Final report

1.1 Project details

Project title	Industrial adaptation of a prototype flap system for wind turbines
Project identification (program abbrev. and file)	Journalnr.: 64010-0458
Name of the programme which has funded the project	EUDP 10-II
Project managing company/institution (name and address)	Technical University of Denmark DTU Frederiksborgvej 399, Campus Risø, DK 4000 Roskilde
Project partners	Hydratech Industries Rehau Dansk Gummi Industri DTU
CVR (central business register)	30060948
Date for submission	01-02-2015

1.2 Short description of project objective and results

English version:
The overall objective of the project has been to develop a prototype active trailing edge flap system for a wind turbine blade. At the beginning of the project the development stage of the technology was that the functionality of the flap system had been tested under laboratory conditions. During the project the corporation between DTU, which originally had developed the system, and the three industrial partners should transform the technology from a laboratory level to an industrial manufacturing and application stage.
This has been achieved for most parts of the technology. New flap designs have been developed and one type has been manufactured in an industrial extrusion manufacturing line. The powering system of the flaps has been developed by the industrial partner Hydratech. Finally, an innovative rotating test rig has been designed and build where the flap system has been tested in a size and under conditions that are comparable with the conditions on a full scale turbine.

Dansk version:
Det overordnede formål med projektet har været, at udvikle et kontrollerbart flapsystem til vindmøllevinger. En prototype af flapsystemet var forud for det aktuelle projekt afprøvet under laboratorieforhold og funktionsprincippet eftervist. Gennem

projektet, med deltagelse af tre industrielle partnere, har målet været at videreudvikle teknologien til et pålideligt og robust lastkontrolsystem for fuldskalavindmøller og demonstrere, at fremstillingen af systemet kan forgå i en industriel produktionsproces.
Indenfor de fleste områder af udvikling af teknologien er de ønskede mål nået. Flere ny flapdesigns er udviklet, og én er efterfølgende fremstillet i en industriel ekstruderingsproces. Aktiveringssystemet af flappen er udviklet af den industrielle deltager Hydratech. Endelig er der indenfor projektet blevet udviklet en innovativ roterende afprøvningsstand, hvor det udviklede flapsystem er afprøvet i en størrelse og under forhold, der er sammenlignelige med forholdene på en fuldskala mølle.

1.3 Executive summary

The background for the initiation of the project in 2011 was an invention in 2006 at DTU (former Risø National Laboratory) of a morphing trailing edge flap concept, the so-called **C**ontrollable **R**ubber **T**railing **E**dge **F**lap (**CRTEF**), which was patented same year (2006). Before that time research on trailing edge flaps for wind turbines had shown, based on numerical simulations that there were big load alleviation potentials by using flaps or morphing trailing edges on wind turbine blades.
After the invention followed 4 years research and development work at Risø with the objectives of proving the concept and documenting its performance. The work comprised manufacturing of small prototypes that were tested in the laboratory and late 2009 a wind tunnel test was conducted that showed good aerodynamic performance of the CRTEF.
The present project has then had as overall objective to develop the technology from a stage where the functioning has been proven under laboratory conditions to a new stage where the technology is adapted to industrial manufacturing processes and where the flaps are tested under conditions closer to what is present on a full scale turbine. The research work to fulfil these objectives was carried out in the present INDUFLAP project with three industrial partners, Rehau, Hydratech and Dansk Gummi Industri working together with DTU.
The research and development work has been organized in five work packages. The design work on the flaps in WP1 has led to the conclusion that the flap design with voids in spanwise direction, and thus well suited for manufacturing in an extrusion process, are superior in robustness compared with the other flap design with voids in chordwise direction. Further the chosen flap design has few parts and in a mass production the few parts can be co-extruded which gives a high robustness.
In the work on flap manufacturing in WP2 it has been demonstrated by the partner Rehau that the chosen flap design can be extruded. Several meters of flap has been extruded and other manufacturing processes as e.g. the gluing of the end covering plates have been developed. The 2m long flap prototype for testing in WP4 on the rotating test rig was also manufactured.
The industrial partner Hydratech has studied the powering options, hydraulic or pneumatic, for activating the flap. A new pneumatic system was developed that reduces the necessary power considerably. The system was then designed and built for the 2m long blade section with the flap that was tested in WP4. During the project work it became clearer, e.g. based on input from end users (wind turbine manufactures) that the pneumatic system has too many components and that a hydraulic system seems to be preferable. Hydratech has therefore sketched a hydraulic system for a full scale turbine.
The biggest challenge in the project has been the development, design and building of the rotating test rig which is thought as a testing method that is between wind tunnel testing and full scale testing on a MW turbine. There is no similar test rig in

the world so the development had to be based on simulations and experience from other engineering fields. The building of the test rig has attracted visits by other groups working with flap technology, e.g. from DLR in Germany. At the end the test rig was finished in June 014 and after some time for the final instrumentation the tests could be initiated in the late summer 2014. Experiments were conducted for a rotational speed up to 30rpm with the blade section on the 10m long boom and it gives a *g* loading that is comparable with what is present on a MW rotor on the outboard part of the blade. The flap system sustained this loading which was a key result of the experiments. An important result is also that the measured performance of the flaps system showed that about 3 deg. change of flap angle gives the same change in load as 1 deg. change in pitch. This is somewhat lower than the 2 deg. flap for 1 deg. pitch that has been modelled. However, in the models the atmospheric flow characteristics are typically not taken into account so the present findings thus indicate how important it is to test in real operating conditions on a small scale before going to MW turbine application. A final important result is that the time constants of the flap system using the pneumatic powering system are too high and the hydraulic powering system should be tested in the future.
Based on results of the above described work packages an overall sketch of the components of the flap system for a full scale turbine has been derived. The main objective of the last work package WP5 has then been to estimate the load alleviation potential of the flap system implemented on a MW turbine. An aeroelastic model of a 5MW turbine has been used as basis and a flap covering about 30% of the radius has been used. The simulations have comprised almost all the cases that are necessary in an industrial certification process. The flap alleviation potential has been compared with the load alleviation that can be obtained with cyclic pitch which is the industry standard today. However, the use of the cyclic pitch is not so widespread because the wear of the pitch bearing is a problem. The simulations show that the flap technology gives the same load alleviation as the cyclic pitch. Therefore there is a good basis for future studies comparing the costs of the flap technology with the costs of cyclic pitch systems and the maintenance of such systems.
Finally, a PhD work on lightning risk and lightning protection of the flap system has been carried out within the project. Comprehensive numerical and experimental studies of lightning resistance of the different considered flap materials have been carried out. At the end a full-scale lightning test on a 2m blade section with the flap was conducted and no major damage was found on the flap. This was a very import result as the lightning risk is one of the concerns from wind turbine manufactures by implementing the new technology.
During the end phase of the project the INDUFLAP project group presented the flap technology for Siemens Wind Power at two meetings. Siemens has expressed interest in corporation with the INDUFLAP partners on a further development of the technology with the objective at a suitable time to test the concept on a full scale turbine.

1.4 Project objectives

Background for the project

Research on trailing edge flaps during the last 10 years comprising numerical studies have shown substantial potentials for load alleviation on wind turbine blades as well as on other turbine components (in the order of 20 to 40 % reduced fatigue loads), even with reduced pitch activity of the blades. Fully exploited this will lead to reduced cost of energy from wind turbines. However, a very important precondition is the adaptation of adequate functional principle and technology of the flap systems. The unambiguous requirement from the wind turbine industry is that the flap system is robust, reliable and does not add new costly requirements for service and replacements. One promising flap technology is the so-called "Controllable Rubber Trailing Edge Flap" (CRTEF) developed at DTU (former Risoe) from 2005-2009 and patented in 2006. The functionality is simple as the flap deflection is controlled by pressurized air or a fluid in a number of voids in the flap made of elastic material.

Objectives

The overall objective of the project has now been to develop the CRTEF system from its stage (2010) of proven functionality under laboratory conditions to a new stage (2014), where it constitutes a complete, reliable and robust flap system for a full scale turbine. This is a challenging task as the operational conditions on the rotating blade of the turbine are much different from the laboratory conditions, where the flap system has been tested so far. The real operational conditions include the risk of lightning; the influence from radiation from the sun and the external loads on the system covering centrifugal forces and blade vibrations.

1.5 Project results and dissemination of results

Project organization

The project work has been organized in the following five work packages:

WP1 Design/optimization of flap prototypes and integration in blade
WP2 Manufacturing and testing of flap prototypes
WP3 Design of pneumatic/hydraulic power- and control system
WP4 Aeroelastic testing of flap/control system in rotating rig
WP5 Adaptation of flap system for prototype test on a full scale turbine.

The project work and results have been reported in 6 separate reports [1,2,3,4,5,6] where report [1] mainly is reporting of WP1 and WP2; [2] is reporting of parts of WP3; [3,4] is reporting of WP4 and also partly on WP3 and finally is [5] reporting of WP5. Then as an important part of the project a PhD study on blade lightning issues and protection has also been part of the INDUFLAP project and the final PhD report is [6].

WP1 Design/optimization of flap prototypes and integration in blade

Objectives of WP1

- define design requirements for a robust flap system
- clarify lightning risks for flap system and sensors and adapt design requirements
- develop new flap designs with improved performance and robustness, considering material selection and manufacturing process
- investigate different designs for attachment of flap system to the main blade

Results of WP1

The original invented flap design originating back from 2006 had two basically different designs as shown in Figure 1. Flap design 1 shown to the left in Figure 1

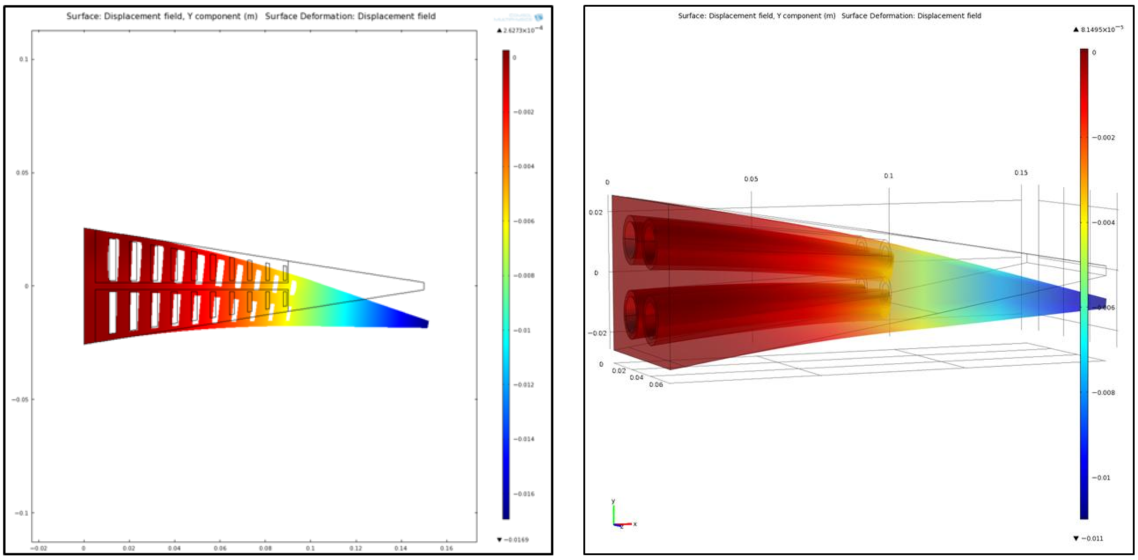

Figure 1 The two basically different flap designs; to the left flap design 1 with spanwise voids and to the right flap design 2 with chordwise voids.

has voids in spanwise direction (length direction of blade) and is thus well suited for manufacturing in an elastomeric material using an extrusion process which is the key competences of one of the industrial partners in the project, Rehau. The manufacturing will be described under WP2. The drawback of the extrusion manufacturing process is that the flap then will have constant dimensions along the span which is not fully compatible with the requirements on a real wind turbine blade where the dimensions change along the blade span.

The optimizations of the blade designs have comprised extensive finite element simulations requiring a lot of computing time. The simulation time for the fine grid (lower model in Figure 2) for one pressure level (one deflection) was 17 hours whereas the coarse grid used on the upper model took only 15 minutes.

One of the optimizations that have been carried out had the objective to find the optimal shape of the voids. As an example it is illustrated that going from sharp corners of the voids (upper model in Figure 3) to rounded corners (lower model in Figure 3) reduced the stress level on the surface of the flap as seen in Figure 4. The yellow color corresponds to a high stress level and has almost been removed on the optimized design shown as the lower model in the figure.

