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A MORPHING TRAILING EDGE FLAP SYSTEM FOR WIND TURBINE BLADES

Helge Aagaard Madsen[*], Thanasis Barlas[†], Tom Løgstrup Andersen[†]

[*]Technical University of Denmark
DTU Wind Energy, Campus Risoe
Frederiksborgvej 399, DK 4000 Roskilde
hama@dtu.dk

[†]Technical University of Denmark
DTU Wind Energy, Campus Risoe
Frederiksborgvej 399, DK 4000 Roskilde
tkba@dtu.dk
toan@dtu.dk

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Summary: *The development of a morphing trailing edge system for wind turbines, also called a flap system, is presented. 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 an elastic material. It is thus a robust system as no mechanical or metal parts are used. The prototypes tested in the laboratory and on a blade section in a wind tunnel in the period from 2007-2010 demonstrated the functionality and the aerodynamic performance of the flap concept. In a recent research and development project INDUFLAP from 2011-2014 the flap system has been further developed in corporation with the industrial partners Hydratech Industries (DK) and Rehau (DE). A new trailing edge flap design with spanwise voids (channels) and with a chord of 15cm suitable for a 1m chord blade section was developed. It was then manufactured by extrusion and glued together with a load carrying part with a connector part that allows an easy attachment on the blade section. After tests in the laboratory the flap was mounted on a 2m long blade section mounted on a newly developed test rig. A 10m long boom with the blade section was installed on a 100kW turbine hub where the original blades were taken down. It means that the flap system was tested under realistic rotating conditions with real atmospheric turbulent inflow and with a g loading up to 10g which represents the conditions on the outer part of a MW turbine blade. The measured performance of the flap system shows that 3 deg. flap deflection gives the same lift change as 1 deg. pitch of the whole blade section.*

1 INTRODUCTION

Several numerical studies [1] during the past 10 years have shown big potentials for load reduction on MW turbines using distributed control for alleviation of the fluctuating loads along the blade span. However, the requirements by the wind turbine industry of robust actuator solutions where the strongest specifications mean no metal and electrical parts in the blades have so far limited the use of the smart blade technology on wind turbines.

The numerical and experimental analyses in the past have mostly been focusing on trailing edge flaps as the distributed control concept. Although small scale blade and rotor experiments [2], [3] in wind tunnels have been conducted in the past these concepts are not considered to be directly up-scalable for modern large scale wind turbine blades, without any additional mechanical amplification parts.

The lack of technology solutions for flap control on MW wind turbines initiated back in 2006 a development work at Risoe (now DTU Wind Energy) with the main objective to develop a robust and efficient flap system for implementation on MW scale turbines. In the present paper this development work is summarized but with main focus on the recent activities of transferring the technology to industry as concerns manufacturing methods and testing. This work was carried out within the 3½ years project INDUFLAP (2011-2024), funded by the Danish Energy Agency through the EUDP 2011 programme. The industrial project partners in the project were Rehau (DE), Hydratech Industries (DK) and Dansk Gummi Industri (DK). DTU was coordinator of the project.

2 FLAP ACTUATION CONCEPT

The initial investigations back in 2006 of finding a suitable, robust flap actuation concept led to the design of the Controllable Rubber Trailing Edge Flap (CRTEF). A design concept that fulfills the requirements of: 1) no mechanical parts; 2) no metal parts and 3) no electronics in the blade. The CRTEF is a trailing edge flap manufactured in an elastic material such as e.g. rubber or a polymer material and with suitable voids that can be pressurized with a medium such as air or a liquid and, thus giving the desired deflection of the flap. If the lower row of voids are pressurized the flap will deflect upwards as shown in

