfoils, but also that the lift-drag ratio was the same for all three airfoils, however with a design lift at appr. 1.4 for the Risø-C2 airfoil and appr. 1.25 for the DU and FFA airfoils. The comparisons between the existing airfoils lead to the conclusion that flapwise stiffness can be obtained either by increasing relative thickness or increasing box length and in the same time maintain the aerodynamic performance.

To complete the analysis, also the edgewise stiffness and torsional stiffness were included in the plots. It showed that the lift-drag ratio not always was inversely proportional to the edgewise stiffness, where the DU and FFA airfoils seem to have similar edgewise stiffness for different relative thicknesses. It also showed that the torsional stiffness followed the same trend as the flapwise stiffness, however with stiffness values that were approximately 10 times lower.

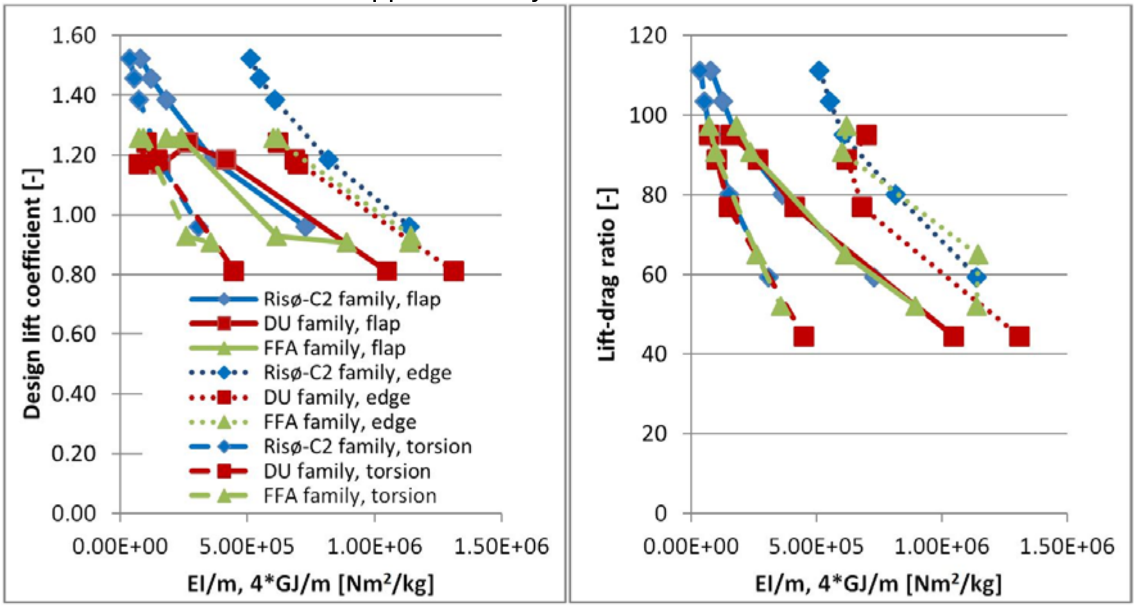

Figure 5 Left: Design lift coefficient as a function of stiffness per mass, EI and GJ. Right: Lift-drag ratio as a function of stiffness per mass, EI and GJ.

The analysis of the existing Risø-C2, DU and FFA airfoil families reflected that the lift-drag ratio is decreasing for increasing flapwise stiffness and relatively independent of airfoil design, but the design lift coefficient is varying depending on the design philosophy. The results also showed that for a given flapwise stiffness, the design lift coefficient in general increases if the box length reduces and at the same time the relative thickness increases. To complete the analysis, also the edgewise and torsional stiffness were analyzed, where the torsional stiffness followed the same trend as the flapwise stiffness and the edgewise stiffness was somewhat more scattered, but with an overall trend of a reduction in the design lift coefficient and lift-drag ratio as a function of edgewise stiffness.

5.2.3 *Airfoil design tool*

A new airfoil design tool was developed in this project based on OpenMDAO. The primary solver used in the tool is XFOIL, but a key objective with this work was also to explore the possibilities of using 2D CFD in place of XFOIL, since CFD is regarded as more accurate for thick airfoils, which was the focus in this project. An interface to the in-house 2D CFD solver EllipSys2D was thus developed. In addition to this, interfaces to an internally developed noise prediction code and the cross sectional structural tool BECAS were developed, which enabled multi-disciplinary shape optimizations of an airfoil considering both aerodynamics, acoustic and structural characteristics concurrently.

Figure 6 shows a flow chart of the different components in the airfoil optimization using 2D CFD. The optimizer, which based on gradients of the objective and constraints changed the design variables towards an optimal design; the airfoil geometry builder, which generates a parameterized airfoil shape; the mesh generator, which takes an airfoil shape as input and generates a CFD ready mesh; the flow solver which computes the flow over the airfoil and resulting forces acting on it, and finally the objective function which computes a measure of goodness based on the flow solution.

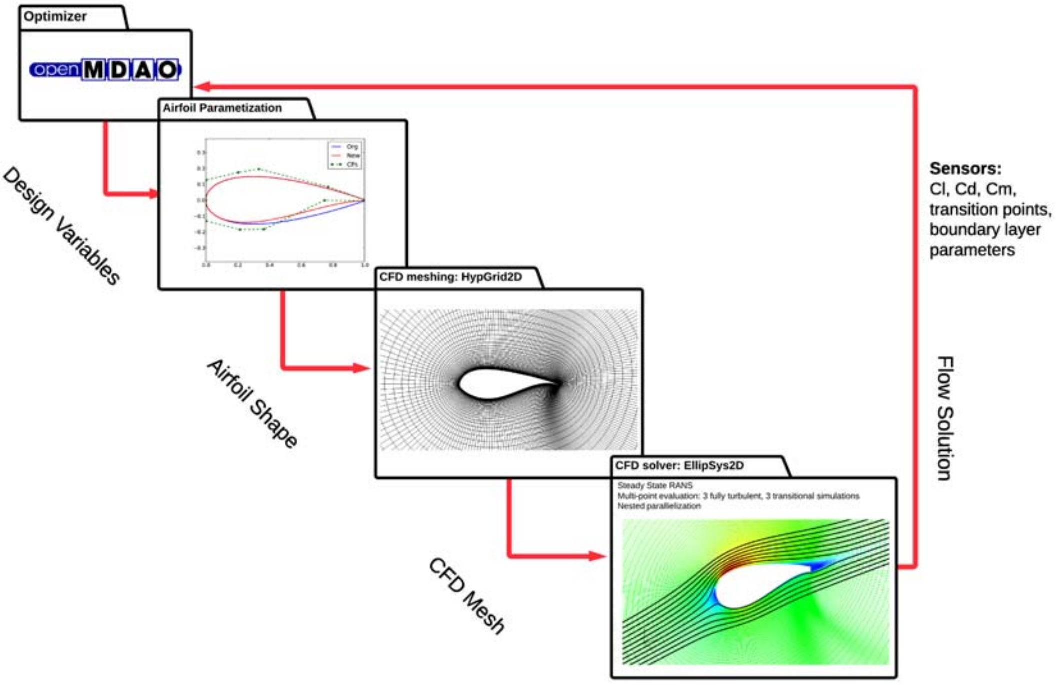

Figure 6 Flowchart showing components in optimization framework.

In the following a brief overview of each of the components is provided.

- *Optimizer*
  Several optimizers were explored in this work. Initially, the gradient based Sequential Linear Programming (SLP) optimizer called GTO, developed at Risø National Laboratory, used in the codes AirfoilOpt and HAWTOPT was used, since it has been used successfully in the design of numerous rotors and airfoils. However, also optimizers made available through the PyOpt plugin in OpenMDAO were used such as PSQP and SNOPT.
- *Airfoil Shape Parameterization*
  To effectively design an airfoil a suitable parameterization of the airfoil shape is necessary, which with as few parameters as possible can produce smooth generalized shapes. In the present work, Bezier curves are used since this class of curves is characterized by a high degree of controllability, while still maintaining gentle curvature changes.
- *Flow Solution*
  The aerodynamic forces acting on the airfoil can be predicted using two different simulation codes; XFOIL, which is a panel code, and EllipSys2D, a 2D CFD solver. While EllipSys2D is of higher fidelity and more suited for thick blunt trailing

edge airfoils, XFOIL is very attractive in an optimization context since it is orders of magnitude faster than EllipSys2D.

- *Mesh Generation*
  A central part of a robust CFD-based optimization strategy is the meshing, which needs to be very robust in order to produce valid meshes for all design points. The meshes for the optimization were generated using the hyperbolic mesh generator using 256 cells in the chordwise direction and 128 cells in the normal direction. For the subsequent evaluation of the airfoils, meshes with 768x256 cells were used.
- *Noise Prediction*
  The noise model implemented here is simulating trailing edge noise for a flat plate, based on the flow over the actual airfoil shape calculated using XFOIL or a CFD code (e.g. EllipSys2D). The basis of the model is originating from the so-called TNO model. The first theoretical background behind this model is the incompressible turbulent boundary layer analysis and the modeling of the associated turbulent surface pressure fluctuations near the trailing edge, which is characterized as the so-called pseudo-sound. The present implementation of this model is an improved version of this theory including turbulence anisotropy, which is related to the boundary layer mean pressure gradient, and which proved to produce model results in better agreement with experimental data measured on airfoils in wind tunnels.
- *Structural Properties*
  While the airfoils designed in this project were not optimized considering the detailed structural characteristics, a tool for aero-structural airfoil design was developed using the interface to the cross-sectional finite element software BECAS. This tool allows the user to set specific targets for quantities such as flapwise edgewise and torsional stiffnesses, structural pitch, elastic axis, shear center and center of gravity. This potentially eliminates the need to impose geometric constraints typically needed to ensure ample room for the internal structure, since constraints can be imposed directly on the quantities of interest.
- *Objectives and Constraints*
  The objective function was defined as a multi-point compound objective. The most often used objective is the lift to drag ratio, however, for very thick airfoils, including C_l directly in the objective may be necessary, since for such airfoils there will typically be higher weight on high lift rather than L/D. To achieve an airfoil with both good performance under clean surface conditions and soiled surface conditions, the objective typically included cases with both transitional and fully turbulent flow. For aero-acoustic optimizations, the objective can be formulated as a mixed objective maximizing L/D while minimizing the sound pressure level. However, it was generally found difficult to obtain good results with this strategy, whereas optimizing for either aerodynamic or acoustic performance and constraining the other, was found to be more efficient. Besides the basic bounds on the design variables, different types of constraints could be imposed in the airfoil optimizations on both geometric and flow-based parameters.