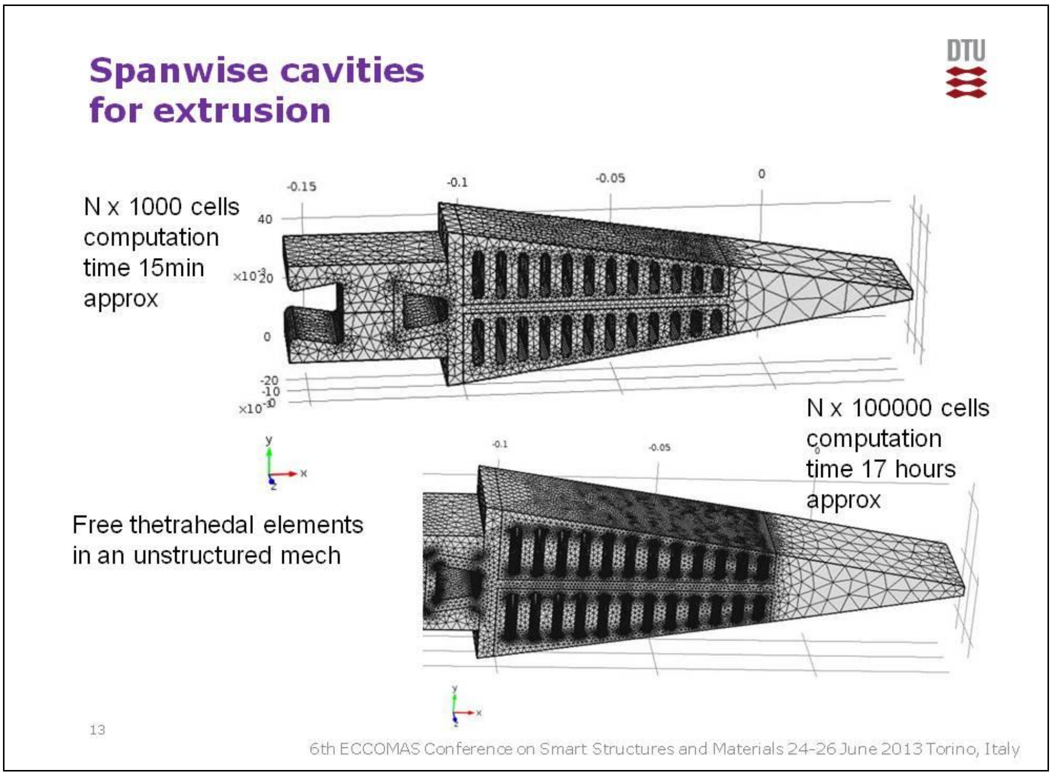

Figure 2 3D finite element model of one flap design using a corase grid (upper model) and a fine grid (lower model).

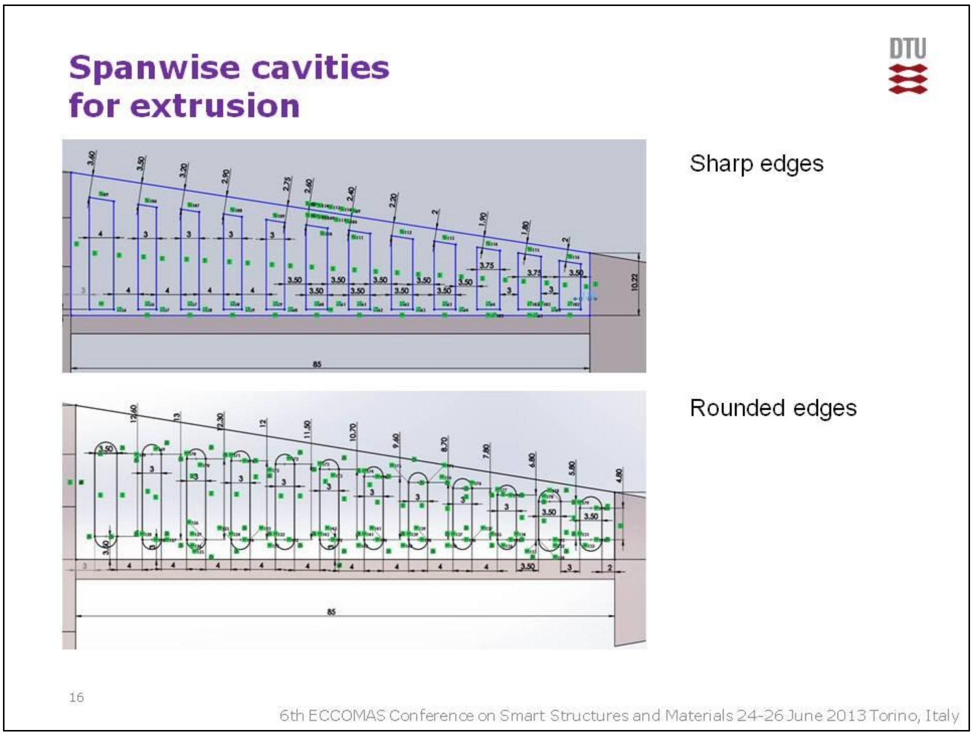

Figure 3 The detailed geometry of the voids has been investigated. Upper model with sharp corners and lower model with rounded corners.

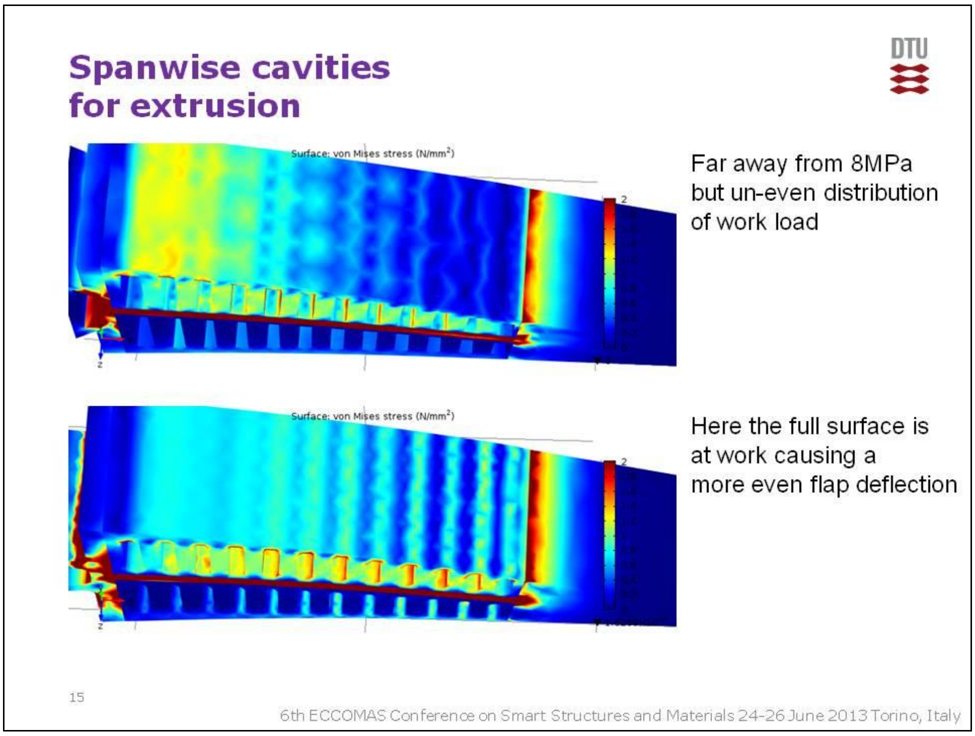

Figure 4 The influence on the stress level from the design of the voids. Upper model with sharp corners of the voids has a higher stress level on the surface (blue low, yellow high level) than the lower model that has rounded void corners.

The final design of flap type 1 is shown in Figure 5 including the developed system for integration in the blade. The connecting system also shown in Figure 6 is developed so that the flap can easily be mounted on the blades at the site of the turbine so that damage during the transport of the blades can be avoided. It is also designed in a way so it allows a change of the flap on a blade mounted on the turbine if a repair is needed. This is a very important characteristic as this will lower the cost for maintenance.

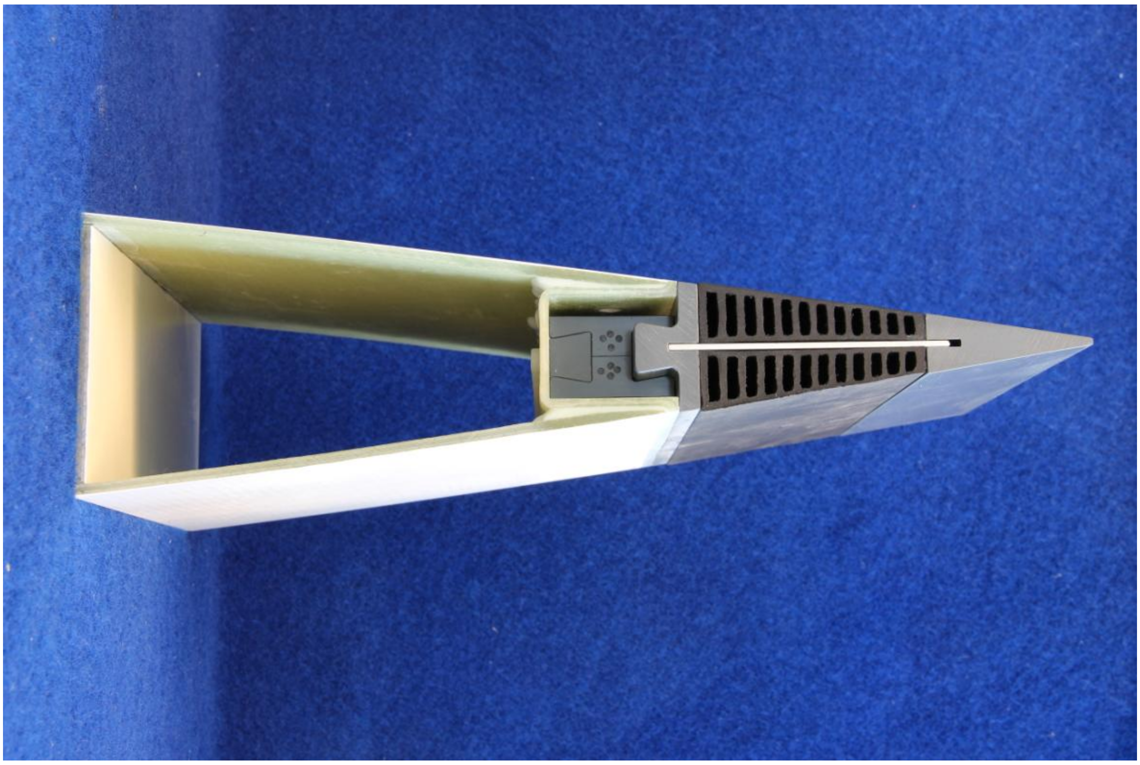

Figure 5 The final design of the flap with spanwise voids including the developed system for integration in the blade.

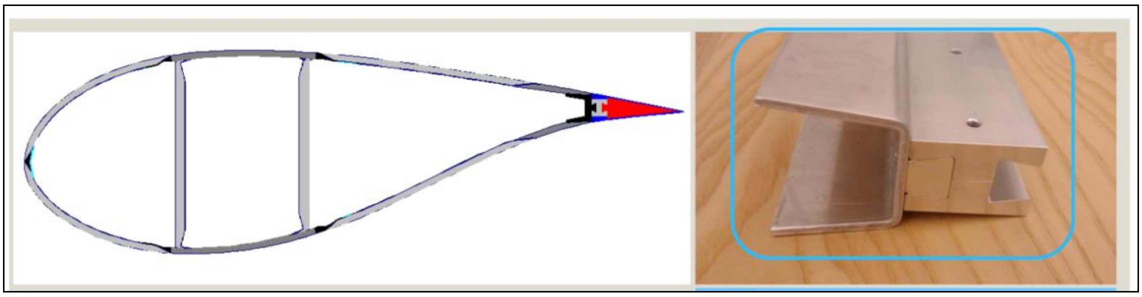

Figure 6 The system for connecting the flap to the blade developed in the project.

WP1 – Lightning, PhD project

Regarding lightning protection of blades equipped with the developed flap system Controllable Rubber Trailing Edge Flap (CRTF), the project objectives were covered by focusing on the following topics, the character of which emphasizes the complexity of lightning protection in wind turbines:

- Lightning attachment to wind turbine blades
- Lightning protection of wind turbine blades
- Lightning current and voltage distribution in wind turbine blades
- Degradation of rubber materials exposed to high electric fields
- Field measurements of lightning strikes to wind turbines

The list indicates the basic approach to the problem. Initially was worked with the general investigations, necessary for understanding the physical processes regarding lightning attachment on wind turbines followed by protection design and analyses including material aspects.
The initial investigations were characterized by simulation models, developed by the ph.d. student Anna Candela. High voltage tests were conducted in order to evaluate attachment processes and protection measures. This task is in particular challenging, since the structure in many cases is a combination of insulating, semi-conductive and conductive materials. The main approach here, FEM simulations in connection with experimental verification, turned out to be very suitable.
The high voltage laboratory work included testing of materials, small samples, model testing, Figure 7 and full size testing of prototype elements, Figure 8 and Figure 9.
Regarding lightning protection, the main task was design of flap and protection system and validation of lightning protection for the flap system. For a full verification, high voltage attachment tests were performed to the prototype and were related to the general findings under WP1.
The results of the swept channel attachment tests in the high voltage laboratory, Figure 8 and Figure 9, showed that the rubber material of the flap withstood the electric field caused by the leader sweeping the rubber surface without punctures or burns. The voltage applied during the tests in order to reach flashover generated an electric field higher than the value of about 140 kV/m expected from lightning in the field. Therefore, the prototype passed the tests with a very good performance.
The investigation of internal discharges that could not be measured during the swept channel tests was performed by means of FEM simulations. Two cases were compared, with the flap voids filled with air, as it was intended in the first design of the flap system, and with flap filled with polypropylene glycol, as it was decided for the final design and applied to the tested prototype. Although the change from compressed air to polypropylene glycol was made only to improve the mechanical performance of the flap system, it has proven to be an improvement regarding the interaction with electrical discharges, since it prevents partial discharges inside the flap voids, which could prematurely degrade the rubber material.
As seen in the publication list, many findings helped to improve the protection system design and also generated new understanding applicable to wind turbine blades protection and related equipment in general.
Since flap and other systems in modern blades require electronic and mechanic equipment, protection of these is essential. Current distributions were studied and the resulting voltages under lightning exposure were calculated by means of FEM simulations.
In addition to the attachment tests, material investigations were carried out in the laboratory, aiming at finding the most suitable flap material. The flap material chosen, showed satisfying electrical properties, comparable with other electric insulating materials.
The last topic 'Field measurements of lightning strikes to wind turbines' was mainly carried out by means of a stay of the ph.d.-student Anna Candela as guest re-

searcher at the US company EDP – Renewables in the period June – September 2013 (17 weeks).
Field observations of lightning strikes to wind turbines were conducted at EDP – Renewables and combined with analysis of lightning damage on blades performed in wind farms in US. The aim was to determine the mechanisms involved in the lightning attachment to wind turbines and to determine root causes of the lightning damage in blades.
This was a very seldom given opportunity and the ph.d.-student delivered very interesting results. The findings also resulted in a journal paper just being accepted for publication.