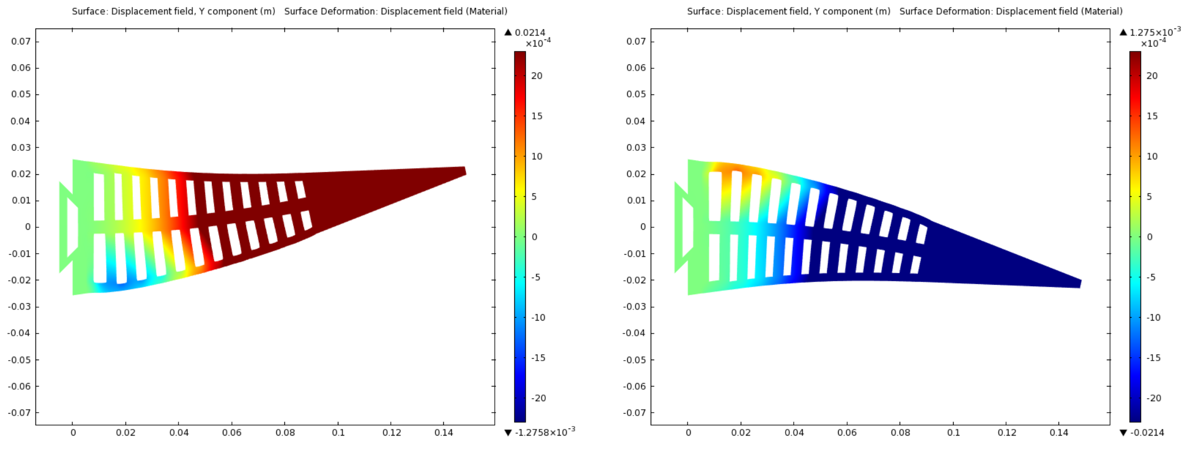


Figure 1: To the left, the lower row of voids is pressurized giving an upward deflection and to the right the upper row of voids is pressurized giving a downward deflection.

the left illustration of Figure 1 and likewise a downward deflection is obtained by pressurizing the upper row of voids.

3 FLAP DEVELOPMENT

3.1 The development work from 2006 to 2010

In this period several different flap prototypes were designed and manufactured as described in [4]. Two basically different concepts were investigated: 1) flaps with voids in the chordwise direction as shown in the left part of Figure 2, and 2) flap designs with voids in the spanwise direction as shown to the right in Figure 2. The flap designs with the chordwise voids were used in the first part of the development work from 2006 to 2010. Prototypes with a dimension of 15cm in chordwise length and 30cm in spanwise length were manufactured in different materials, e.g. silicone and with different reinforcements of the voids [4]. A major milestone was achieved in 2009 where the flap concept was tested on a 1.9m long (spanwise) and 1m (chordwise) blade section in the Velux open jet wind tunnel in Denmark [4]. A maximum change of Cl of about 0.2 was achieved with the prototype flap and the time constant of the actuation was determined to about 0.1s using a pneumatic pressurizing system of the voids [4], Figure 3.