5.2.4 LRP airfoils

This section describes the design and wind tunnel testing of a high-Reynolds number, high lift airfoil series designed for wind turbines. The airfoils were designed using direct gradient-based numerical multi-point optimization based on a Bezier parameterization of the shape, coupled to the panel code XFOIL and the 2D Navier-Stokes flow solver EllipSys2D as described in the section above. The resulting airfoils, the LRP2-24, LRP2-30 and LRP2-36, achieve both higher operational lift coefficients and higher lift to drag ratios compared to the equivalent FFA-W3 airfoils. The two thickest airfoils were designed using EllipSys2D, and tested in the Stuttgart wind tunnel, whereas the thinner 24% airfoil was designed exclusively using XFOIL. In the following, a summary will be given of the performance of all three airfoils, although the focus will be on the two airfoils tested in a wind tunnel.

The LRP airfoils were designed to achieve high operational lift under both soiled and clean surface conditions, through a careful weighting of the turbulent and transitional performance, combined with constraints on the movement of transition points.

The LRP2-30 and LRP2-36 airfoils were tested in the Stuttgart Laminar Wind Tunnel at Reynolds numbers Re = $1.6*10^6$ and $3.0*10^6$ with a model chord of 0.6 m. While these are lower Reynolds numbers than the airfoils were designed for (Re = $9*10^6$), such measurements are important for validating the predicted performance of the airfoils.

Figure 7 and Figure 8 show a comparison of the measured and computed lift and drag polars of the LRP airfoils. The agreement for clean conditions is quite good with only a small over-estimation of $C_{l\text{-}max}$, although for $C_l > 0.8$, the measured drag coefficient is consistently higher than predicted. This was identified as being partly due to a small trailing edge separation, which was not seen in the transitional simulations, but only in the fully turbulent ones at the lowest Reynolds number of $3.0*10^6$. It is at present unclear what the explanation for the overall higher drag level is in the experimental data compared to computations. The measurements with zig-zag tape on the leading edge at x/c=0.05 on the suction side and at x/c=0.10 on the pressure side show a poorer performance than the fully turbulent CFD simulations. A likely explanation for this could be that the tape due to its height not only trips the boundary layer, but also introduces an additional disturbance of the boundary layer that is not modelled in the simulations.

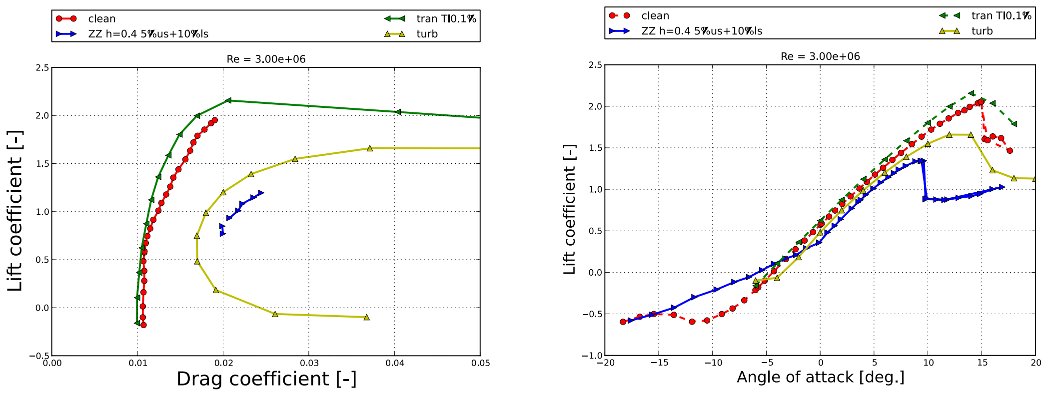

Figure 7 Measured and computed lift and drag polars for the LRP2-30 airfoil at Re = $3.0*10^6$.

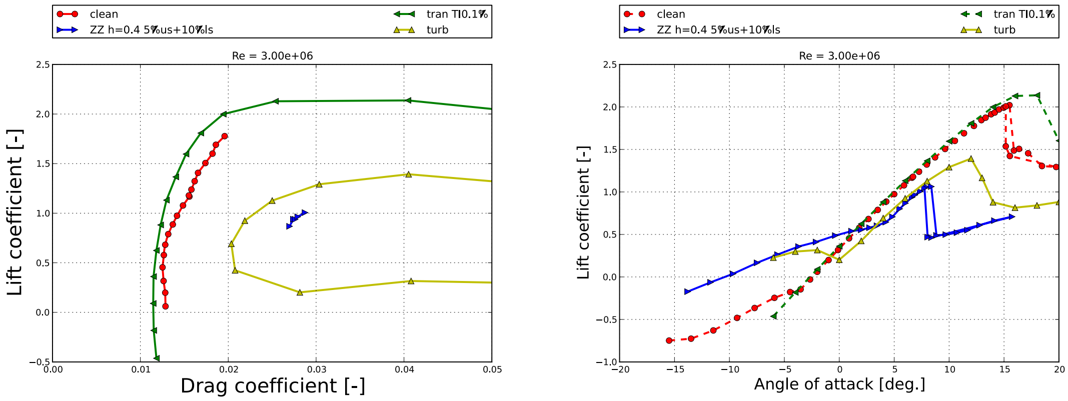

Figure 8 Measured and computed lift and drag polars for the LRP2-36 airfoil at Re = $3.0*10^6$.

Figure 9 and Figure 10 show a comparison between the LRP2-30 and LRP2-36 airfoils with the equivalent FFA-W3-301 and FFA-W3-360 airfoils, also tested in the Stuttgart Laminar Wind Tunnel. The LRP airfoils achieve an overall higher lift level for both rough and clean conditions, while maintaining comparable or improved L/D ratios.

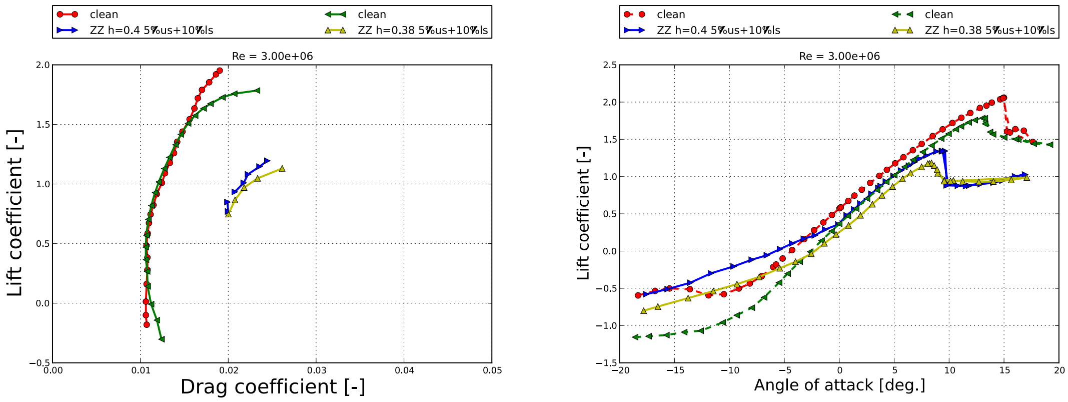

Figure 9 Comparison of the measured lift and drag polars for the LRP2-30 and FFA-W3-301 airfoils at Re = $3.0*10^6$.

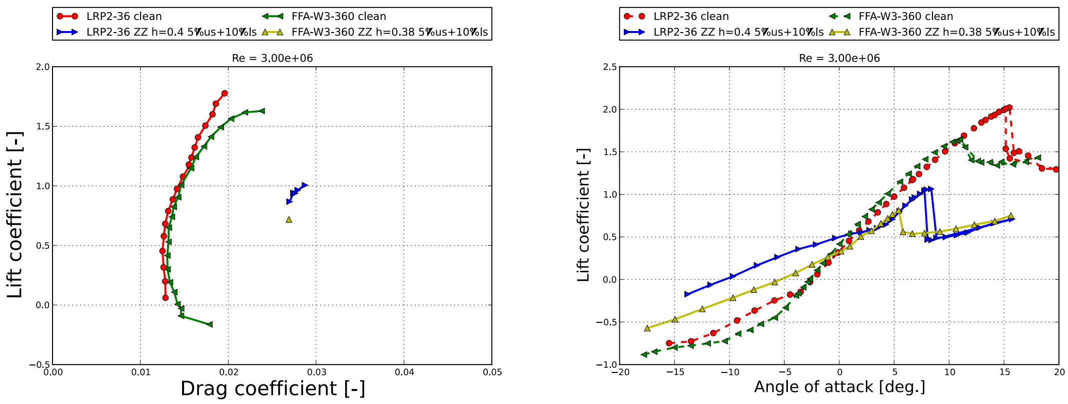

Figure 10 Comparison of the measured lift and drag polars for the LRP2-36 and FFA-W3-360 airfoils at Re = $3.0*10^6$.

5.3 Aero elastic rotor design

5.3.1 DTU-10MW-RWT

As part of the *Light Rotor* project a 10-MW reference rotor was designed. This was done so that future designs can be compared to the rotor. Even though the focus in the project is the rotor design, the existence of the entire wind turbine is needed to understand the rotor performance in its interaction with the entire system including the structural dynamics of the blades, the tower and the drive train. That is the reason to establish an entirely new wind turbine, the *DTU 10-MW Reference Wind Turbine (DTU 10MW RWT).* This turbine is used to reveal the performance of the blade and is inspired by the artificial *NREL 5 MW Reference Wind Turbine* made at NREL, US. Even though new methods are developed in the *Light Rotor* project the methods used for designing the *DTU 10MW RWT* were the existing ones following a sequential workflow to also reveal the effect of using updated methods in the rotor design process later in the project. Thus, the blade weight was minimized using existing methods, but no new concepts or materials were used. Therefore, a significant reduction in rotor mass was not expected compared to existing upscaled rotors.

Also, at the kick-off meeting for the big EU project *InnWind* it was clear that a 10 MW wind turbine was needed to test simulation models. Therefore, it was decided to use the *DTU 10MW RWT* in the *InnWind* project, because it was an offshore wind turbine and had a rather traditional design. Further to this, many more national and international projects all over Europe are now using the *DTU 10MW RWT* and this has led to much interest and many contacts between DTU and other research institutions and companies.