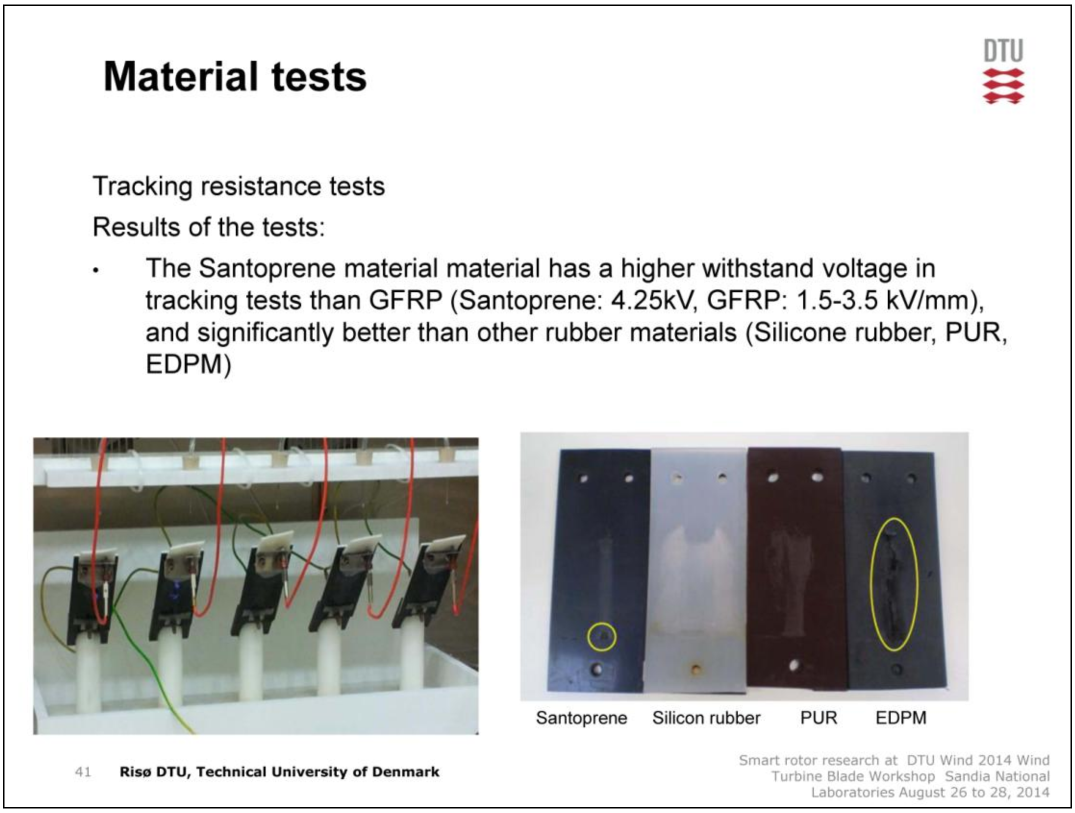

Figure 7 The chosen flap material Santropene showed good performance in the different tests performed in the lightning PhD research work [6].

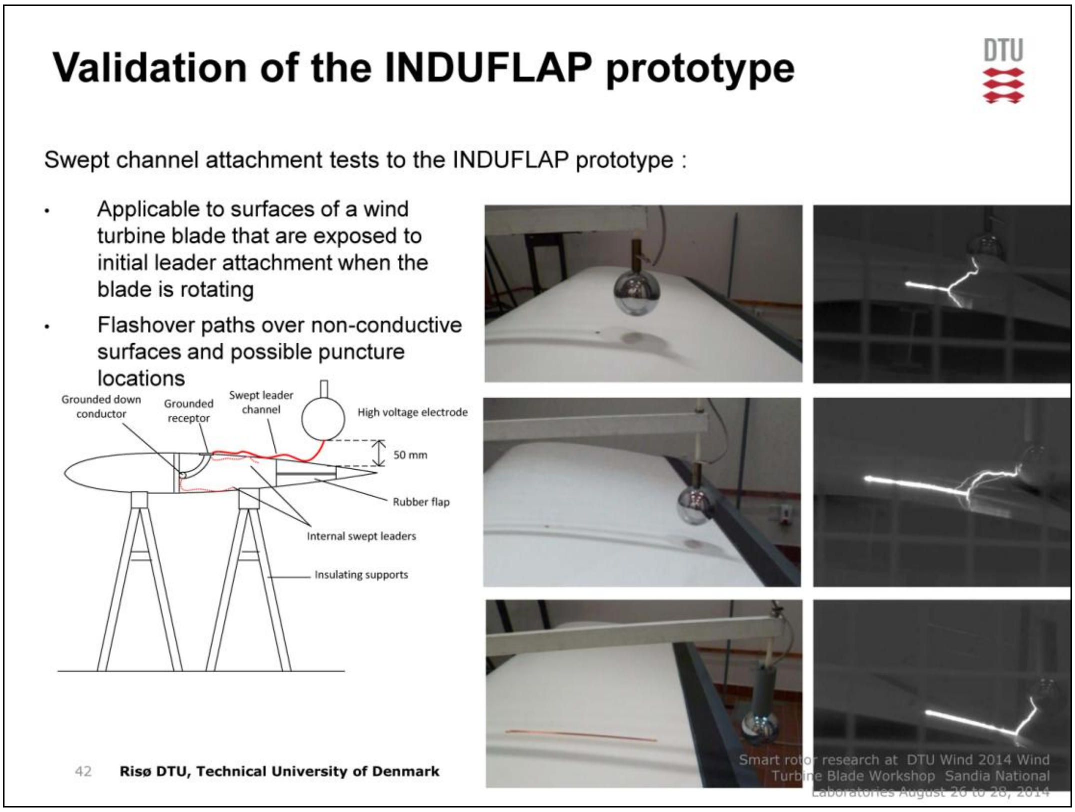

Figure 8 The lightning tests of the flap system were performed on a 2m long blade section with a 15% flap (the chord wise length of the flap is 15% of the blade chord). The scale of the blade is thus only slightly lower compared with the outer part of the blade on a MW turbine.

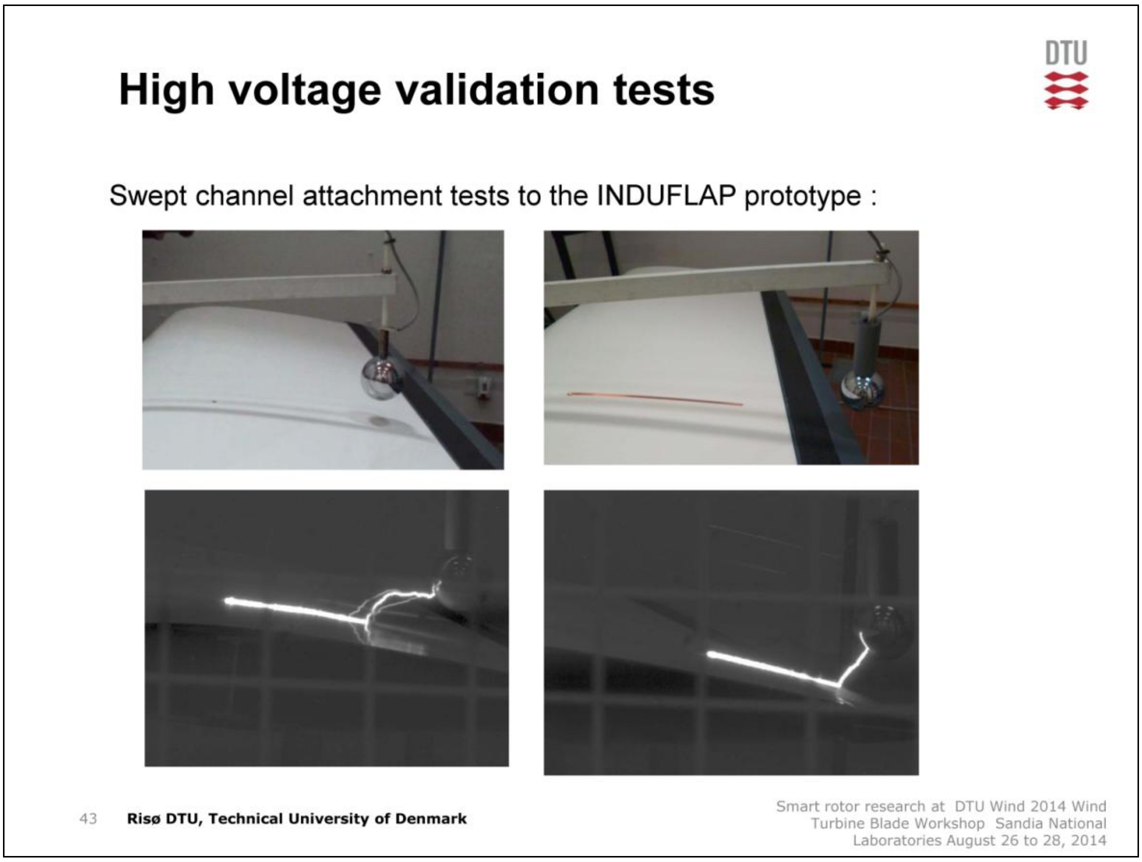

Figure 9 The blade section with the flap was exposed to lightning that hit the flap. No major damage was seen.

WP2 Manufacturing and testing of flap prototypes

Objectives

- manufacture 0.3m flap prototypes in different materials/fiber reinforcement and versions
- test 0.3m flaps in rig for response amplitude and time constant
- perform material tests and component fatigue tests
- manufacture two 2m flaps for aeroelastic testing in outdoor rotating rig

Manufacturing of flap type 1

Although this flap design is mainly intended for extrusion, as will be shown below, several 30cm flaps were mold manufactured to study different materials and different design details. The closing of the flap with an end cap is one of the design details that have been studied as shown in Figure 10 and afterwards tested in a test rig, Figure 11.
The extrusion of the flap in an industrial extrusion process has been demonstrated by the industrial partner Rehau. The tools for an extrusion process are expensive and the control of the production process is complicated. However, when all this has been solved in the initial prototype production a mass production can be conducted fast and at low relative cost. In the present case only a few meters of flap should be extruded and the different parts for the flap before assembling are shown in Figure 12. The assembled flap parts are presented in Figure 13 to the left in a fully non-metallic version and to the right is shown a flap with the parts glued together and with end caps.

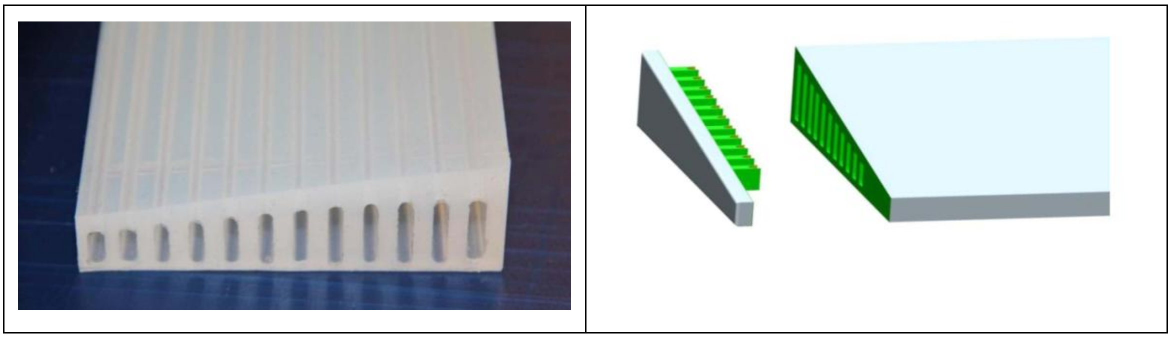

Figure 10 Mold manufactured flap with spanwise voids in order to study details of the gluing of the endplates shown to the right.

Figure 11 Testing of flap deflection as function of pressure in a small test rig.