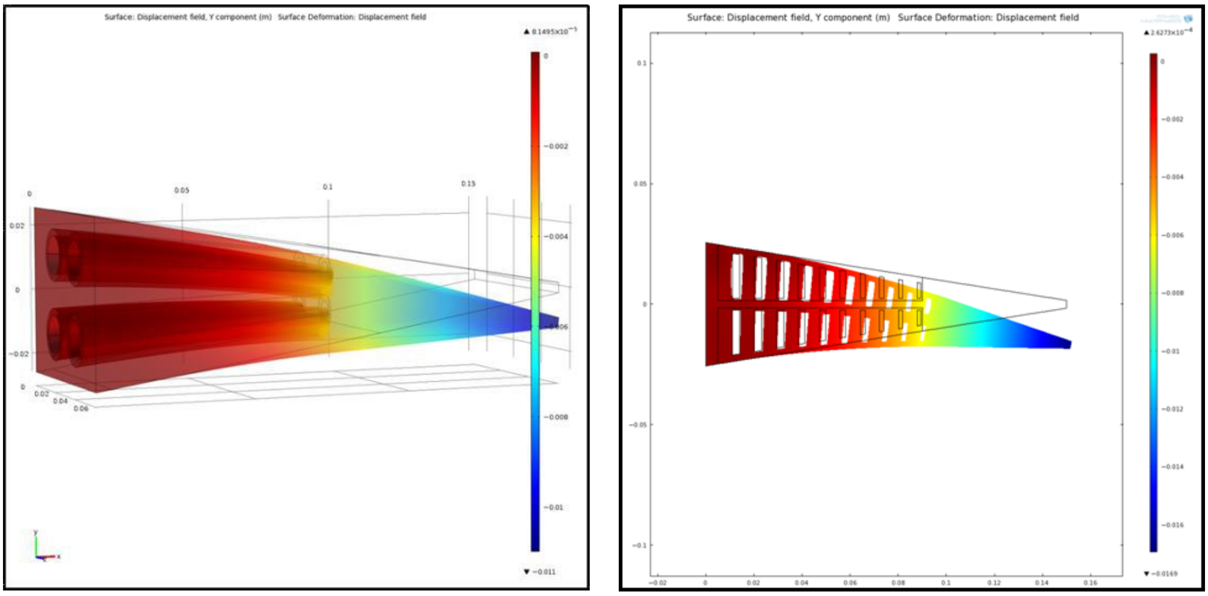


Figure 2: To the left the flap design with voids in the chordwise direction and 2) flap design with voids in the spanwise direction.

3.2 The development work from 2011 to 2014

After the prove of the concept by the wind tunnel testing in 2009 the development work has, as mentioned above, continued within the INDUFLAP project with focus on transferring the flap technology to industry as concerns manufacturing and testing. Basically the work has been within four main areas:

1) **Flap design, materials and manufacturing techniques**
    a. The industrial partner Rehau has worked with manufacturing flaps with voids in spanwise direction in an extrusion process
    b. The industrial partner Dansk Gummi Industry has carried out mold manufacturing of flap designs with chordwise voids
    c. DTU has worked with mold manufacturing techniques of both flap designs

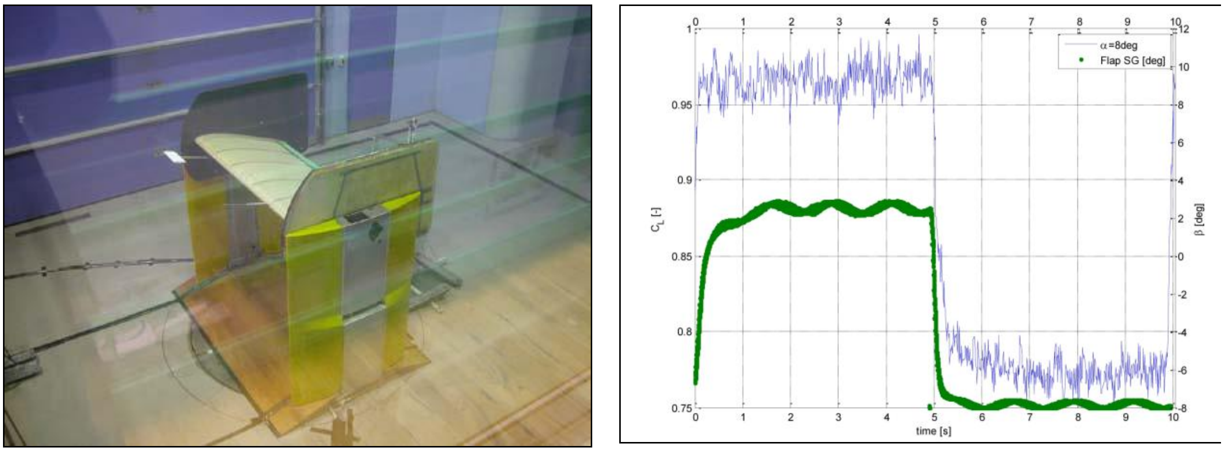


Figure 3: Photo to the left shows the 1.9x1m blade section with a 15% flap for the wind tunnel tests in 2009 in the Velux open jet tunnel in 2009. The graph to the right shows the change in lift (blue line) for the flap moving from a 2 deg. flap angle to -8 deg. flap angle (green curve).

2) Powering (pressurizing of voids) and control of flaps
   a. These activities have been carried out by the industrial partner Hydratech.