This chapter contains a brief description of the aerodynamic and aeroelastic design for the *DTU 10MW RWT*. An upscaling to obtain a light weight rotor was managed by increasing the thickness to chord ratio of airfoils along the blade span and adjusting the thickness of load carrying structural elements in the blade, rather than just keeping relative thicknesses and adjusting the thickness of load carrying elements. The impact of increasing the thickness ratio along the blade is that the weight and edgewise loads scale better with the flapwise loads while considering the negative impact from higher thickness ratio on power and thrust.

In the design process there were several iterations. In general the process was as follows:

- Aerodynamic design
- Structural design
- Load calculations using an aeroelastic tool

This procedure was run through at least three times, where e.g. the entire aerodynamic planform was changed, the aerodynamic characteristics were adjusted, the structural layup was changed or the aeroelastic setup was adjusted.

A comprehensive data repository was made and contains all necessary data for modeling the *DTU 10MW RWT* using a variety of simulation tools. The repository contains separate packages relating to the reference geometry, aero-elastic modeling, CFD modeling, and structural modeling. The repository is accessible via the webpage *http://dtu-10mw-rwt.vindenergi.dtu.dk*. By August 2014 persons from all over the World registered to download the model.

As no existing turbine was in the size range of the *DTU 10MW RWT*, it was not possible to base the design on data from existing turbines as, e.g. in the description of the *NREL 5MW reference turbine*. Though a detailed design of all of the structural components could be performed it was out of the scope of this work. Therefore it was decided to design the *DTU 10MW RWT* by upscaling the *NREL 5MW Reference Turbine*. The upscaling procedure was reviewed and compared to the next generation of large wind turbines that will soon enter the market. In this process it was decided to redesign several components and scale the values based on more recent turbine data.

The wind turbine had a rated power of 10MW, was designed for offshore siting for an IEC class 1A wind climate and was in general a traditional three-bladed, upwind wind turbine. The offshore wind climate was chosen, because it was the assumptions that the very large turbines in general will be dedicated offshore sites, since transport of these constructions are a major issue. An overall description of the wind turbine is seen in Table 1. In this table also data from a direct upscale of the *NREL 5MW RWT* is seen.

Table 1 Key parameters of the DTU 10 MW Reference Wind Turbine compard to a direct upscale of the NREL 5 MW Reference Wind Turbine.

Parameter	DTU 10MW RWT	Upscaled NREL 5MW
Wind Regime	IEC Class 1A	IEC Class 1B
Rotor Orientation	Clockwise rotation - Upwind	Same
Control	Variable Speed	Same
	Collective Pitch	Same
Cut in wind speed	4 m/s	Same
Cut out wind speed	25 m/s	Same
Rated wind speed	11.4 m/s	Same
Rated power	10 MW	Same
Number of blades	3	Same
Rotor Diameter	178.3 m	Same
Hub Diameter	5.6 m	4.24 m
Hub Height	119.0 m	127.0
Drivetrain	Medium Speed, Multiple-Stage Gearbox	High Speed, Multiple-Stage Gearbox
Minimum Rotor Speed	6.0 rpm	4.9 rpm
Maximum Rotor Speed	9.6 rpm	8.6 rpm
Maximum Generator Speed	480.0 rpm	1173.7 rpm
Gearbox Ratio	50	97
Maximum Tip Speed	90.0 m/s	79.9 m/s
Hub Overhang	7.1 m	Same
Shaft Tilt Angle	5.0 deg.	Same
Rotor Precone Angle	-2.5 deg.	Same
Blade Prebend	3.332 m	0.000 m
Rotor Mass	227,962 kg	311,127 kg
Nacelle Mass	446,036 kg	678,823 kg
Tower Mass	628,442 kg	982,765 kg

An overview plot of the wind turbine is seen in Figure 11, but a more thorough description of the wind turbine is made by Bak et al.[2].

Figure 11 The DTU 10MW RWT

[2] C. Bak; F. Zahle; R. Bitsche; T. Kim; A. Yde; L.C. Henriksen; P.B. Andersen; A. Natarajan, M.H. Hansen; “Design and performance of a 10 MW wind turbine”, J. Wind Energy, To be accepted.

5.3.2 *Aero elastic rotor design tool*

The size of modern wind turbines continues to increase and with this comes challenges to the designers to reduce the overall cost of energy. To meet this challenge it is becoming increasingly important to design the turbine considering the inherent couplings between the different disciplines involved in the design at an early stage in the design process. It is widely recognized that multi-disciplinary optimization can be used to systematically evaluate and balance the trade-offs between conflicting objectives, and thus reach better designs.

The key aim with the development of a new wind turbine rotor design tool was to enable simultaneous design of both the aerodynamic shape and internal structure of a blade, enabling detailed aeroelastic tailoring of a blade's performance in terms to aerodynamic performance, mass properties, aeroelastic stability and controllability. These goals are made possible through the dedicated development of advanced aeroelastic and structural simulation codes at DTU Wind Energy. This section will not describe these in detail, but focus more on describing the coupling of these into an integrated aero-elastic rotor design tool.

As described in the section about OpenMDAO the optimization framework is designed to be as flexible as possible, allowing the user to easily restructure the workflow and dataflow via a high level configuration script, without modification to the individual code wrappers. The design tool can thus been used for a wide array of applications such as maximizing AEP assuming a fixed structure, tailoring of aeroelastic frequencies and dampings through modification of the structural properties, tuning of a controller for a specific turbine, and finally the combination of both minimizing mass and maximizing AEP, including detailed modelling of both the structural and aeroelastic properties. This section will focus on the latter, in which both the structure and planform are optimized simultaneously.

Figure 12 shows a diagram of the overall architecture of the design tool. The *Planform Splines* and *Structural splines* handles the parameterization of the blade, which is a central part of an optimization tool. The input parameters to these components are controlled by the optimizer, and the updated blade shape and structure are subsequently passed to the structural and aeroelastic solvers. The structural solver is responsible for computing the structural properties of the blade, which is handled by a series of cross-sectional computations, that outputs beam properties suitable for an aeroelastic solver. Secondly, the structural solver computes the stresses based on a set of IEC design driving load cases to ensure that the design remains within the ultimate stress limits of the materials. Subsequently, the aeroelastic solver computes the AEP, loads and frequencies of the turbine based on the updated planform and structure. Finally, the cost function is computed, which in this case is a weighted sum of mass and AEP or mass moment and AEP. An important point to make is that the optimization architecture used in this work enables computation of the fully coupled sensitivities.

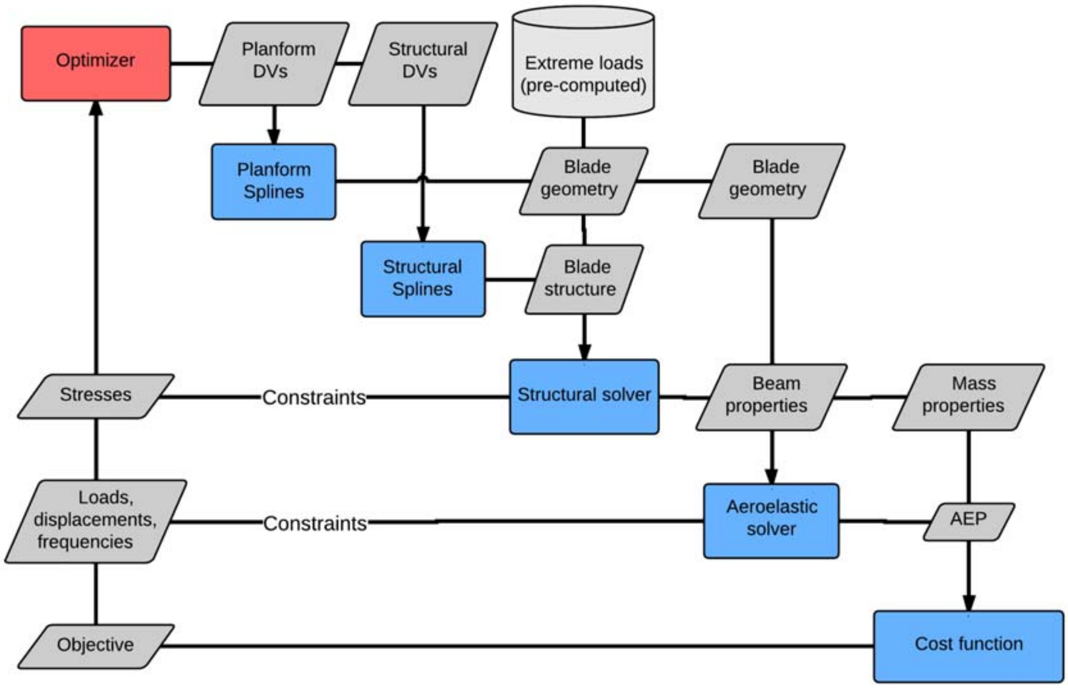

Figure 12 Flowchart showing components in the rotor optimization framework.

- *Blade Parameterization*
  To enable optimization of both the structure and aerodynamic shape of the blade, suitable parameterizations have to be chosen of the geometry and material distribution. The parameterization is on the one hand required to be general enough to not limit the design space, while on the other hand be as simple as possible in order to limit the number of design variables required. The composite layup is likewise described by a series of smooth splines describing the thicknesses of individual layers.
- *Structural Solver*
  a) BECAS
  In this work the general purpose finite element based cross sectional analysis software BECAS is used to predict the structural properties of the blade and recover the stresses in the cross-sections resulting from the forces and moments computed using the aeroelastic code HAWC2. In order to interface it to the OpenMDAO based optimization framework, an interface was written that translated the parameterized blade structure described above into the format used by the tool *ShellExpander*, distributed along with BECAS.
  b) CSProps
  Another cross-sectional analysis tool, *CSProps*, was implemented and interfaced to the rotor optimization tool. CSProps is an analytical model with a very simple set of inputs. In the model the cross-sectional shape is assumed to be symmetric, and the structural layout fixed to a standard three cell configuration.
- *Aeroelastic Solver*
  To compute the aerodynamic loads, blade deflection (including torsion), aeroelastic frequencies and damping ratios, the frequency domain based aeroelastic solver HAWCStab2 is used, which uses a Blade Element Momentum (BEM) method for the aerodynamics and Timoshenko beam elements in a co-rotational finite element formulation to describe the turbine structure. HAWCStab2 includes linear models of actuators and controllers, which enables closed-loop aero-servo-elastic eigenvalue analysis useful for controller tuning and for aero-servo-elastic stability analysis, which, however, is not demonstrated in this work.