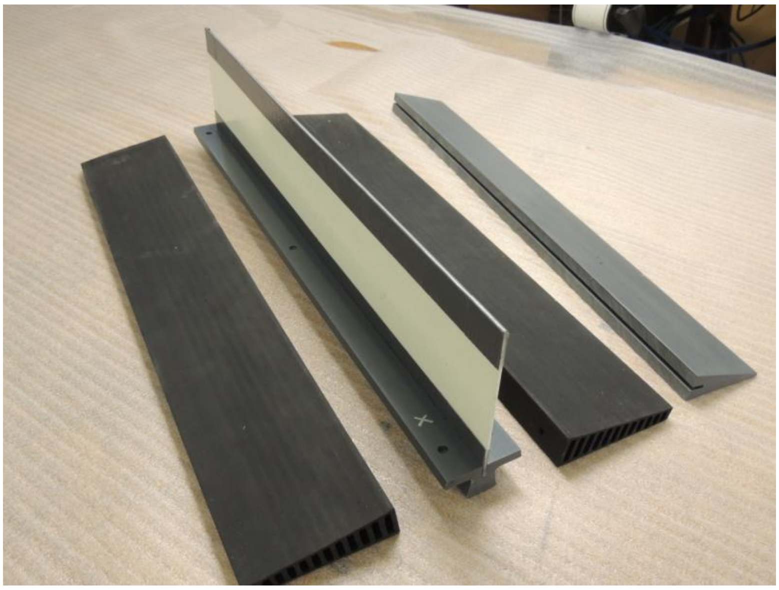

Figure 12 The two flap parts with voids were extruded whereas the other two parts were machined and glued together.

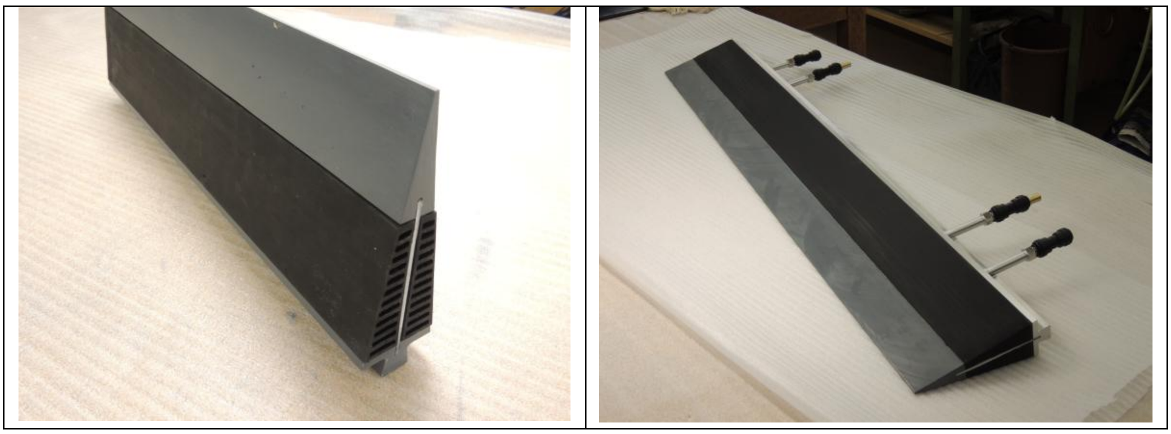

Figure 13 To the left the flap parts are assembled but not glued together (non metallic flap version). To the right a fully assembled flap with a few metal parts

Manufacturing of flap type 2

As mentioned above this flap type has the voids in chordwise direction and can only be manufactured in a mold. The big draw back with this design is that the voids have to be reinforced. Otherwise the expansion of the voids will deform the outer shape. Several different methods for reinforcement were tested. The use of metal springs is shown in Figure 14 and the method of using non-metallic springs can be seen in Figure 15.

Figure 14 Manufacturing of flaps of design 2 requires reinforcement of all the voids. In the present version it is with steel springs.

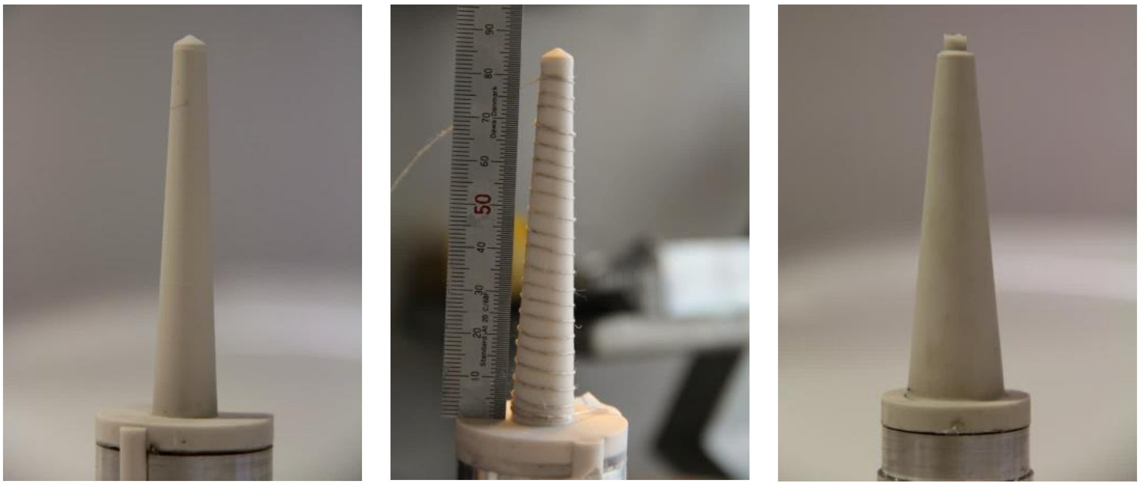

Figure 15 Concept for manufacture of non-metallic springs. Step1: Casting of inner liner, step 2: Winding of non-metallic spring element and step 3: Fixation of reinforcement by second casting.

The work with testing and manufacturing flaps of design 2 led to the conclusion that this design has too many parts and is too complicated to manufacture so that during the last part of the project all the flap design work was devoted to design 1.

WP3 Design of pneumatic/hydraulic power- and control system

Objectives

- Overall design of the flap power system for a full scale turbine including the control system in interaction with the pitch system and control sensors
- Design of the specific pitch/flap power system for the rotating aeroelastic test facility
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Results

The initial design studies on the flap powering system resulted in three main requirements:

- Weight: Low weight of the full system is essential to decrease the impact on the blade design as much as possible
- Time constant: The system must be able to achieve the time constants necessary to achieve the desired load alleviations. Aero elastic simulations showed that an actuation time of 100ms was desirable
- Environment: The system should have no leakages to the surroundings, which can harm the environment
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After setting up the requirement specification, different powering system possibilities were investigated. Initially it was discussed whether to go for a hydraulic or a pneumatic solution. Each of the two solutions has different advantages:

- Weight: The pneumatic system will have a lower weight, due to the low density of the air
- Time constant: Generally, a pneumatic solution will have a larger time constant due to the high compressibility of the air compared to a hydraulic fluid
- Environment: If the system have a leakage, air as media will be an advantage, as this will not harm the environment
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Based on the advantages in two out of three points, the pneumatic solution was chosen for further investigation with significant focus on finding a solution with a suitable time constant.

A number of different pneumatic solutions were investigated. It was found that pneumatic proportional valves generally are not made with focus on efficiency. Instead, a simplified system was designed, comprising only on/off valves.

The complete system is seen in Figure 16. A compressor (1) is mounted either in the nacelle or the hub delivering air pressure to the flaps (2) mounted on all three blades. The air pressure from the compressor is divided out to three pressure regulator valves (3) delivering a constant pressure level to each of the three pressure lines (4-6) going through each blade. To be able to make variable control, distributed over the blade length, the controllable flap is divided into several individual flaps, each controlled by a set of eight on/off valves (7-8). The valves consists of two sets, one controlling the downwards movement of the flap (7), and one controlling the upwards movement (8). Three of the valves from each set are connected to a pressure line, while the last opens to ambient pressure.

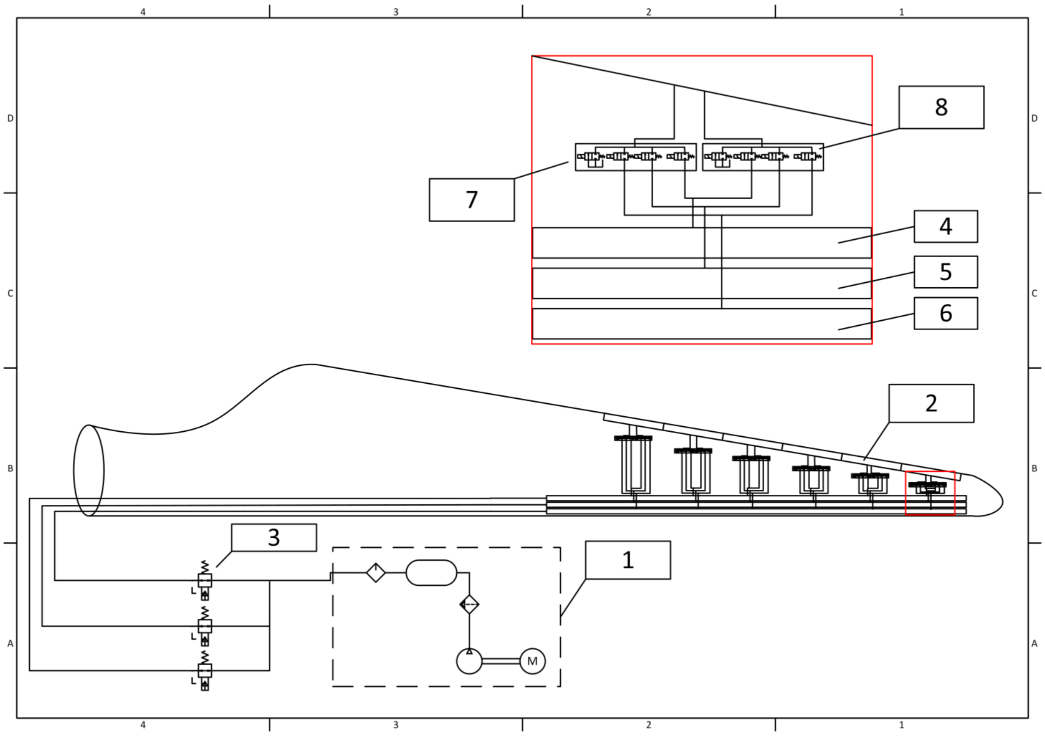

Figure 16 Sketch of powering and control system for flaps in a blade.

The valves are controlled using a very simple strategy, seen on Figure 17. An overall control system is sending a pressure reference to the pneumatic system. This pressure reference is compared to the six pressure levels seen to the right in Figure 17. If the pressure reference e.g. is between pressure level 1 and 2, valve number 3 and 5 must be opened, yielding no pressure in the lower chamber and medium pressure in the upper chamber.

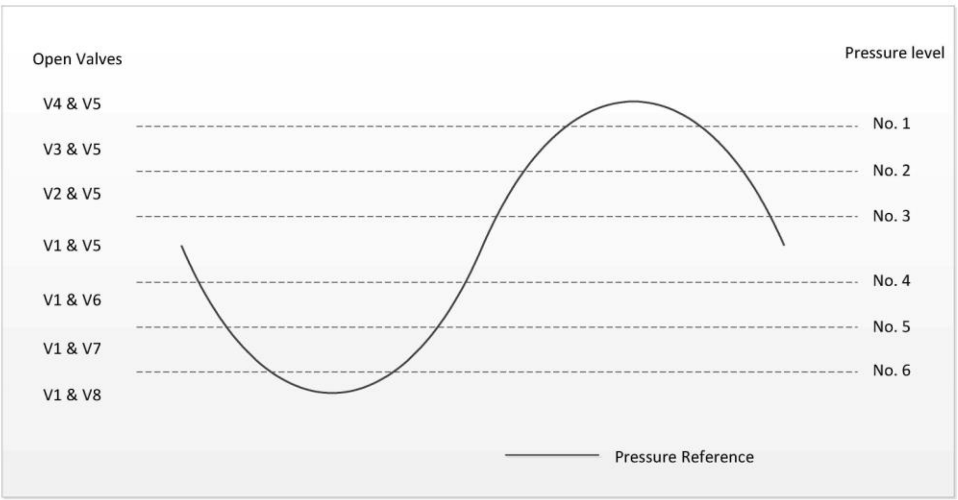

Figure 17 Control strategy for the eight on/off valves.

This setup gives the possibility of seven distinct positions of the flap, three upward, three downward and one neutral position. Simulations of the system showed that even though the control is using discrete steps the resulting movement of the flap is almost continuous.

After testing the system in the laboratory, it was implemented in the blade section for the rotating test rig as shown in Figure 18 and Figure 19.

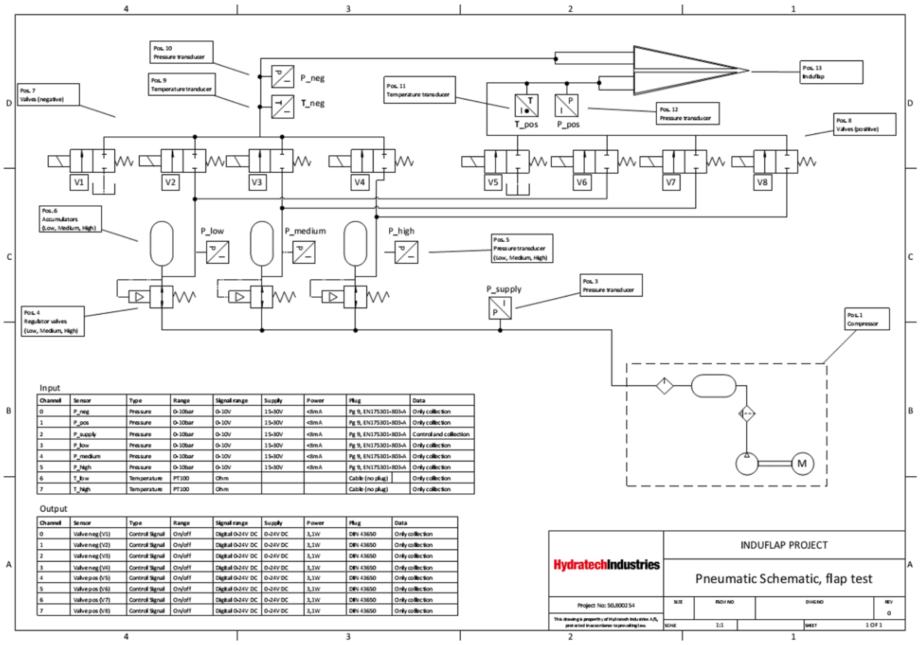

Figure 18 The complete control system for the blade section on rotating test rig.