3) Investigation of lightning protection
   a. DTU Electrical Engineering has carried out modelling of impact of lightning as well as conducting lightning test on material samples as well as on a wing section with the flap system

4) Testing of flaps on an outdoor test rig
   a. DTU has been responsible for developing the rotating test rig and Hydratech contributed with input on the powering system of the flap and the control system

3.3 Flap design and manufacturing at Rehau

The detailed design of the flaps was mainly done by the use of the COMSOL software [5] simulating the complex stress distribution in the flaps with voids [6]. As an example is shown a design case in Figure 4 where the geometry of the voids and the wall thickness were

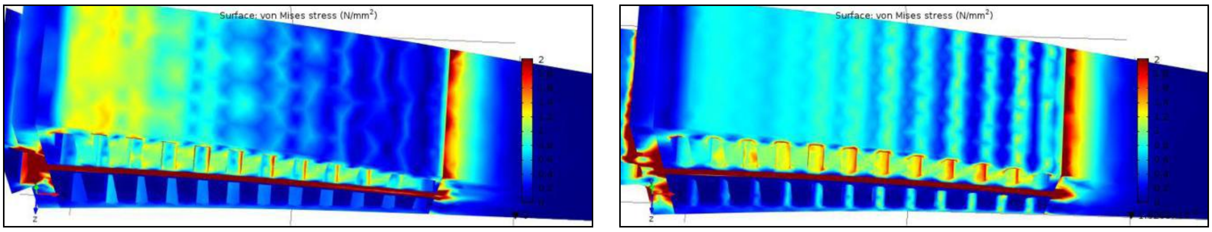


Figure 4: Computed stress contour levels on the flap with baseline void geometry to the left and another design to the right. The latter design was optimized with respect to achieve a more uniform stress level (less yellow areas) on the surface.

optimized to achieve a more uniform stress level on the surface of the flaps. The industrial production of prototypes has been performed at REHAU in a multi component system that comprises an load structure, left photo in Figure 5, and two elastic active elements regulated in deformation by a pressurized fluid medium, right part of Figure 5. Fabrication of the active elements was performed by a continuous thermoplastic extrusion process in form of a quasi endless 12 chamber hollow profile. For manufacturing the sealed ends of the hollow profiles, a special method of a contact welding process has been developed.

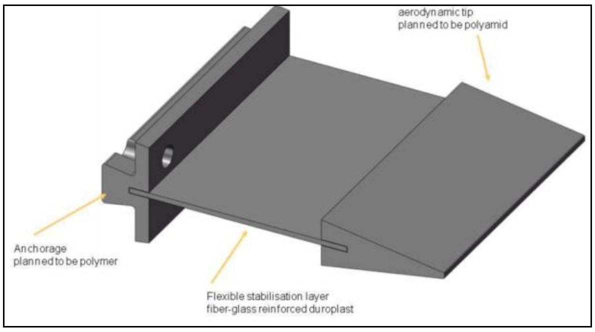


Figure 5: To the left is shown the load carrying components of the flap. To the right the parts are assembled but not glued together.

3.4 Actuating system for the flaps

In the design of the actuating system, great focus has been on efficiency, reliability and an environmentally friendly solution. Several different solutions were discussed, but especially the environmental focus turned the design towards a pneumatic solution, which would not have any environmental issues with leakage. The initial design was made with standard on/off valves to increase efficiency and reliability. The setup with these simple valves was able to yield seven different deflections of the flaps. Even though the input to the flap, with this solution, was by discrete steps, the actual output deflection turned out to be a satisfying continuous result. Therefore, a scaled system for the rotating test rig was designed to investigate the behavior in a rotating environment and with external loads.

Further studies on the actuating system have turned the focus back to a solution with an incompressible fluid as the actuating media. Several advantages with a fluid solution can be found, and one advantage with the fluid solution is that the number of actuators will be limited to maximum two actuators per flap or perhaps as low as two actuators per blade depending on the control strategy. It will also be possible to remove the actuators from the blade and into the hub. This will of course be an advantage, as the ease of service would increase significantly. Furthermore, the stiff fluid system will decrease the response time.

4 INTEGRATION OF THE FLAP SYSTEM INTO THE BLADE

One of the advantages with the flap system is that the main blade is designed and manufactured without the normal trailing edge. Instead it is proposed that a web is inserted in the blade around 10-15% chord length from the trailing edge and the flap is easily connected to the blade with a two part connector as shown in Figure 6. All parts have been manufactured in non-metal material.