5.3.3 New rotor designs

This section describes the results obtained using the rotor design tool described in the section above. The first set of cases optimizes the *DTU 10MW RWT* with a varying degree of complexity: The first test case attempts to minimize mass only through optimization of the internal structure with the outer shape fixed, constraining the power production of the rotor; the second set of test cases expands the design problem to include also the aerodynamic planform using the FFA-W3 airfoil family also used on the original blade, where the objective was to minimize mass and maximize AEP, where the bias towards either reduction of mass or increase in AEP is varied systematically. Finally, a set of test cases are presented in which the newly designed LRP airfoils described in a section above are used to design a 10 MW rotor for the existing *DTU 10MW RWT* platform, with the same compound objective as used for the FFA-W3 based rotor designs.

- *Planform and Structural Design*

  This section presents a series of designs made in which both the outer shape and the internal structure were optimized simultaneously. Two families of designs were made: one using the FFA-W3 airfoil series and another using the newly designed LRP airfoil series. Below, the objective function, design variables and constraints are listed, where w_{pow} is a number between 0 and 1 and describes the weighing factor between optimizations only to reduce mass and optimizations only to increase AEP, respectively.

  In each family, a number of blades were optimized using a different weighting between mass and AEP in the objective function. Figure 13 shows the set of pareto optimal designs for each blade family. As can be seen the blade mass was reduced significantly for both families although the lowest achieved mass was found for the LRP-based blades. However, blades with a strong bias towards reduction of mass were not very efficient aerodynamically and produced a lower AEP compared to the reference blade. One design stood out in the LRP family, that was the design with w_{pow}=0.95, which achieved the highest AEP of all designs with an increase of almost 2% compared to the *DTU 10MW RWT*, while the mass was reduced by 12%.

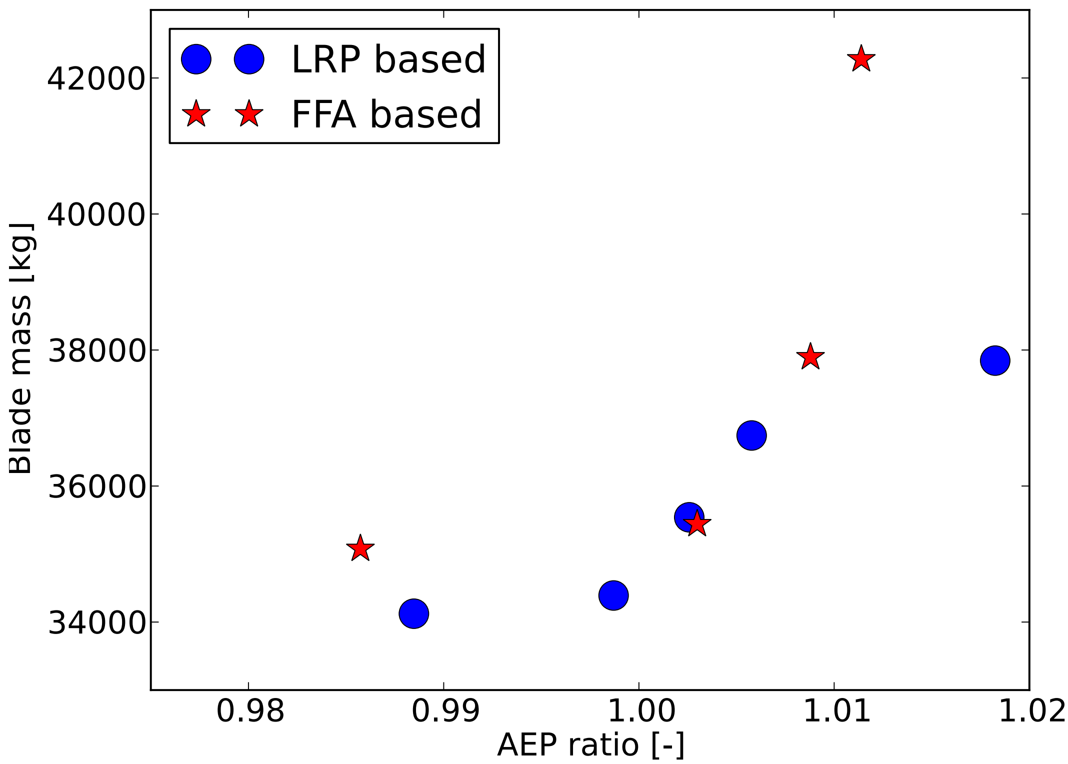

Figure 13 Pareto optimal designs for the LRP and FFA based blade designs.

Figure 14 shows the planforms for the LRP-based designs for different blend factors. All blades have significantly higher relative thickness airfoils over most of the blade, except for at the tip where a constraint ensured that the relative thickness on the outer 10% span was 24%. The primary reason for which the new designs still out-perform the reference blade by almost 2% for the best case, is the use of the LRP airfoil series which on average has a 15% better L/D compared to the FFA family. Secondly, the new designs are optimized taking into account the torsion of the blade during operation which will also have an impact on performance.

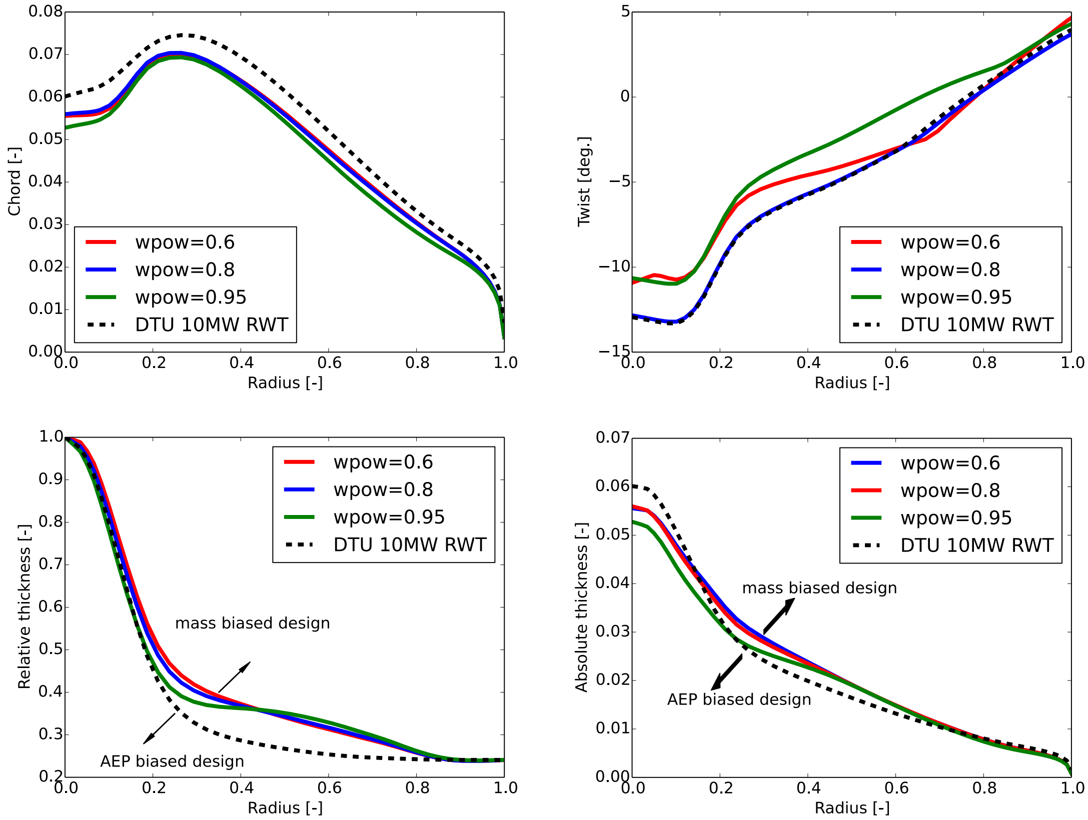

Figure 14 Blade planform for the LRP based blade designs.

Figure 15 shows comparisons of the LRP based design and the DTU 10MW RWT design for selected sensors as function of wind speed. As can be seen the power below rated is consistently higher for the LRP based design, while the maximum loads and deflections are not increased for the LRP based design. Figure 17 shows the structural characteristics of the blade, where it can be seen that both the flapwise and torsional stiffnesses are increased considerably midspan while reduced significantly in the root compared to the baseline design.

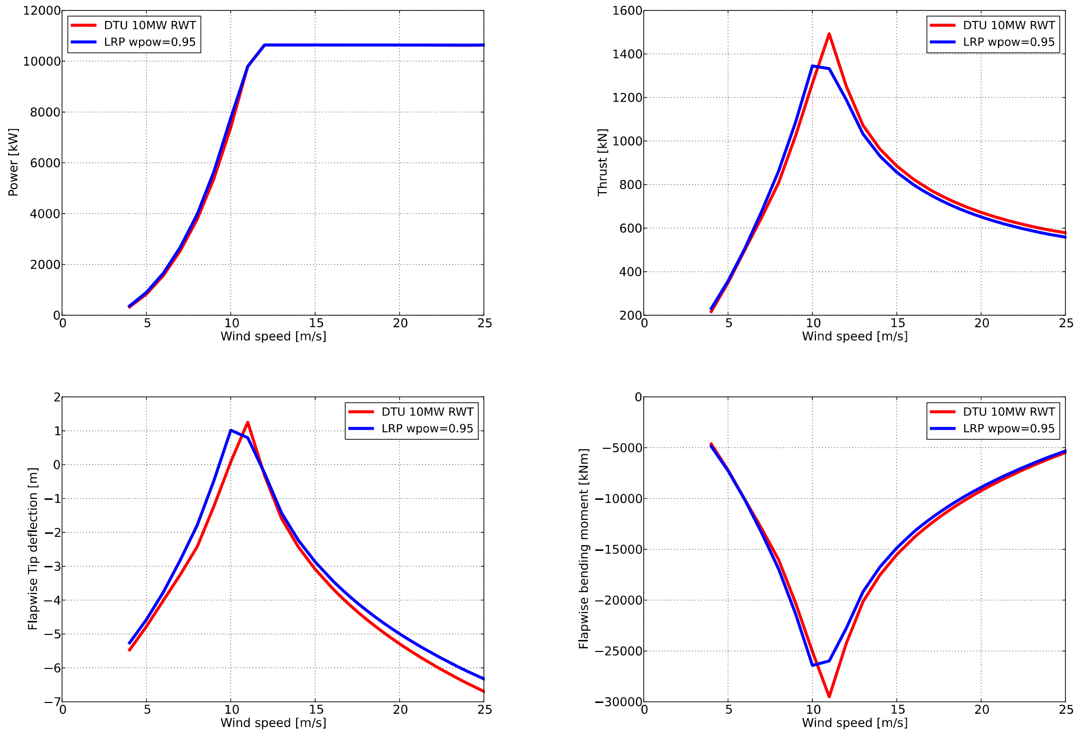

Figure 15 Aerodynamic characteristics for the LRP based blade designs.