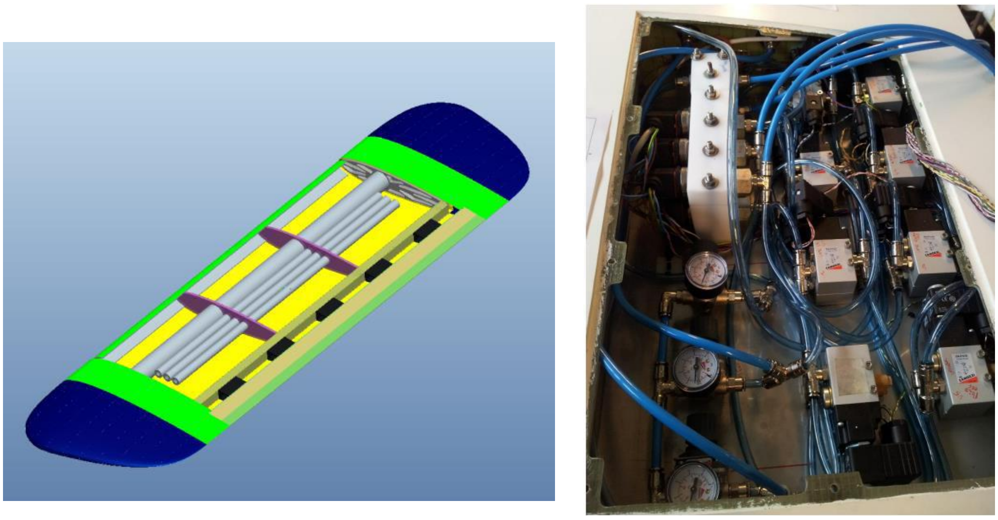

Figure 19 To the left is shown a sketch of the blade section for the rotating test rig and to the right the pneumatic control system is installed in the blade section.

After testing the pneumatic system and having discussions with possible end users (wind turbine manufactures), it was concluded that a hydraulic solution had to be investigated to decrease the time constant and to simplify the system. One of the weak points of the pneumatic system is the large number of valves, which gives the complete system a significant risk of failure.

When switching to a hydraulic solution the main focuses were on:

- Decrease time constant compared to the pneumatic system
- Simplify the system to increase reliability
- Remove actuating components from the blade
- Minimum risk of leakage

The developed hydraulic system comprises two separate closed systems, as seen on Figure 20 and Figure 21. The actuating part, a linear actuator, Figure 21, is

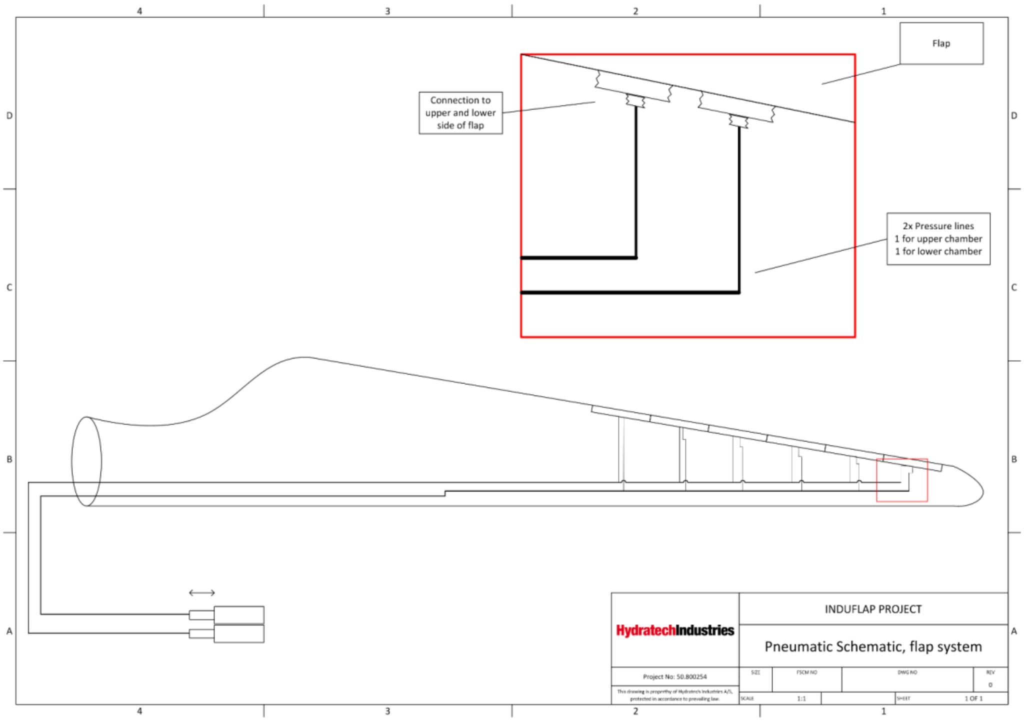

Figure 20 Sketch of the hydraulic flap powering system for a turbine.

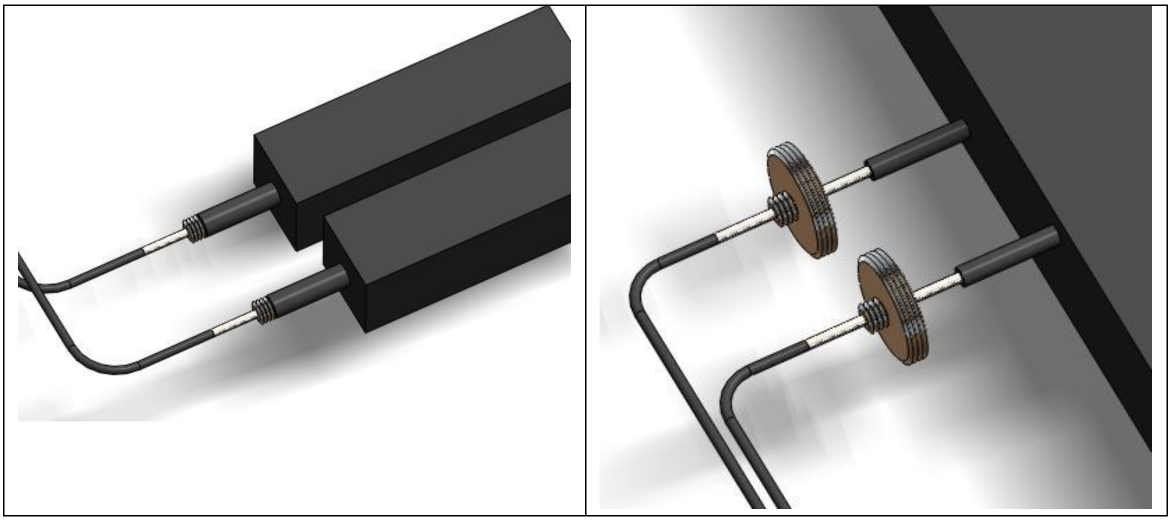

Figure 21 Two important components for the hydraulic powering system. To the left are the two linear actuators, each connected to a bellow and that part of the system is positioned in the hub. To the right the connection of the hydraulic lines to the flap is through two bellows on each hydraulic line.

positioned in the hub. It compresses a bellow, which compresses fluid in a pressure line going through the blade. On the end of the pressure line is yet another bellow, which is positioned against a bellow connected to the flap. The actuation from the linear actuator in the hub is thereby transferred to the flap. By using the bellows as the parts to transfer the force from one system to another it is avoided to introduce any seals which would have a risk of leakage.

A downside of changing to a fluid as actuating media instead of air is the increased weight of fluid in the flap and the pressure lines. When the blade rotates, the centripetal force acts on the fluid and thereby increases the pressure. If the system was made as one system from the actuation in the hub all the way to the flap the amount of fluid would create a too high pressure in the flap and a redesign of the flap would have been necessary to be able to handle this high pressure. When inserting the bellows between the pressure line and the flap it is possible to reduce the force transferred from the pressure line to the flap by making different sizes of the two bellows as seen on Figure 21. This split up also makes exchange of the flap easier as there is no rigid connection between the two systems.

WP4 Aeroelastic testing of flap/control system in rotating rig

Objectives

- Conduct tests of the controllable rubber trailing edge flap (CRTEF) system under realistic inflow conditions in a rotating test rig
- Although there is only one main objective in this WP it was the biggest work package as concerns man months and the most complicated to carry out.
- The work was organized in the following tasks:

Tasks

- Overall design of test rig based on aeroelastic simulations
- Detailed design of boom including pitch system and attachment of blade section
- Manufacturing of and installation of boom and power system on the 100 kW Tellus turbine
- Instrumentation of test rig and blade/flap sections
- Carry out tests of different flaps, control systems and sensor systems

Results Task 1-2

In order to fill out the gap between testing the flap system on a full-scale MW turbine and conducting wind tunnel tests of the flap system the 100 KW Tellus turbine situated at the test field at DTU Campus was rebuild to a rotating test rig during the INDUFLAP project to serve as a rotating test rig.
The rotor on the turbine was taken down in March 2013 as shown on the photo to the left in Figure 22. Later in 2014 the rotor was replaced by a boom with a 2m blade section with the flap system as shown in the sketch to the right in Figure 22. Besides the main boom, a counter weight is mounted to balance the boom and the aerofoil section. The constant speed induction motor was during the renovation of the turbine replaced by a new 100kW variable speed drive so that the rpm during the tests could be set to the desired value.
Main advantages of the rotating test rig setup include:

- very suitable to test prototypes of flap systems and inflow sensors
- detailed measurements of the performance of the flap system can be carried out as the blade section is equipped with a surface pressure measurement system
- testing of the flap system under realistic g loading (up to 10g which corresponds to the loading on the outer part of the blade of a MW turbine)
- easy access to the test rig for short measurement campaigns
- a size where installation of equipment does not require a huge crane
- very suitable to perform aeroelastic experiments
- the measurement of aerodynamic characteristics in free wind are an important supplement to wind tunnel measurements on aerofoil sections

Figure 22 The rotor of the Tellus turbine at DTU Campus Risoe was taken down in March 2013 so that the turbine could be rebuild to the rotating test rig shown in a sketch to the right.

After the overall design of the test rig as shown in the sketch to the right in Figure 22 was completed the detailed design of the boom and the blade section started. The final assembly drawing of the 10m long boom is shown in Figure 23. Its weight is more than 2 tons.

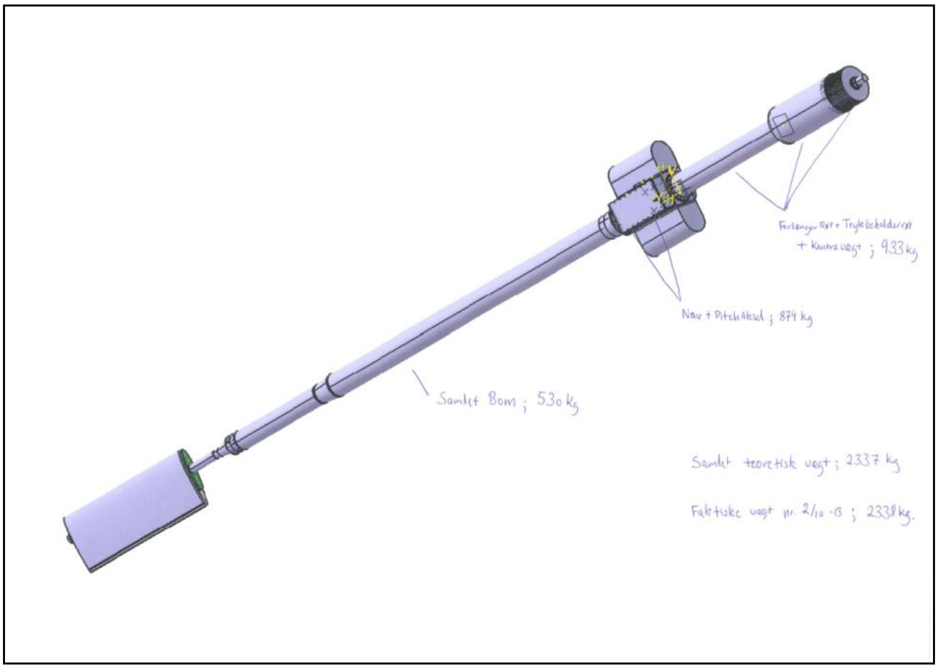

Figure 23 The final design of the 10m long boom with a weight of more than 2 tons.

The design of the 2m blade section was challenging as a considerable amount of instruments + all the valves and pressure tanks had to be installed inside the section. The CAD drawing of the section before these parts were inserted is shown in Figure 24.