A blade design without the sharp trailing edge part and instead with the small trailing edge web is expected to be structurally preferable and to allow for considerable savings in finishing the blade trailing edge, as no finish work after inserting and gluing the web would be necessary. Furthermore, design studies indicate that the flaps could be mounted on the whole blade span from 50% radius and to the tip or started even closer to the root so that a blade with flat back airfoils on the inner part could continue directly into the part where the flaps are mounted. Part of the flaps could be passive and mounting of the flaps could be carried out at the installation site and in sections of 2-3m.

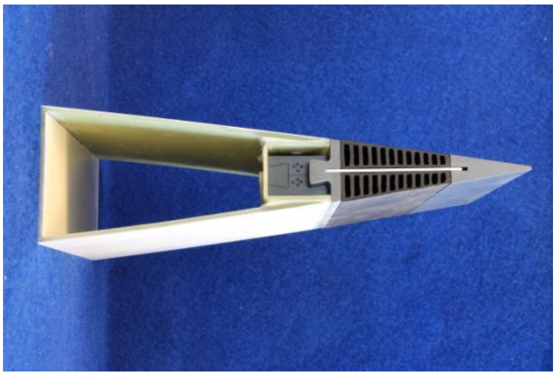
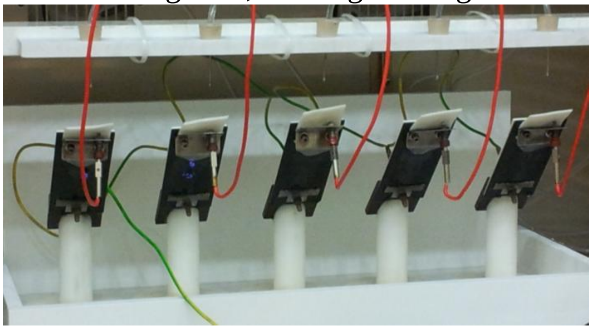


Figure 6: To the left is shown a sketch of the principle of mounting the flap onto the blade. To the right is shown the two part connector mounted on the web in the blade on the one side and on the flap on the right side.

5 INVESTIGATION OF LIGHTNING PROTECTION

Wind turbine blades are expected to be struck by lightning several times during their life time. The flap system, as part of the blade, will be equally affected by direct and indirect effects of lightning discharges. The assessment of the effects of lightning on the flap system comprised the study of the lightning attachment on the blade, the lightning current distribution in a blade struck by lightning and the electrical stress on the flap insulating materials due to the high electric fields caused by lightning.

The erosion and degradation of the blade rubber materials due to the lightning discharges have been determined by performing breakdown and tracking resistance tests. Breakdown strength tests were applied to a sample of the rubber material used in the flap structure as can be seen in Figure 7, left. Figure 7 right shows how the breakdown of the samples was. The



Santoprene - Silicon rubber - PUR - EDPM

Figure 7: Test setups for determination of the blade rubber materials performance under lightning discharges. Left: Breakdown test setup. Right: Damage on different samples.

Santoprene material showed a higher withstand voltage in tracking tests than GFRP (Santoprene: 4.25kV, GFRP: 1.5-3.5 kV/mm), and significantly better than other rubber materials (Silicone rubber, PUR, EDPM) [9], [10]. Next lightning tests were conducted on a blade section of 1m chord and 2m span with the flap system mounted as shown in Figure 8 and Figure 9. 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. No major damage of the flap material and no puncture of the voids occurred during the lightning exposure.

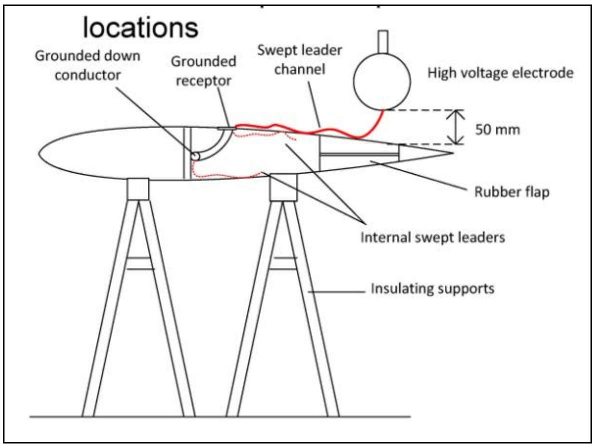


Figure 8: The experimental set-up for the lightning tests on the 1x2m blade section with flap system.