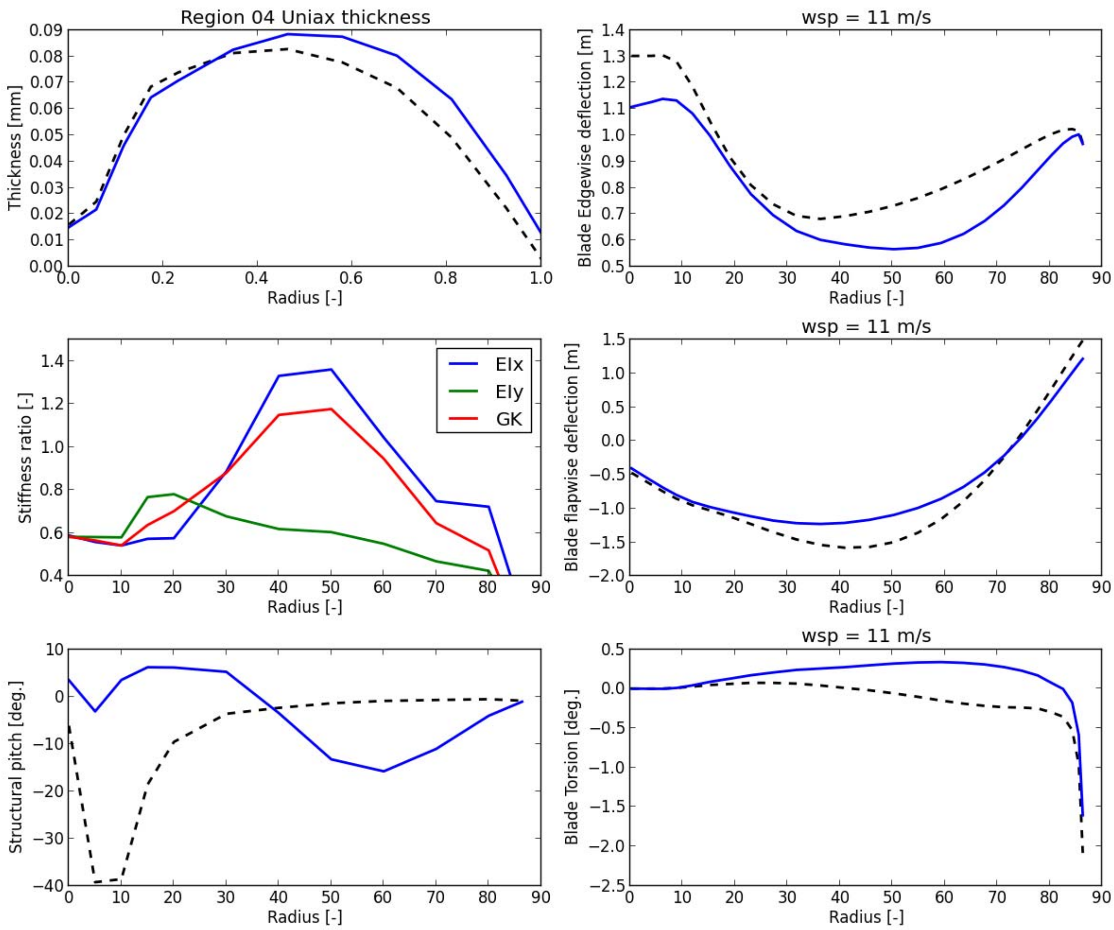

Figure 16 Structural characteristics for the LRP based blade designs.

Figure 17 and Figure 18 show a comparison of selected load sensors for HAWC2 time domain simulations for a series of IEC load cases. In general the new design does not exceed the original design loads.

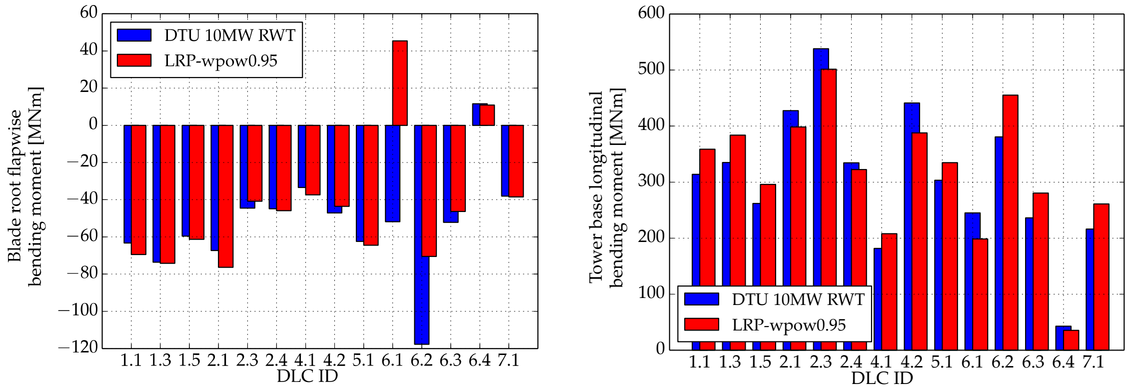

Figure 17 Selected ultimate loads for IEC load cases computed using HAWC2, see appended technical report for complete set of loads.

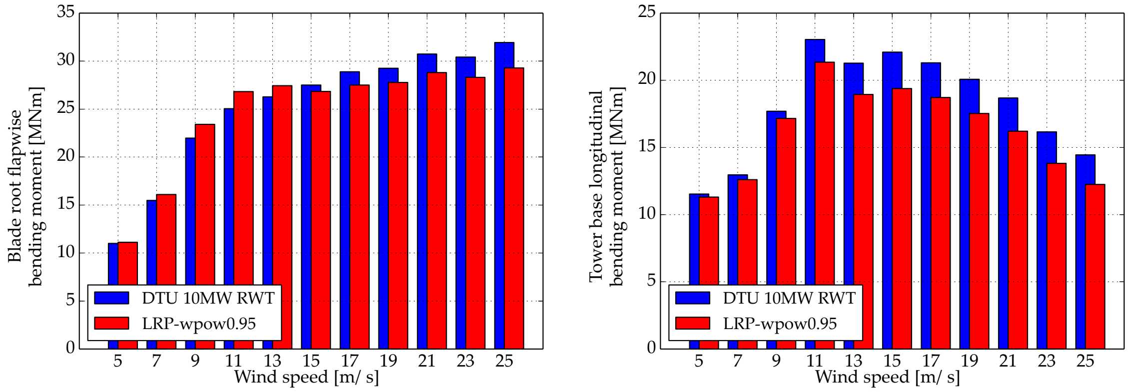

Figure 18 Selected fatigue loads for IEC load cases computed using HAWC2, see appended technical report for complete set of loads.

5.4 Structural design

5.4.1 Structural workflow

Figure 19 shows the workflow used for the design of the DTU 10MW reference wind turbine blade from a structural mechanics perspective. The first iteration starts with the definition of the blade in terms of geometry, material and composite layup. Based on that an ABAQUS 3D finite element shell model and a set of input files for DTU Wind Energy's cross section analysis software BECAS are automatically created. BECAS, that is described in Section 5.4.2 below, computes the cross section stiffness and mass properties of the blade, which are used to build the beam finite elements representing the blade in the DTU Wind Energy's aero-elastic code HAWC2. HAWC2 computes the ultimate loads (cross section forces and moments) in the blade, which are then used again in BECAS to compute the local stresses, strains, and composite failure criteria. The ultimate loads from HAWC2 are also used to analyze the buckling response of the blade using the ABAQUS finite element shell model. The design is changed based on the analysis results and a new iteration starts.

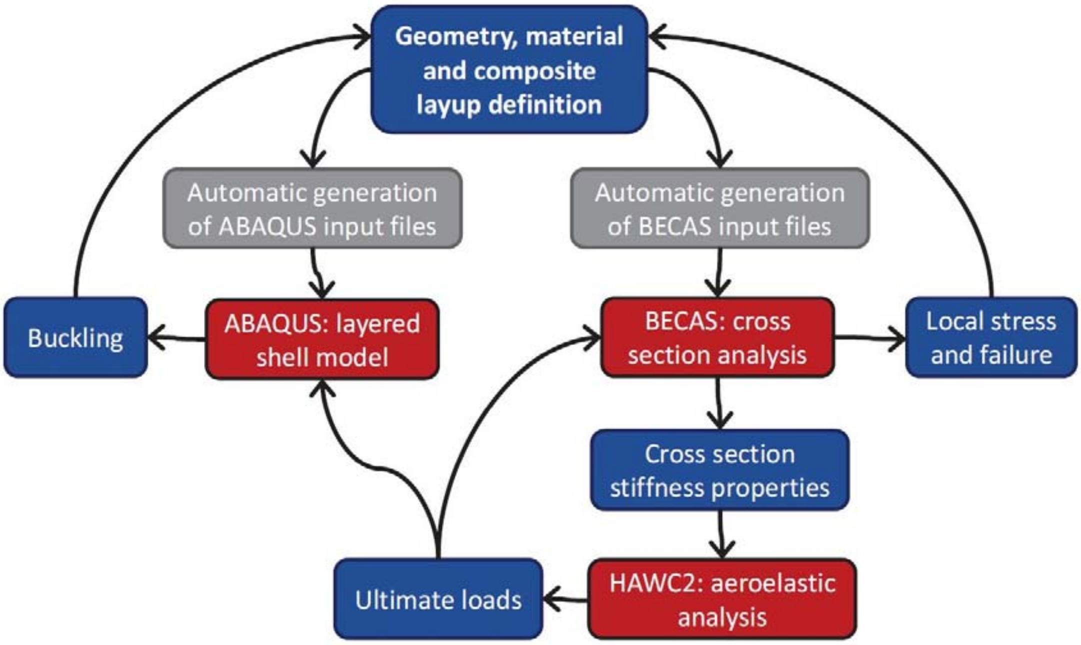

Figure 19 Workflow used for the design of the DTU 10 MW reference wind turbine blade from a structural mechanics perspective.

Buckling analysis of various blade designs was performed using the 3D ABAQUS finite element shell model and linear eigenvalue buckling analysis. Generally, geometrically non-linear analysis performed using finite element models with controlled geometrical imperfections yields more accurate results than linear eigenvalue buckling analysis. However, linear eigenvalue buckling analysis is computationally far more efficient, and was therefore used exclusively in the project.