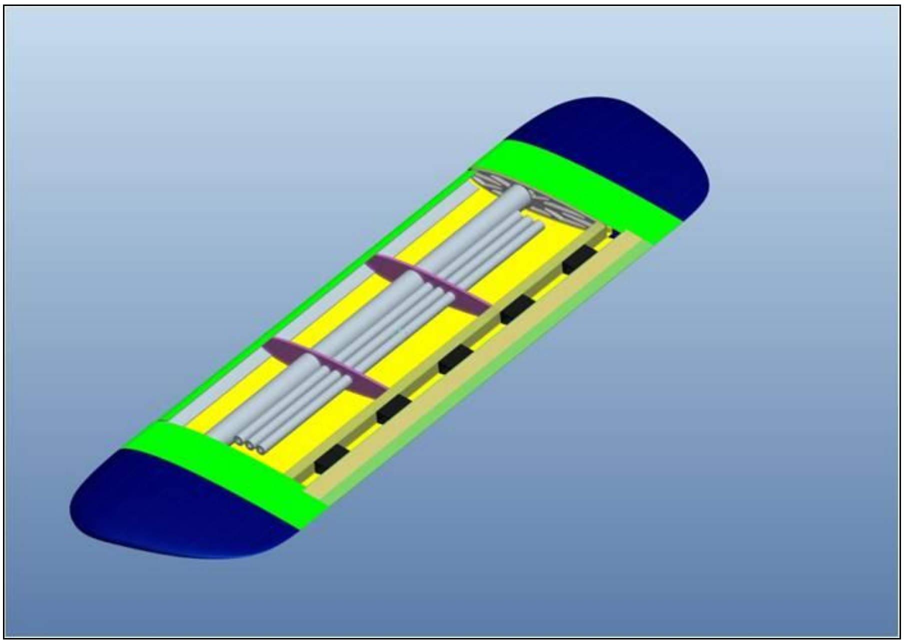

Figure 24 A CAD drawing of the 2m blade section to be mounted on the rotating test rig. The flap is attached on the right side of the blade section on the black connectors.

Results Task 3-4

Most parts of the boom were manufactured at the workshop at DTU, Campus Risoe where also the assembling of the boom was carried out as shown in Figure 25.

Figure 25 The assembled boom in the workshop at DTU Campus Risoe

The 2m long and 1m chord blade section with a NACA0015 airfoil section was also manufactured at DTU Campus Risoe, Figure 26 . The blade section is build with an inner aluminium structure covered with two shells of composite material. The aluminium structure consists of an ø110/100 tube, two rib structures and a U-profile web. Aluminium parts were welded together. The tube makes it possible to mount and dismount the wing section on the boom and the U-profile web at the trailing edge is for fixation of different morphing trailing edge flaps to be tested.

Figure 26 The manufacturing of the 2m long blade section in the fiberlab workshop at DTU.

The next step was to make the assembling between the boom and the blade section as shown in Figure 27. A detailed testing of the measurement systems and the control of the flap was carried out before the access lids on the blade section finally were closed.

Figure 27 Assembling the blade section with part of the boom.

The nacelle of the Tellus turbine was also taken down from the tower and into the workshop where the instrumentation was carried out as well as mounting a new hub, Figure 28.

Figure 28 The compressor for the pneumatic activation of the flap was mounted on the hub as seen on the photo to the left. To the right the slip rings are seen which were both transmitting the measurement signals as well as supplying electrical power to the compressor

Finally, the boom was mounted in June 2014 and the measurement campaign could begin, Figure 29

Figure 29 The boom was installed on the turbine in June 2014. In the lower right photo the team behind the project can be seen.

Task 5 results from experiments

In total about 50 measurement runs of 10min length were carried out during different campaigns in the autumn 2014 until the boom was taken down again at the end of October.

An overall important result of the tests was that it was demonstrated that the flap system could function in the real, rotating environment. Measurements were carried out for rotational speeds up to 30 rpm and this corresponds to the g-loading on outboard part on the blade of a full scale MW turbine.

Next a series of measurements were carried out to demonstrate how much change in aerodynamic loading the flaps can create. From Figure 30 it can be seen that the flaps clearly can change the aerodynamic loading F_N perpendicular to the chord by comparing the values at the same inflow angle for a positive flap angle of 5 deg. (green curve) and a negative flap angle of about -5 deg. (red curve). The difference is close to 200 N/m.

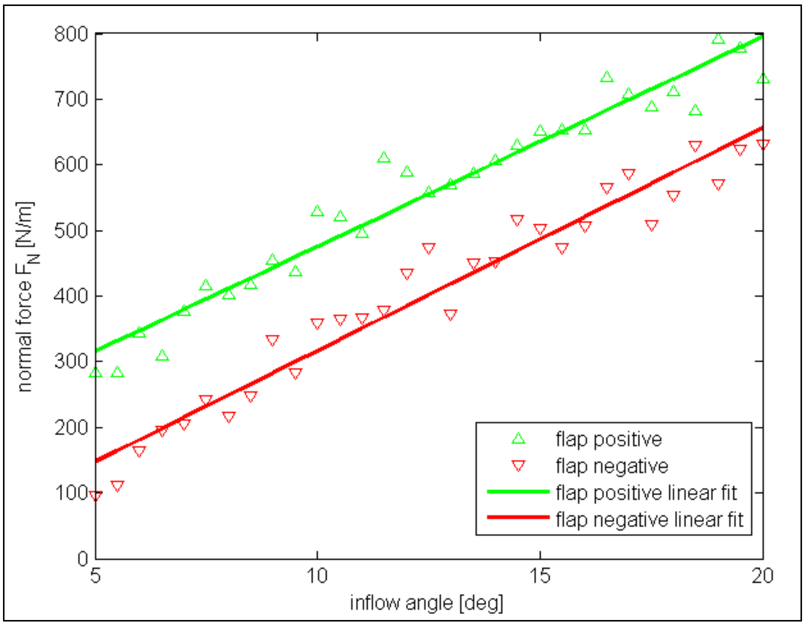

Figure 30 Normal force loading on the blade segment for the flap in max. positive and negative flap angle [+5,-5 deg.].

However, a better way to show the performance of the flap is the data in Figure 31 where the loading again is shown for the flaps in its max positive and negative flap angle and then for different pitch settings of the blade section. In this way the capability of the flaps to change the loading can directly be compared with the load change that can be obtained with a pitch change which is the traditional technology. From the figure it can be derived that the max amplitude flap angle of 10 deg. (from -5 to +5 degree) gives approximately the same change in loading than what 3 to 3.5 degree of pitch can do. It means that 3 deg. flap has the same effect as 1 deg. in pitch change. This is somewhat lower than what models typically predict for this size of flaps. A typical computed value is that 2 deg. flap corresponds to 1 deg. pitch. There can be many reasons for this difference but one important one is that we here have measured in real inflow conditions with unsteady flow whereas simulations so far have been performed with steady inflow. The flap performance in real atmospheric inflow and the difference to steady flow conditions is thus an important result from the present project as the goal was to see what happens when we go to test in real conditions.

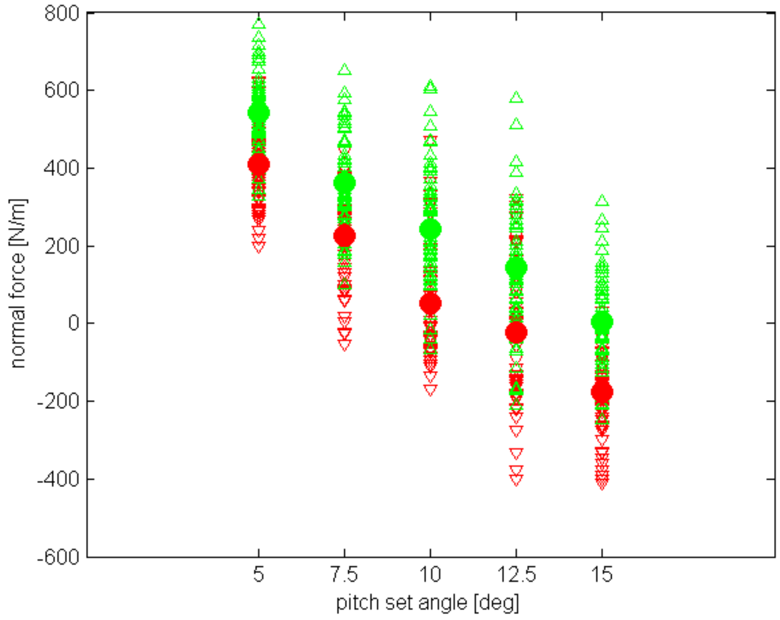

Figure 31 Normal force loading on the blade segment for the flap in max. positive and negative flap angle [+5,-5 deg. flap angle] as function of pitch set angle.

Finally, an example of a time trace of some of the different parameters measured are shown for a 10 min period where the flap angle is changed from -5 to 5 to -5 .... deg. each 10 sec. in Figure 32. The lowest graph in the figure shows in blue the normal force loading on the blade section and the red curve is the flap position. The correlation between the flap position and the normal force loading can be seen in the way that when the red curve (flap) is in top the same tendency can be seen for the load (blue curve) although the unsteady inflow disturbs the picture to some degree.

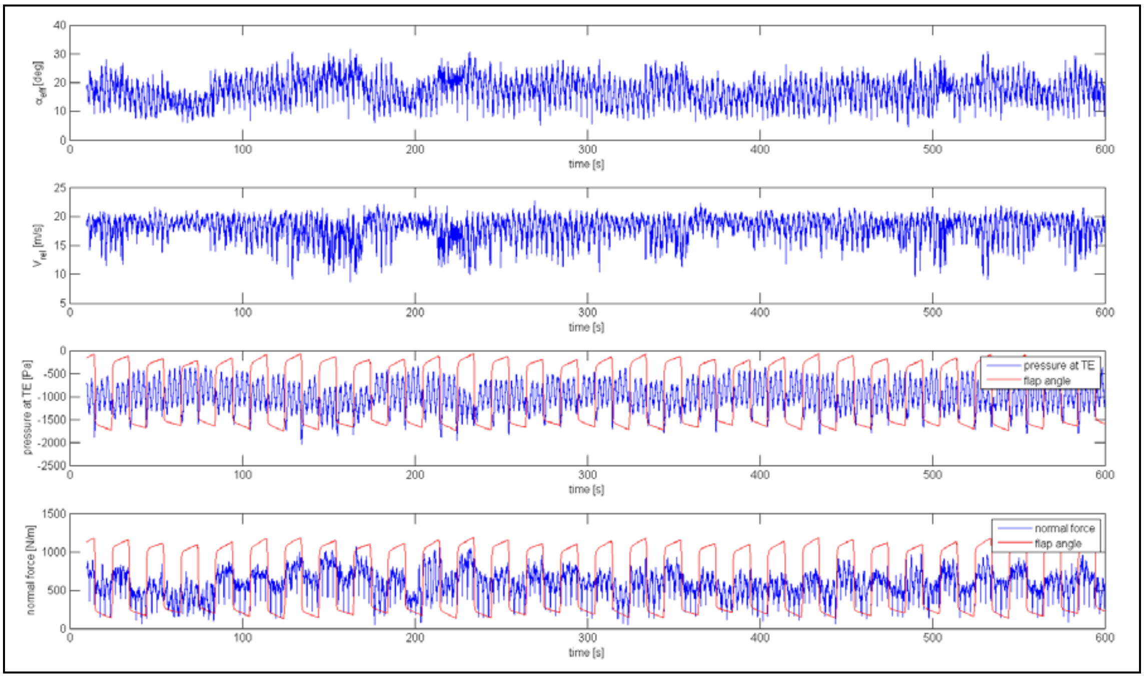

Figure 32 Aerodynamic parameters for a case of 20 rpm and 5deg pitch with square flap input shifting each 10 sec. from -5 to 5 to -5 …….. deg.

WP5 Adaptation of flap system for prototype test on a full scale turbine

Objectives

- Work out a design of a flap system for prototype test on a full scale turbine

Tasks

- set up an aeroelastic model of the full scale test turbine including sub models for the flap system
- carry out aeroelastic simulations in order to define the design loads for the flap system and the turbine, using the response characteristics of the flap system measured in WP3 and WP4
- carry out the overall design and test of the flap system for the full scale turbine

Model set-up

This WP is intended as a demonstration of the flap system on a full scale turbine by numerical simulations. The flap powering system for a full scale turbine was sketched in WP3 and in the present WP the aeroelastic simulation model and the results of the simulations will be presented. Based on the detailed reporting [5] we will just describe the modelling set-up briefly here as well as presenting only the final results.

Main characteristics of the simulations:

- Certification-type design load base setup close to industrial standards
- Representative wind turbine / flap system configuration
- Realistic controllers for full range of operation
- Wind turbine model

The NREL 5MW Reference Wind Turbine (RWT) [7] is used for the simulations in the aeroelastic code HAWC2 [8], as a representative modern multi-MW wind turbine model which has been used extensively for comparison studies involving blade aerodynamic controls. The main geometrical and operational properties of the reference wind turbine are shown in Table 1. In this investigation, the IEC class has been changed from the originally used IB to IA for evaluation of the load reduction potential in more aggressive wind conditions.
For the simulated flap configuration it was initially at the project start planned to use derived flap characteristics from the rotating test rig results in WP4 for the simulation of the flap characteristics on the full scale turbine model here in WP5. However, as it was mentioned in WP3 the studies on the powering system during the project has shown that it is necessary to go for a hydraulic powering system in order to obtain time constants in the system that will only have a minor impact on the load reduction potential by the flaps. In the present simulations we have thus used a time constant of 100ms that was obtained with the present flap technology in wind tunnel tests in 2009 [9]. The other characteristics of the modelled flaps are shown in Table 2 where it can be seen that we have simulated flaps that in total for each blade has a length of 17.8m which corresponds to 29% of the blade length. This should be fully realistic with the present flap technology.