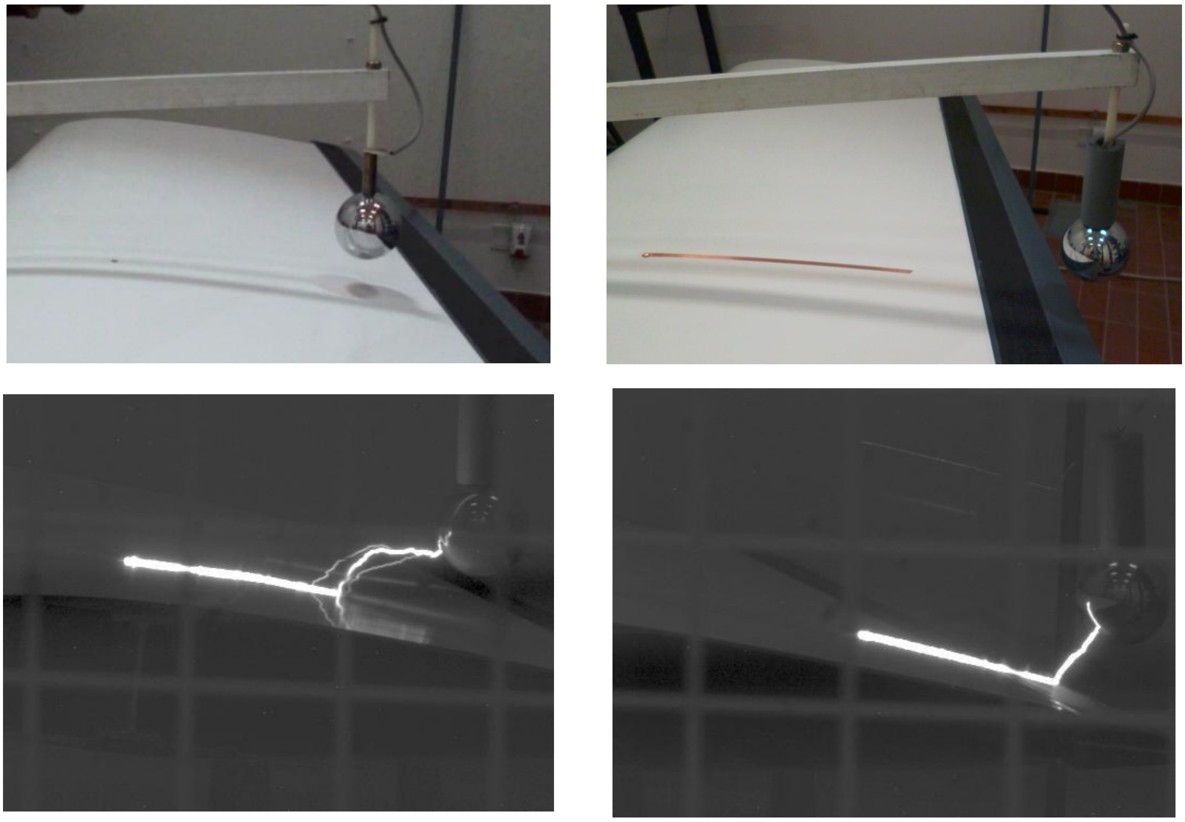


Figure 9: The lightning tests of the flap system were performed on a 2m long blade section with a 15% flap (the chord wise length of the flap is 15% of the blade chord). The scale of the blade is thus only slightly lower compared with the outer part of the blade on a MW turbine.