The loads applied during buckling analysis are the results of an aeroelastic simulation in terms of combinations of cross sections forces and moments given at a certain cross section. Static loads are then applied to the 3D finite element shell model in such a way that the given combinations of cross sections forces and moments are obtained at the cross section of interest. This form of load application is much more straight forward and less prone to error if the model is split up into overlapping radial segments as shown in Figure 20. Moreover, splitting the model up into several radial segments that are analyzed individually, speed up the buckling analysis considerably.

Kinematic coupling constraints were applied at both ends of the section, forcing the end sections to move like rigid bodies. This avoids the prediction of nonphysical buckling modes at the model boundaries. Loads were applied to the reference nodes of the coupling constraints in such a way that the cross section investigated was loaded by the given combinations of cross sections forces and moments. It is apparent that these stiff boundary conditions have a small effect on the predicted buckling loads. However, the advantages of the chosen analysis approach in terms of convenience and computational efficiency outweighed the disadvantages.

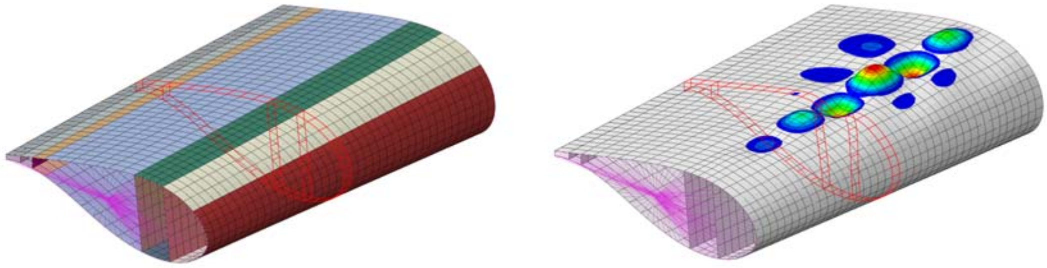

Figure 20 Example buckling model with the cross section investigated highlighted (left) and first eigenmode (right).

5.4.2 Becas

BECAS is a general purpose, finite element based cross section analysis software. It determines cross section stiffness and mass properties of almost any type of beam cross section. BECAS was initially developed by José Pedro Blasques (DTU Wind Energy) between 2010 and 2011. In the framework of the *Light Rotor* project, starting in 2010, BECAS was used in a blade design context for the first time. This led to a number of developments including automatic pre- and post-processing tools for BECAS. Essentially, the *Light Rotor* project turned BECAS from a cross section analysis tool into a blade design tool.

The design and certification of wind turbines requires the analysis of a large number of aero-elastic load cases. These analyses are typically conducted using specialized wind turbine aero-servo-elastic codes, like HAWC2. In these programs the wind turbine blades and the tower are typically modelled using beam finite elements. This modelling approach offers a convenient trade-off between accuracy and computational efficiency. The generation of beam finite element matrices entails the determination of the cross section stiffness and mass properties. For isotropic beams with simple geometries (e.g. the tower) the determination of these properties is usually trivial. The development of accurate beam models to represent the blades, however, is more challenging. The blades have complex geometries and are made of combinations of different composite materials with different degrees of anisotropy. Simplified approaches have been used in the past to estimate the blade cross section properties. However, these tools do not meet the desired level of accuracy for future blade designs.

The wind turbine blade design and engineering community, in an effort to improve the accuracy of its aeroelastic models, has in recent years looked into new methods for developing high-fidelity beam models to represent the blades. The open source BEam Cross section Analysis Software – BECAS – described here is a result of this effort. BECAS is able to accurately account for effects stemming from material anisotropy and inhomogeneity in cross sections of arbitrary geometry. As a result it is possible for blade designers to tailor these properties to improve the aeroelastic performance of the blade.

A schematic description of a typical BECAS workflow for structural blade analysis and design is described in Figure 21. BECAS is first used in a pre-processing phase to generate the beam finite elements representing the blade in the aeroelastic analysis code. A series of pre-defined cross sections along the blade are analysed. The analysis is based on a finite element mesh of the cross section. The material properties are defined at each element and may present any level of anisotropy. The resulting beam finite elements are used to represent the blades in the wind turbine assembly inside the aeroelastic analysis tool. Finally, based on the cross section forces and moments resulting from the aeroelastic simulations it is possible to recover the detailed three-dimensional stress components.

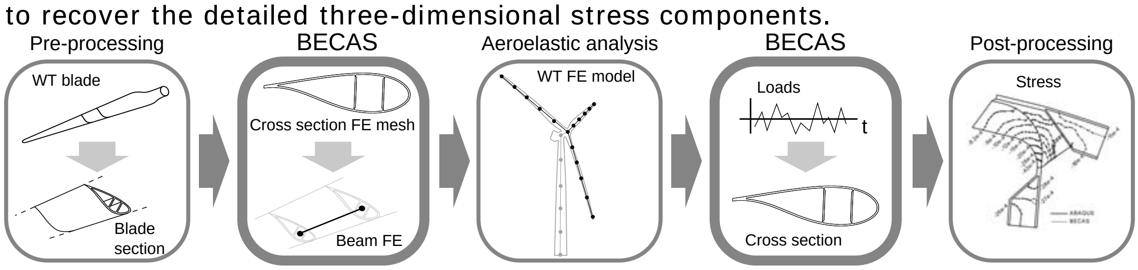

Figure 21 Schematic description of the BECAS workflow for structural analysis and design of wind turbine blades.

In the BECAS workflow described above, the generation of the cross section finite element mesh is an important step. In the framework of the *Light Rotor* project a dedicated finite element preprocessing software was developed that automatically generates cross section finite element meshes and the corresponding material and orientation assignments based on information contained in a finite element shell model. Each shell element is converted into a stack of three-dimensional solid elements by *expansion* in the local normal direction, which is why the software was named *Shellexpander*. The two-dimensional mesh for BECAS is then found by projecting the front faces of the three-dimensional elements to an appropriate plane. 4-node and 8-node quadrilateral shell elements result in 4-node and 8-node quadrilateral BECAS elements, respectively. *Shellexpander* also has special features for dealing with thickness discontinuities, T-intersections and local coordinate systems. Further details are described in the *Shellexpander* documentation available at http://www.becas.dtu.dk.

A simplified version of *Shellexpander* called *airfoil2becas* does not require a 3D finite element shell model as input. This program is mainly used for educational purposes. Both, *Shellexpander* and *airfoil2becas* are available as a part of BECAS at http://www.becas.dtu.dk.

The Light Rotor project turned BECAS from a cross section analysis tool into a blade design tool.

The structural design of the 10MW reference turbine also allowed an assessment of the precision achieved by BECAS based finite element beam models when compared to computationally far more expensive 3D finite element shell models. Results of such a comparison were published and show excellent agreement. As a consequence the ABAQUS 3D finite element model was not used for stress analysis during the design of the reference blade, but BECAS was used for that purpose exclusively.

The design cycle used for the structural design of the reference blade was found to be slow. As a consequence many important design variables had to be frozen after performing only a relatively small number of iterations. For example, the root diameter of the blade was probably chosen too large. The large root diameter results in a relatively small wall thickness in the root region, which in turn promotes buckling and may make it difficult to integrate the root steel bolts. From a structural mechanics perspective the root diameter could be decreased without violating strength or stiffness requirements.

These experiences highlight the importance of using a fast design cycle in the early design phase. In order to facilitate such a fast design cycle an interface to BECAS was created in the Multidisciplinary Design Analysis and Optimization framework OpenMDAO. Another important contribution to a fast design cycle would be the development of a fast buckling analysis procedure in the OpenMDAO framework. Such a procedure could be based on analytical methods, or could be an extension of BECAS. Other future work includes the fatigue life analysis of the blade based on time series of local stresses and strains computed by BECAS.

The work on the structural design of the DTU 10MW reference wind turbine blade also showed that the assumed material properties and the chosen partial safety factors had a strong influence on the design and final blade mass. This should be kept in mind when comparing the mass of two blades of similar size, or when comparing blades of different size using scaling relations.

The structural design of a blade is governed by stiffness (tip displacement) and strength requirements (allowable stress/strain). The decision to prebend the DTU 10MW reference blade eased the tip displacement requirements and therefore led to a more strength governed design. The longitudinal strains associated with the ultimate load cases are very close to the allowable values, except from the root region and the tip region.

When BECAS started to be used for strength analysis in the *Light Rotor* project no composite failure criteria were implemented in BECAS yet. Therefore, strength analysis was performed using a simplified method, comparing the local longitudinal normal strain to allowable values. By the time of writing this report the Tsai-Wu failure criterion has been implemented in BECAS.

5.4.3 *Blade topology optimization*

In this section a study on topology optimization of the *DTU 10MW RWT* blade structure is presented. The goal of the investigation is to find out if existing topology optimization tools can produce reasonable blade topologies and if the results are in any way similar to the blade designs existing nowadays. The study is also aimed at highlighting the issues related to the topology optimization process applied to the wind turbine blade structures. Below the method and results from the analysis are described.

- *SIMULIA Tosca Structure - topology optimization software*
  The chosen optimizer is SIMULIA Tosca Structure software package in version 8.1.0 by Dassault Systems. It is known to be one of the most advanced commercial optimization software packages presently available on the market. Tosca is essentially a set of scripts that provide optimization routines and use external commercial codes as finite element (FE) solvers. The FE model of the subject is to be developed externally within the chosen FE code and to be fed into Tosca. Later on the user sets up the optimization problem with Tosca, and further, the software ensures proper data exchange with the FE solver during the optimization process. Tosca can cooperate with different commercially available finite element codes like: ABAQUS, ANSYS, NASTRAN, etc. Presently ABAQUS is used for the blade FE model development and as a FE solver.

  One of the few limitations of the existing Tosca software version is that it is incapable of handling multiple materials. That means that anisotropic properties of composite materials such as glass- or carbon-fiber reinforced plastics (GFRP and CFRP acc.) could not be fully utilized. For this reason only single-material topology optimizations were performed within the present investigation.

- *DTU 10MW RWT blade geometry and mesh*
  The DTU 10MW RWT blade is a long slender structure with 86.35 meter between the root and the tip. The outer blade surface is originally formed by ca. 100 cross-sections - the airfoils designed for this blade. For simplification reasons this cross-section set was rarefied such that there is at least 1 meter between the neighbor cross-sections. To create a solid 3D blade geometry from the given airfoils ABAQUS CAE tool called “loft” was used. The obtained 3D solid blade body was further cut by planes at five radial positions where later the loads were to be applied: 16.68m, 33.46m, 51.35m, 68.28m and 85.43m from the blade root.