Table 1 Summary of data for the 5MW turbine used for simulations of the flap potential load reduction

NREL 5MW Reference Wind Turbine	
Rated power	5 MW
Number of blades	3
Rotor diameter	126 m
Blade length	61.5 m
Hub height	90 m
Overhang, tilt, precone	5m, 5°, 2.5°
Rated rotor speed	1.267 rad/s
Rated wind speed	11.4 m
Cut-in, cut-out wind speed	3 m/s, 25 m/s
Baseline controller	Variable speed, pitch regulation
IEC class	IA

Table 2 Flap parameters

ATEF flap configuration	
Chordwise extension	10%
Deflection angle limits	±10°
Spanwise length	17.8m (29% blade length)
Spanwise location	43.05m-60.88m (from blade root)
Airfoil	NACA64618
Max ΔC_l	0.4
Deflection rate limit	100°/s
Actuator time constant	100ms

As mentioned above the present simulations comprise a big number of simulations and are close to what is necessary for a certification of a turbine. It means that the results constitute a very good basis for evaluation of the different rotor/control and pitch/flap configurations that are investigated here. They are:

- Baseline
- Cyclic pitch
- Flap control
- Combined cyclic pitch and flap controls

The baseline configuration means a turbine with a collective pitch control for power regulation. This is the most common control and the control does not reduce loads but only controls the power.
The cyclic pitch is used to some degree by industry today and it is a control where the blades pitch continuously to alleviate the so-called 1p loads which e.g. are caused by wind shear and turbulence.
Then there is the flap control and also a control which is a combination of the pitch and flap control.

Results of aeroelastic simulations of the flap technology
The overall results from the comprehensive numerical analysis reported in [5] are summarized in Figure 33 and Figure 34. The fatigue loads, which in most cases determine the material dimension of the turbine components which again are important for the cost of the components, are shown for a number of turbine components in Figure 33 for the 4 different control cases as described above. In particular for

the loading called MbXR, which is the flapwise loading in the blade root, a considerable reduction is seen for both the cyclic pitch control and flap control. The combinations of the two controls give an additional reduction. Also for the load called MxTB which is the bending moment in the bottom of the tower there is a reduction when using flaps and as the tower is a component that contributes with 20-25% of total turbine costs this small reduction has a value. It can be seen that both the cyclic pitch and the flap control also reduce several of the other load components. It can thus be concluded that cyclic pitch and flap control gives a comparable load reduction and the combination of the two even more.
However, this should be evaluated together with the fatigue of the pitch bearing shown in Figure 34 where it can be seen that with the flap system the pitch bearing fatigue is reduced with more than 50% using the flaps. This is an important result as it seems that the pitch bearing becomes a more and more critical and expensive component as the turbine size increases.

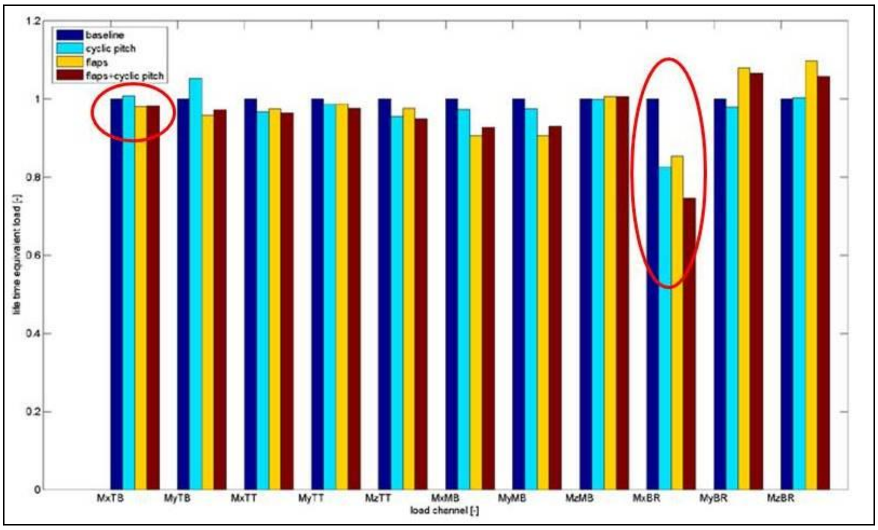

Figure 33 Comparison of lifetime fatigue loads between cases (loads normalized by baseline loads).

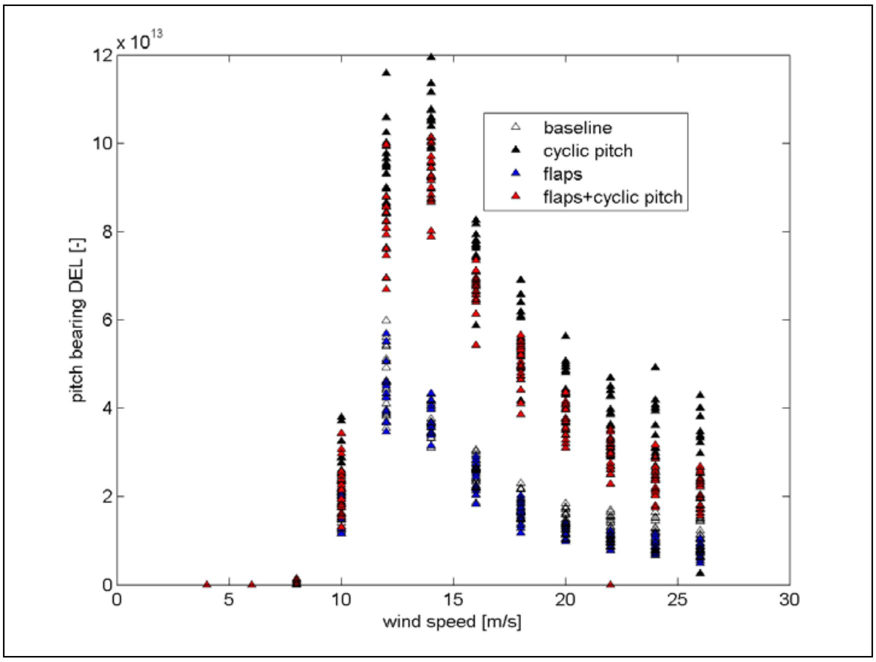

Figure 34 Comparison pitch bearing short term fatigue equivalent loads between cases for DLC 1.2.

1.5a Summary of results

Flap design and manufacturing

- The flap design with spanwise voids (pressure chambers in the rubber part of the flap) has shown to be superior to the other main design concept with chordwise voids as concerns design complexity and manufacturing
- A good flap concept with a passive part carrying mainly the loads and two active elements has been developed
- It has been demonstrated that the flap can be extruded in an industrial manufacturing process which has the main advantage that only a minimum of parts have to be assembled – the two end plates, so that the types of failure modes have been reduced to a minimum
- In a final manufacturing process it is foreseen that all the parts in the flap and the attachment parts for connection to the wind turbine blade can be co-extruded which will make the flap more robust
- It has been proven that the flap system can be manufactured without metal parts
- The chosen inlet system to flap has shown to be the weak part of the present design
- In the PhD work on lightning carried out within the INDUFLAP project it has been proven that the selected elastic flap material has the same resistance against lightning as the resistance of the reinforced glass fibre which means a very good resistance to lightning

Flap testing in the laboratory

- Simple flap deflection tests in a stationary test rig have been carried out to document steady and unsteady response

Powering options

- A new pneumatic powering system developed by Hydratech reduced the necessary power consumptions considerably but the time response is too low
- The above system from Hydratech has been tested and worked satisfactorily under realistic g loading (*10g*) on the rotating test rig
- Due to the complexity of the pneumatic powering system (many valves with electronic connections) a hydraulic powering system seems to be preferable in most cases of application of the flap technology
- A hydraulic powering system for a full scale turbine has been sketched with main components
- Initial tests with a hydraulic powering has been carried out in the laboratory

Development of rotating test rig and testing

- A unique rotating test rig has been developed, designed, build and operated in the project
- The test rig offers a unique possibility of testing prototypes of the flap technology under realistic operational conditions before going to tests on full scale turbine

- The first test campaign in the autumn 2014 has proven that it is valuable test rig for validation of performance of the flap system and influence of important parameters such as rotational speed and pitch setting has been verified
- The results show that the load control capability of the flap system is such that 3 deg. flap angle gives the same load change as 1 deg. pitch (the traditional way to control loads). It is somewhat lower than what has been simulated so far and the difference can be ascribed to the real atmospheric inflow conditions that are easily taken into account in the simulations
- This is thus a first important result from the test rig together with the operation of the system at 10g loading.

Evaluation of the load reduction potential of the flap technology

- A comprehensive numerical study using aeroelastic simulations has been conducted to quantify the load reduction potential
- The main result is that the load reduction with flaps is comparable to what can be achieved with cyclic pitch which is a well-known technology but has the disadvantage that wear of the pitch bearings is a major problem
- Using flaps and obtaining the same level a of load alleviation as cyclic pitch the simulations showed that the wear of the pitch bearings is reduced with more than 50%

1.5b Summary on project management, organization and mile-stones

During the project 9 meetings have been held for all the project participants. Additionally several meetings with only 2 partners have been held for discussing specific issues.
Additionally internally at DTU about 45 project meetings have been held. It has mainly been for people from 4 different sections/teams at DTU Risoe; 1) TEM, measurement and testing; 2) KOM flap design and manufacturing, manufacturing of 2m blade section; 3) Workshop – has manufactured most of the rotating rig parts and made the assembling; 4) AED project management; design of flaps; rotating test rig; planning measurement campaign; analysis of measurements; simulating flap potential.

Comment on project evolving

During the first ½-1 year of the project it turned out that the project partner Dansk Gummi Industri DGI did not really have the resources to go into the project work. It is a small company manufacturing rubber and plastic parts by moulding processes and vulcanization. Back in 2006 they manufactured the first prototype of the flap in a rubber material so it was obvious to include them as partner in the INDUFLAP project. Separate meetings between the project management DTU and DGI were held to see if they could get an active role in the project and in the beginning they carried out some manufacturing of flaps.
However, as it during the work on design of flaps became more and more clear that the flap design with chord wise voids, which should be manufactured by DGI, was too complex their contribution became less important and they have not been an active partner in a major part of the project. The project resources have then been focussed on the flap design with spanwise voids.

Milestones

The following milestones were part of the project application

M1: Design of 1st prototype
M2: Design of 2nd prototype
M3: Design of 2m prototypes (1st and 2nd)
M4: Sketched CRTEF control system for full scale turbine
M5: Report which evaluates the results for full scale tests

Then in the letter from EUDP with confirmation of funding additional two commercial mile stones were formulated:

M6: Calculate total system price
M7: Have a wind turbine manufacture engaged in the project, with possibility for full scale testing

The fulfilment of the milestones as the project evolved has been described in the annual reports for the project. One minor change is that when it was decided to stop further design of flaps (2nd prototype with chordwise voids) after manufacturing several versions in the small 30cm size, it was not relevant to design and manufacture a 2m version.

M5

The milestone is fulfilled with the work at the end of the project with the measurements on the rotating test rig and associated report plus the simulations of the load alleviation potential in WP5.

M6 Calculate total system price

For the industrial partners Hydratech and Rehau it is a challenging task to estimate the system price at the present stage as the detailed design has not been carried out.

Hydratech manufacturing and delivering the powering and control system part has estimated the following prices:

- Price A – € 17.000 for each flap actuation system based on existent components of high quality but presently are not in mass production. Life time 20 years

- Price B - € 1.700 for each flap actuation system after development of the system and in mass production

Rehau has for the flap part estimated the following:

- € 100 /m flap

The system price for the simulated 5MW reference turbine with 18m flap on each blade can thus be worked out:

Flap cost:

- 18m * 100 €/m flap — 1800 € for each blade

- Flap actuation system prototype: — 17.000 € for each blade
- Flap actuation system in mass production: — 1.700 € for each blade
-
- **Total flap system cost – prototype: — 18.800 € for each blade**
- **Total flap system cost – mass production: — 3.500 € for each blade**

System price compared with cost savings:

Above in Figure 33 the flapwise lifetime load reduction was simulated to be in the order of 15%.

The flapwise load carrying part is assumed to be 40% and with a fixed geometry the weight scales linearly with the load.

- The weight reduction is then 15% x 40% = 6%.

Blade weight for the 61.5m blade on the simulated 5MW rotor is 18600 kg. According to a cost model from the EU project Innwind the blade cost is: 13.084*Weight-4452.2 = 240 k€ or 1.8 MDkr.

- Weight saving = 6% of 18600 kg = 1100 kg
- Cost saving approximately 13.084*1100 €/kg = **14392 €/Blade**

It can be concluded that in a mass production the cost of adding the flap system is favorable low compared with the reduced cost of the blades due to the blade mass savings.

M7 Have a wind turbine manufacture engaged in the project, with possibility for full scale testing

Fulfilled with the future cooperation with Siemens as described below under **1.6**.

1.5c Dissemination

The project work and results have been described in 5 technical reports [1,2,3,4,5] and one PhD report [6].