  As mentioned, Tosca software cannot handle multiple materials and only single material was used in the optimization problems. GFRP is most widely used material for the blade load carrying structures and thus the material chosen for the blade FE model is linear isotropic with the same Young's modulus and density as of GFRP.

- *Load case*
  Flap-wise bending load case is chosen for the topology optimization problem of the RWT blade fully clamped at the root. The load case can be seen as a static equivalent of the maximum dynamic blade loading in operation calculated using aeroelastic code HAWC2. Following the *DTU 10MW Reference Wind Turbine* report, the maximum flap-wise bending moment at each cross-section occur for different design load cases (DLC) which makes this static load case not realistic but still a good approach for simulation simultaneous maximum loading of all blade cross-sections. The flap-wise bending moment originally calculated in the elastic axes coordinate system at each radial position is transformed to the blade coordinate system creating two bending moment components along the blade. The distribution of the bending moment components along the blade is approximated by applying concentrated forces at five stations along the blade length. Each force is applied to the master node arranged at the cross-section elastic center position. The master node is then coupled with all the nodes of the cross-section so that the load applied to it is uniformly distributed among all the nodes of the cross-section.

- *Topology optimization problem formulation*
  After a number of trial optimization problem setups on the *DTU 10MW RWT* blade FE models with coarse meshes it was decided that for the final fine mesh blade FE model the optimization problem is to be setup as minimization of the blade compliance under prescribed loading conditions with constraint on the total material volume. The given volume constraint is equivalent to the blade mass constraint due to presence of only one isotropic material in the problem. The limit is set to 5% of the full solid blade total mass. This value corresponds to the blade mass of slightly higher than the original blade structure design. Setting lower limits on the volume can rise convergence issues due to FE mesh being not fine enough. This problem has been observed during trial optimization runs on coarse FE meshes.

  All the finite elements were considered as design variables. The elements to which boundary conditions and loads were directly applied were automatically excluded by Tosca software from the design variables. The sensitivity based algorithm was used with the maximum number of iterations limited to 50 in addition to the default stop condition defined by the Tosca software.

- *Results*
  The topology optimization for the *DTU 10MW RWT* blade meshed with 10-node tetrahedral elements with average size of 0.1 meter was executed on two CPU cores running at 2.8 GHz with 128 GB available operative memory. Fifty iterations took nearly two weeks to be finished. The problem converged to a stable value already at the 30-35th iteration, but the optimization continued until the iteration limit was reached, see Figure 22. The volume constraint was satisfied with a certain margin to the maximum allowed value.

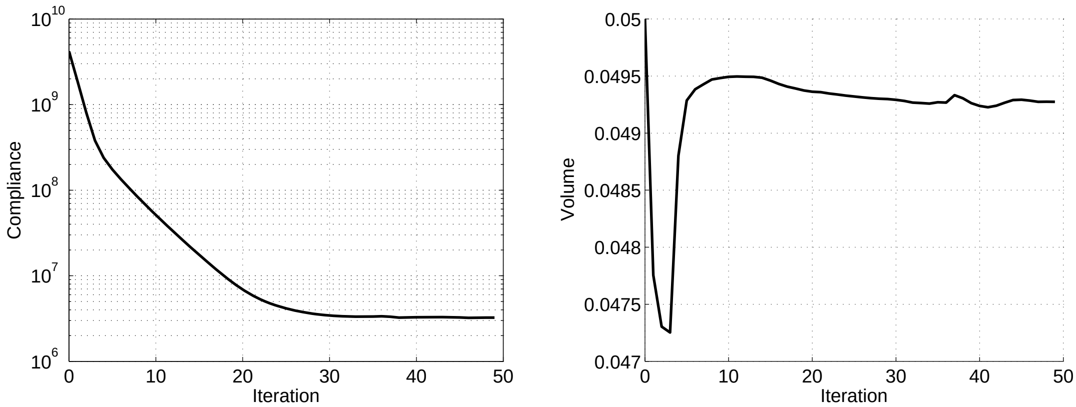

Figure 22 Variation of DTU 10MW RWT blade compliance and volume(mass) during optimization process.

The results of the optimization process are presented in two formats: Original output and smoothed output. The original output implies visualization of the elements, where material density is non-zero, therefore excessive areas with very sparse material are visible. In contrast, the smoothed output is obtained by passing the original output through a built-in Tosca post-processor with the default parameters so that the sparse material is removed. Overview of the optimized structure as top view and side view, are given in both formats in Figure 23 and Figure 24.

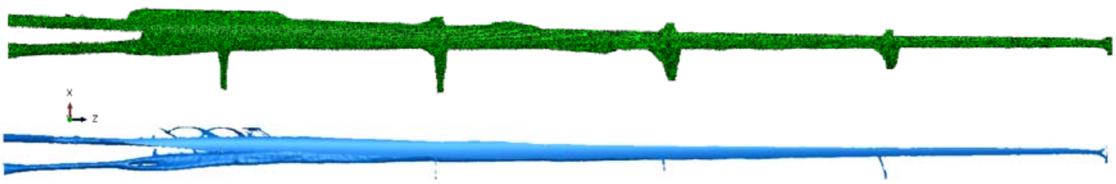

Figure 23 Optimized RWT blade structure, top view. Top - original output, bottom - smoothed output.

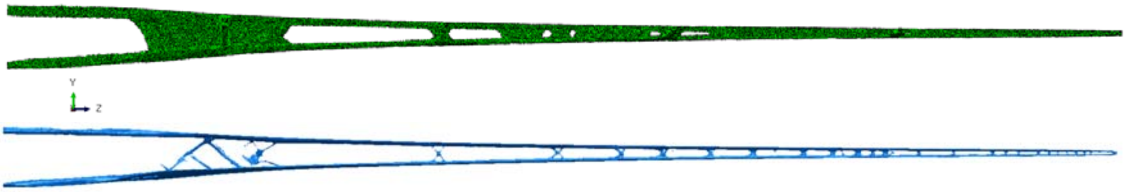

Figure 24 Optimized RWT blade structure, side view. Top - original output, bottom - smoothed output.

First thing that attracts attention is appearance of two separate spar flanges on both pressure and suction sides of the blade. The flanges seem to be not straight along the blade length. Their ends at the blade root are found to be placed in such a way that the structure most probably ensures effective resistance to the total bending moment at the root. The spar width does not vary significantly with the blade length even though some thinning of the flanges occurred near the root section. This is more pronounced in the smoothed structure and could likely be caused by the smoothing process configuration.

Next, appearance of some kind of ribbed structure can be seen at the leading edge near the blade root. The ribs are visible in the smoothed output and are 45° inclined with respect to the blade pitch axis. The rib orientations clearly indicate that they provide higher shear stiffness of the blade structure at the root, where the shear loads are at their maximum. While appearance of the spar was anticipated, this ribbed substructure is something new and is not known to be used in application to blades.

A number of small connection ribs/bridges also appeared between the spar flanges along the most of the blade length. In the figures with the original output they look solid, but the pictures with smoothed output reveal their frame-like structure especially closer to the blade root. Again the predominant orientation of 45° to the pitch axis of the small ribs indicates their shear resistance function.

Based on the results of the trial optimization runs the five thickenings found along the blade, cf. Figure 23, are known to be caused by the loads applied at these positions. Their positions correspond to the positions of the cross-sections where the concentrated forces are applied. Furthermore, it has been observed, that the cuts made to the 3D solid blade for further load application also cause similar material appearance around the cut surface. For example, when 100 cuts were made along the blade and the loads were applied only at five cross-sections, extra material appeared at all 100 cut surfaces and the final optimized structure seemed like having ribs for no good reason. This tells that the meshing process can significantly affect the topology optimization results.

The flap-wise displacement of the blade tip is found to be 14.7 meter. This parameter has not been constrained or anyhow explicitly mentioned in the present optimization problem, but is always of strong interest and therefore is reported here. An isometric view of the entire optimized blade after smoothing is given in Figure 25.

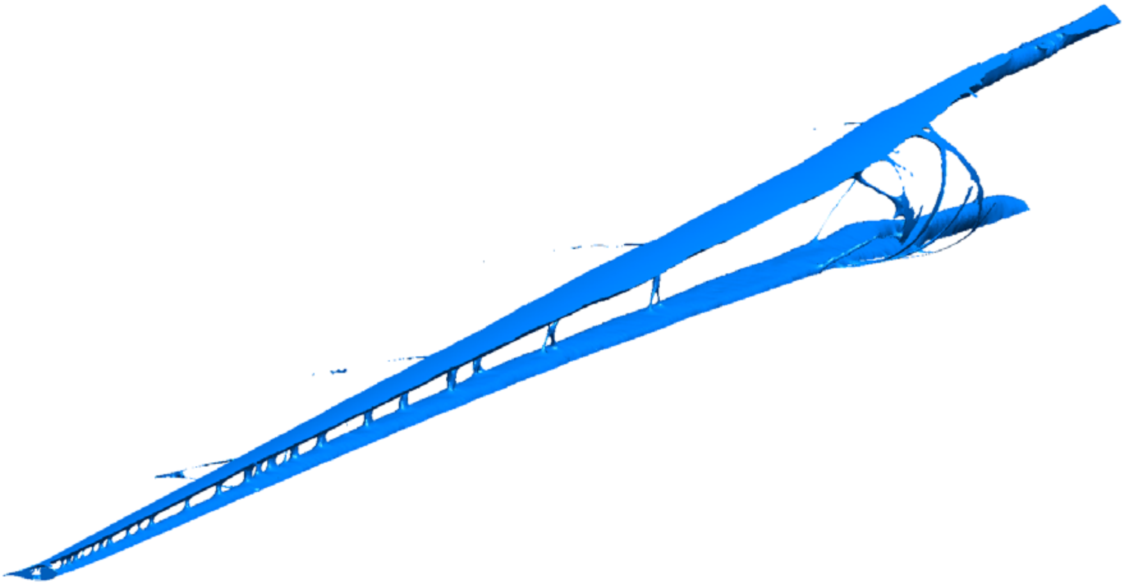

Figure 25 Overview of optimized RWT structure. Smoothed.

5.5 Summary

The results described in Chapter 5 can be divided into four subjects. A summary with the most important findings is given below.

- Integrated design: OpenMDAO
  Development of a frame work, where integrated design can be carried out. This frame work is based on the open source code *OpenMDAO* and coupling different tools to this, numerical optimization of the inter-disciplinary set up can be carried out. Connections are build up between existing simulation tools and the frame work to be able to use the existing tools in a multi-disciplinary optimization complex. The tool is developed to a level where both airfoil design and aeroelastic rotor design can be carried out. Demonstrations of the tool are shown in terms of the new Light Rotor Project (LRP) airfoils and examples of new rotor designs.
- Airfoil design
  - Test of two existing FFA-W3-xxx airfoils with relative thickness of 30.1% and 36.0%, which serve as references for the further airfoil design and for investigation of the use of vortex generators.
  - Investigation of the relation between the structural stiffness of airfoils and the design lift and the lift-drag ratio showing that the flapwise stiffness can be obtained also with highly cambered high lift airfoils if the relative thickness is increased.
  - Design of the Light Rotor Project (LRP) airfoils family, where advanced flow simulations, Computational Fluid Dynamics, have been used to predict the performance and where the balance between aerodynamic performance and structural stiffness has been investigated. Two of these airfoils with high aerodynamic performance and maintaining the structural performance were furthermore tested in a wind tunnel and showed the expected performance.
- Aero elastic rotor design
  - Establishment of a 10 MW reference wind turbine that is now used worldwide, the DTU 10MW Reference Wind Turbine or in brief *DTU-10MW-RWT*. The turbine can be found at [http://*dtu-10mw-rwt.vindenergi.dtu.dk*](http://dtu-10mw-rwt.vindenergi.dtu.dk), where all kinds of details are described so that it can be modeled in detail and where it can be downloaded for free. This turbine has been designed using traditional methods and concepts and serves as a reference for further designs of rotors, but also for other components. The *DTU-10MW-RWT* has attracted much attention and is now used in several national and international projects like the very big EU project *InnWind*.
  - Design of rotors to obtain more energy production for the same rotor weight or the same energy production at lower rotor weight compared to the *DTU-10MW-RWT*. Rotors with two different airfoil families have been designed; one set of rotors using the commonly used FFA-W3 airfoils and one set of rotors using the LRP airfoils developed in the Light Rotor project. The blade mass was reduced significantly for both families although the lowest achieved mass was found for the LRP-based blades. However, blades with a strong bias towards reduction of mass were not very efficient aerodynamically and produced a lower AEP compared to the DTU 10MW RWT blade. One design stood out in the LRP family, which was the design with main focus on the power, 95% on power and 5% on reduction of mass, which achieved the highest AEP of all designs with an increase of almost 2% compared to the *DTU 10MW RWT*, while the mass was reduced by 12%. This opens up for design of bigger rotor diameters to the same mass and thereby bigger energy production.
- Structural design
  - BECAS is a general purpose, finite element based cross section analysis software. It determines cross section stiffness and mass properties of almost any type of beam cross section. The Light Rotor project turned BECAS from a cross section analysis tool into a blade design tool and can now be used in a multi-disciplinary framework with automated procedures and prediction of structural performance.

- Topology optimization of the entire DTU 10MW RWT blade was carried out to explore the possibilities for rotor weight reductions by changing the structural lay-up of the blade. Topology optimization of blade in maximum flap-wise bending load case revealed anticipated spar-like structure with two flanges and some shear support components that are generally not too far from the existing shear webs concept in blades. The unexpected result was a ribbed structure that appeared near the root area at the leading edge side. With the ribs at 45° to the blade pitch axis with its main function to increase resistance to shear loads.

6. Utilization of project results

The objective of the Light Rotor project was to develop the basis for design of wind turbine blades for use on the order of 10MW rotors with lower weight, tailored aeroelastic response and optimized aerodynamic efficiency. Thus, considering the great potential and the distance to the market, much of the work in this project was focused on research, which was necessary to push the existing blade design towards significantly lower cost. Despite of the main focus on research, the work in the project created much knowledge and several products that can be utilized after the project. The main output is listed below.

- The FFA-W3 airfoil measurements have created new knowledge about the performance of the commonly used airfoils. Also, more knowledge about the installation of vortex generators and Gurney flaps has been created.
- The LRP airfoil family with high aerodynamic and structural performance that was designed exclusively for Vestas. These airfoils are now in the Vestas portfolio of airfoils and might be used when reviewed in future blade design projects internally in Vestas. The blade design work in this project has demonstrated the advantage of these airfoils.
- The multi-disciplinary design framework, OpenMDAO that is now dedicated airfoil design and blade design, including aerodynamics, structure and aeroelastic degrees of freedom. This framework is open source, but the simulation codes coupling to this framework, like aerodynamic, structural or aeroelastic tools are not part of the framework and therefore gives DTU the possibility to license more design tools such as Becas, Hawc2, HawcStab2 or EllipSys.
- The DTU 10MW Reference Wind Turbine (DTU 10MW RWT) has been designed and is used by more than 260 persons Worldwide. These persons are mainly located in Europe, but also China, India, US and more are represented. The persons are both from the research society, but also from manufacturers, where development engineers need an example of large wind turbines to study different trends. The DTU 10MW RWT is used in several national and international research projects and has ensured several contacts, and ensured that DTU is part of networks, where they did not participate before the Light Rotor project was carried out. Further to this, the DTU 10MW RWT is now used in the education of PhD and Master students for them to learn about loads, aerodynamics and control of wind turbines.
- The project demonstrated that multi-disciplinary procedures can create designs that is both more light weight and generates more energy. Even though designs cannot be created with just a “push at a button” it reflects some design directions that can be investigated in specific future blade designs. Thus, the work demonstrated that the many disciplines included in the blade design loop with advantage can be included simultaneous in contrast to the common way of designing, where the design is sequential considering each discipline at a time.

The Light Rotor project carries out research in several areas strategically important to Vestas.

- The project provides a useful benchmark for up-scaling current technologies to 10MW reference rotor size, which is a good approximation of the next generation offshore blade, and therefore highlights the gaps and challenges, which need to be overcome for these blades to become technically and commercially viable.
- The OpenMDAO optimisation framework developed and applied within the project could potentially become an 'industry standard' and Vestas is looking into adopting this framework for development of its future products. This would also further enhance its collaboration with DTU and accelerate adoption of outcome of future research projects, since implementation of new simulation methods could become significantly more cost effective when developed within a common software framework.
- The key element of the project is development of new and improved techniques for airfoil design and optimisation, and specifically airfoils with improved structural efficiency, which enable the goal of further structural optimisation of future blades. This is of vital importance to Vestas and the plan is to adopt the outcomes of the project - both the airfoil designs as well as the design technique - in its future product range. This will enable both up-scaling to the rotor sizes

beyond the current technology limits for offshore blades, as well as development of longer and more slender blades for low wind onshore sites - both markets with a strong growth potential.

- In addition to the airfoil design and optimisation the project has carried out an important research on aerodynamic devices such as Gurney flaps and Vortex generators, which can further enhance the blade performance. The project developed both simulation techniques as well as experimental data, and the outcome of the project feed directly into a Vestas program of aerodynamic enhancements of its current product fleet, bringing additional value to its customers and new revenue stream into Vestas.

With the demonstration of the aeroelastic rotor design showing e.g. 2% increase in energy production and 12% decrease in rotor mass, future blade designs will likely be more cost effective. This will clearly contribute to the realization of the energy policy objectives.

7. Project conclusion and perspective

The objective of the Light Rotor project was to develop the basis for design of wind turbine blades for use on the order of 10MW rotors with lower weight, tailored aeroelastic response and optimized aerodynamic efficiency. This objective was successfully met. The main conclusions from the project are:

- The basis for design of airfoils and +10MW rotors was developed in terms of the OpenMDAO integrated design complex. This complex couples many disciplines and makes a simultaneous aerodynamic, structural and aeroelastic design possible.
- The simulation tools that were coupled to OpenMDAO were developed, and formats for data exchange was harmonized.
- It is possible to design airfoils that compared to existing airfoils have higher aerodynamic and structural performance. A result of this was the LRP airfoils that were designed and tested in a wind tunnel and showed improved performance compared to the reference airfoils.
- It is possible to design rotors that are lighter and produce more energy compared to the reference wind turbine established in the project and compared to common trends in the increase of mass as a function of blade size. One realization of a rotor design showed 2% increase in energy production and in the same time 12% decrease in blade mass.

Overall the project demonstrated that blades can be optimized further compared to state-of-the-art. The developed design tools and methods need to be implemented in companies and realized in products to obtain full impact.

8. Publications

Publications carried out in the Light Rotor project:

- Christian Bak, Mads Døssing, Slender blades reduce the loads, Wind Turbine Blade Manufacture 2011, 7-8 December 2011, Düsseldorf, Germany
- Christian Bak, Robert Bitsche, Anders Yde, Taeseong Kim, Morten H. Hansen,Frederik Zahle, Mac Gaunaa, José Blasques, Mads Døssing, Jens-Jakob Wedel Heinen, Tim Behrens, Light Rotor: The 10-MW reference wind turbine, EWEA Copenhagen, 16-19 April 2012
- Mac Gaunaa, Frederik Zahle, Niels N. Sørensen, Christian Bak, Effects of Using Slats on the Inner Part of a 10MW Rotor, EWEA Copenhagen, 16-19 April 2012
- E. Branlard, K. Dixon, M. Gaunaa, An improved tip-loss correction based on vortex code results, EWEA Copenhagen, 16-19 April 2012
- Frederik Zahle, Mac Gaunaa, Niels N. Sørensen, Christian Bak, Design and wind tunnel testing of a thick, multi-element high-lift airfoil , EWEA Copenhagen, 16-19 April 2012
- Branlard, Emmanuel Simon Pierre; Dixon, Kristian; Gaunaa, Mac., An improved tip-loss correction based on vortex code results. Proceedings of EWEA 2012 - European Wind Energy Conference and Ex-hibition. EWEA - The European Wind Energy Association, 2012.
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- Blasques, José Pedro Albergaria Amaral; Bitsche, Robert; Fedorov, Vladimir; Eder, Martin Alexander, Applications of the BEam Cross section Analysis Software (BECAS), Proceedings of the 26th Nordic Seminar on Computational Mechanics. ed./ A. Logg; K.-A. Mardal; A. Massing. Center for Biomedical Computing, Simula Research Laboratory, 2013. p. 46-49.
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9. Acknowledgements

The Light Rotor project has produced many important methods, tools and results and shed light over the design of very large wind turbines in the size of 10MW. The project participants want to thank EUDP for supporting the project and make it possible to realize the project.