1) Tom L. Andersen, Helge A. Madsen, Thanasis K. Barlas, Ulrich Mortensen, Peter B. Andersen, "Design, manufacture and test of Controllable Rubber Trailing Edge Flaps", DTU Vindenergi-E-0076(EN), January 2015

2) Mads B. Christensen, "Flap powering system", Hydratech report, January 2015

3) Thanasis K. Barlas, Helge A. Madsen, Tom L. Andersen, "Design and simulation of the rotating test rig in the INDUFLAP project", DTU Vindenergi-E-0063(EN) December2014

4) Thanasis K. Barlas, Helge A. Madsen, Karen Enevoldsen, Kasper Klemmensen, "Flap testing on the rotating test rig in the INDUFLAP project", DTU Vindenergi-E-0064(EN), December 2014

5) Thanasis K. Barlas, Leonardo Bergami, Morten H. Hansen, Mads M. Pedersen, David Verelst, Kenneth Thomsen, Helge A. Madsen, "Load alleviation potential of the Controllable Rubber Trailing Edge Flap (CRTEF) in the INDUFLAP project", DTU Vindenergi-E-0065(EN), December 2014

6) Anna Candela Garolera, "Lightning protection of flap system for wind turbine blades", PhD Thesis, DTU ELEKTRO, September 2014

Further dissemination comprises journal papers, conference papers and presentations without papers.

Journal papers:

A. Candela Garolera, S. F. Madsen, M. Nissim, J. Myers, and J. Holboell, "Lightning damage to wind turbine blades from wind farms in US," Accepted on the 17th October 2014 in the IEEE Transaction on Power Delivery

A. Candela Garolera, S. F. Madsen, K. L. Cummins, J. Myers, and J. Holboell, "Observations of Lightning Discharges to wind turbines in Kansas, US.," Submitted, waiting for acceptance

A. Candela Garolera, K. L. Cummins, S. F. Madsen, J. Holboell, and J. Myers, "Multiple lightning discharges in wind turbines associated with nearby cloud-to-ground lightning," Submitted, waiting for acceptance

Conference papers:

Thanasis K. Barlas, Helge A. Madsen, "Influence of actuator dynamics on the load reduction potential of wind turbines with distributed controllable rubber trailing edge flaps (CRTEF)", Proceedings of ICAST2011: 22nd International Conference on Adaptive Structures and Technoloies, October 10-12, 2011, Corfu, Greece

A. Candela Garolera, J. Holboell, and M. Henriksen, "Breakdown and Tracking Properties of Rubber Materials for Wind Turbine Blades," Conf. Rec. 2012 IEEE Int. Symp. Electr. Insul., pp. 516 – 519, Puerto Rico, June 2012.

A. Candela Garolera, J. Holboell, and S. F. Madsen, "Lightning attachment to wind turbine surfaces affected by internal blade conditions," 2012 Int. Conf. Light. Prot., pp. 1–7, Vienna, September 2012.

Peter Bjoern Andersen, Helge Aagard Madsen, Tom Løgstrup Andersen, Thomas Schettler, "Design and manufacturing of a morphing flap for wind turbine blades", 6th ECCOMAS Conference on Smart Structures and Materials, SMART2013, Politecnico di Torino, 24-26 June 2013, www.smart2013.com

A. Candela Garolera, J. Holboell, and M. Henriksen, "Behavior of Rubber Materials under Exposure to High Electric Fields," Proc. 23rd Nord. Insul. Symp., pp. 175 – 178, Trondheim, June 2013.

A. Candela Garolera, J. Holboell, and S. F. Madsen, "Lightning transient analysis in wind turbine blades," Proc. Int. Conf. Power Syst. Transients, Vancouver, July 2013.

A. Candela Garolera, J. Holboell, S. F. Madsen, and C. F. Miertiz, "Modeling of lightning streamer formation and propagation in wind turbine blades," in International Conference On Lightning and Static Electricity, 2013, Seattle, September 2013

S. F. Madsen, C. F. Miertiz and A. Candela Garolera,"Numerical tools for lightning protection of wind turbines" in International Conference On Lightning and Static Electricity, 2013, Seattle, September 2013

H. A. Madsen, T. L. Andersen, L. Bergami, J. E. Jørgensen, A. Candela Garolera, and J. Holbøll, "Towards an Industrial Manufactured Morphing Trailing Edge Flap System for Wind Turbines," in European Wind Energy Conference & Exhibition 2014, Barcelona, March 2014.

K. L. Cummins, D. Zhang, M. G. Quick, A. Candela Garolera, and J. Myers, "Performance of the U.S. NLDN during the Kansas Windfarm2012 and 2013 Field Programs," in International Lightning Detection Conference, Tucson, March 2014

Presentations without papers

Helge Aa. Madsen and Thanasis Barlas, "Development of the controllable rubber trailing edge flap (CRTEF) technology for MW turbines", Blade Workshop, Advances in Wind Turbine Rotor Blades, 13-15 February, 2012 Swissôtel Bremen

Helge Aagaard Madsen, Christina Beller, Tom Løgstrup Andersen, "Development of Trailing Edge Flap Technology at DTU Wind", Presentation at Wind Turbine Blade Workshop at Sandia National Laboratories, May 29th to June 1st, 2012

Helge Aa. Madsen, Tom Løgstrup Andersen, Peter Bjørn Andersen, "Transfer of flap technology from laboratory to industrial application", Presentation at IQPC - Advances in Rotor Blades for Wind Turbines, 25 - 27 February, 2013 Bremen, Germany

Helge Aagaard Madsen, Tom Løgstrup Andersen, Athanasios Barlas, Leonardo Bergami, Johnny Egtved Jørgensen, Anna Candela Garolera, “Smart Rotor Research at DTU Wind”, 2014 Wind Turbine Blade Workshop, Sandia National Laboratories August 26 to 28, 2014

1.6 Utilization of project results

During the project the flap technology has been presented at different blade workshops and conferences and during these events there have been informal discussions with wind turbine manufactures about their interest in the technology. However, the present INDUFLAP partners found that it would be convenient if collaboration could be formd with one of the wind turbine/blade manufactures established in Denmark. The INDUFLAP project team had a first meeting with Siemens in August 2014 where a brief presentation of the technology took place. A second meeting was held in October 2014 with more people from each side and the results from the comprehensive simulations in WP5 on the load reduction potential were shown. Also the possible future corporation on developing and utilization of the technology was discussed.

This has resulted in an expression of interest between the INDUFLAP partners (Rehau, Hydratech, DTU) and Siemens to continue the corporation on development of the technology, see letter of interest in Figure 36.

An outcome of this expression of interest on corporation it has been decided to work out a EUDP application for an INDUFLAP II project to be sent in, March 2015. The sketch of the project is shown below in Figure 35 and it has the end target to develop the technology to a stage where it is ready for implementation in mass production.

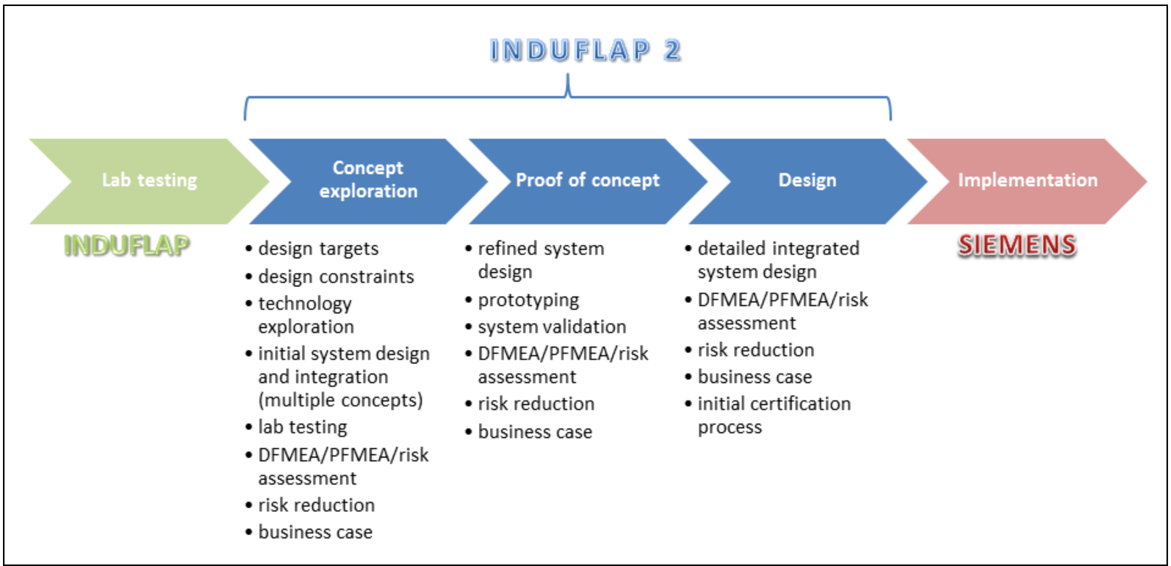

Figure 35 The sketch of an INDUFLAP II project for EUDP-I 2015 in March 2015.

SIEMENS **Energy**

Siemens Wind Power A/S, WP TE R&D LPD B, Borupvej 16, 7330 Brande, Denmark

Dr. Helge Aagaard Madsen
Technical University of Denmark
Dept. of Wind Energy
Bygning 118 Frederiksborgvej 399
DK-4000 Roskilde
Denmark

Name	Peter Fuglsang
Department	WP TE R&D LPD B
Telephone	+45 (9942) 5258
Mobile	+45 (3037) 6524
E-mail	peter.fuglsang@siemens.com
Date	December 19, 2014

Letter of interest

This letter is to confirm, that Siemens Wind Power is interested in future cooperation with the partners in the EUDP INDUFLAP project. We see the direct involvement of an Industrial Partner as a natural step in the development of the Active Flap technology and we believe that we can add value in such cooperation.

We have held two meetings with the INDUFLAP consortium during 2014. We have gained insight into the technology and we have provided our input for how the technology can be assessed from an industrial point of view and how business value as well as business risk can be assessed.

Sincerely yours,

Siemens Wind Power A/S

Peter Fuglsang
Head of Blades Module

Siemens Wind Power A/S

Borupvej 16
7330 Brande
Denmark

Tel.: +45 9942 2222
Fax: +45 9999 2222
www.siemens.com/wind

CVR no: 76 48 62 12

SCF V08.12

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Figure 36 Letter of interest in the technology from Siemens Wind Power.

1.7 Project conclusion and perspective

The INDUFLAP project objectives, achievements and outlook have been presented in the sections above. Although it was the first project where the partners have worked together an efficient and thrust full cooperation developed early in the project. The development of the flap technology has taken a big step forward with the INDUFLAP project and a unique rotating test rig has been developed and build. A very important achievement in the last few months of the project was the presentation of the technology for Siemens Wind Power which found the technology so interesting that they will work together with the INDUFLAP partners to develop it further. A new INDUFLAP II application for the application round in March 2015 will be one of the results of the new cooperation.

Annex

Links to presentations

http://www.slideshare.net/sandiaecis/madsen-38931016?related=1

http://energy.sandia.gov/wp/wp-content/gallery/uploads/2B-B-3-Madsen1.pdf

http://orbit.dtu.dk/ws/files/51513607/IQPC_Bremen_Februar_2012.pdf

http://www.wind-rotor-blades.com/AgendaDay.aspx?tp_day=63287

http://www.vindenergi.dtu.dk/english/News/2014/06/DTU-and-industrial-partners-REHAU-and-Hydratech-Industries-demonstrate-new-smart-blade-technology

Links to magazines and news sites

http://www.renewableenergyworld.com/rea/news/article/2010/02/controllable-rubber-trailing-edge-flap-may-ease-stress-on-wind-turbine-blades

http://www.renewablesinternational.net/danish-researchers-aim-to-lower-the-cost-of-turbine-blades-using-rubber-flaps/150/505/30755/

http://phys.org/news/2011-04-flexible-trailing-edge-blades-power.html

http://www.sciencedaily.com/releases/2011/04/110407093236.htm

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[1] Tom L. Andersen, Helge A. Madsen, Thanasis K. Barlas, Ulrich Mortensen, Peter B. Andersen, Design, manufacture and test of Controllable Rubber Trailing Edge Flaps, DTU Vindenergi-E-0076(EN), January 2015

[2] Mads B. Christensen, Flap powering system, Hydratech report, January 2015

[3] Thanasis K. Barlas, Helge A. Madsen, Tom L. Andersen, Design and simulation of the rotating test rig in the INDUFLAP project DTU Vindenergi-E-0063(EN) December2014

[4] Thanasis K. Barlas, Helge A. Madsen, Karen Enevoldsen, Kasper Klemmensen, Flap testing on the rotating test rig in the INDUFLAP project, DTU Vindenergi-E-0064(EN), December 2014

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[6] Anna Candela Garolera, Lightning protection of flap system for wind turbine blades, PhD Thesis, DTU ELEKTRO, September 2014

[7] Jonkman, J. et al., Definition of a 5-MW reference wind turbine for offshore system development. Technical report, NREL/TP-500-38060, 2009.

[8] Larsen, T. J. et al., How 2 Hawc2, the user's manual, Technical report, Risø-R-1597(ver. 4-4)(EN), 2013.

[9] Helge Aa. Madsen, Peter B. Andersen2, Tom L. Andersen3, Christian Bak4, Thomas Buhl, "The potentials of the controllable rubber trailing edge flap (CRTEF)", Paper presented at EWEC 2010, Warsaw, Poland.