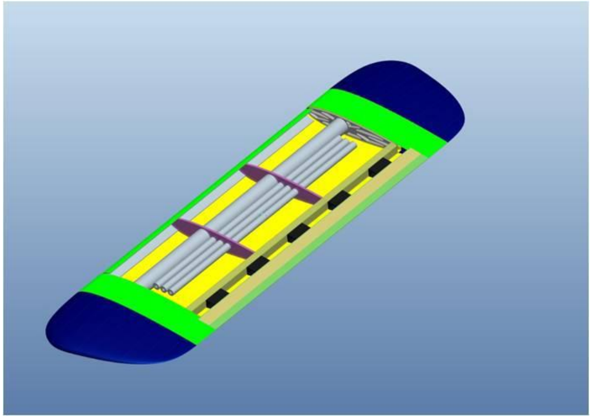
7 TESTING OF FLAPS ON AN OUTDOOR TEST RIG

Testing the performance and robustness of the smart blade technology was an important part of the INDUFLAP project. Wind tunnel testing of the present flap system was done back in 2009 as mentioned previously and proved that the actuation concept works in a wind tunnel envirenment. However, there is big step from wind tunnel testing on a stationary blade section to full scale turbine application and therefore a so-called rotating test rig has been developed in the INDUFLAP project.

The idea behind the test rig is that the testing should be as close as possible to the rotating test environment on the real turbine and have the same unsteady inflow conditions and a size of the flap not that far from full scale. This has been obtained by manufacturing a blade section with a 1m chord and 2m span and mounting it on a 10m long boom as shown below in Figure 10. The basic platform for the rotating test rig is the 100kW Tellus turbine positioned at the old turbine test site at DTU, Campus Risoe. The original three bladed rotor has been taken down and the boom with the blade section was mounted in June 2014, Figure 11. A new full variable speed drive was installed so the rotational speed with the boom mounted is controllable between 0 and 60 rpm.

A comprehensive instrumentation of the test rig was carried out and includes sensors for the blade surface pressure distribution on the mid span position, which enable a continuous monitoring of the instantaneous sectional aerodynamic loading on blade, and thus also allow measuring the exact response of flap actuation. Another part of the instrumentation comprises two five hole pitot tubes of the leading edge of the blade section for measuring the inflow to the blade. Finally, metrological data such as wind speed and wind direction is measured in three heights in a nearby met. mast.

In order to test different control algorithms that would be realistic on a full scale turbine the boom and the blade section can also be pitched. This will be used to test different strategies of combining pitch and flap control.



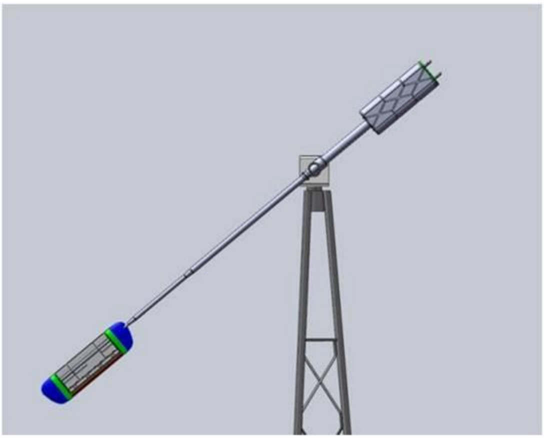


Figure 10: To the left is shown the layout of the blade section. To the right the design of the rotating rig is sketched.

8 TESTING OF THE FLAP SYSTEM ON THE ROTATING TEST RIG

After installation of the boom with the blade section in June 2014, a measurement campaign was conducted in the autumn 2014. A major objective with the testing was to prove that the flap system can work under the rotational conditions. It was proved that the system can sustain a 10g loading which corresponds to the conditions on the outer part of the blade on a MW turbine.

Figure 11: To the left is shown the installation of the boom in June 2014 and the photo to the right shows the blade section with the flap system and two five hole pitot tubes for inflow measurements.

Another major objective was to measure the capability of the flap system to change the lift on the blade section. Therefore a number of measurements were conducted with the flap angle in a plus/minus 5deg. position and the results are shown in Figure 12. From these figures it can be derived that the overall performance shortly can be described in the way that 3 deg. flap angle gives about the same change in lift as 1 deg. pitch. With the target of the final flap system of a plus/minus 10 deg. flap angle this is satisfactory to alleviate the major part of the dynamic loads on wind turbine blade [4].

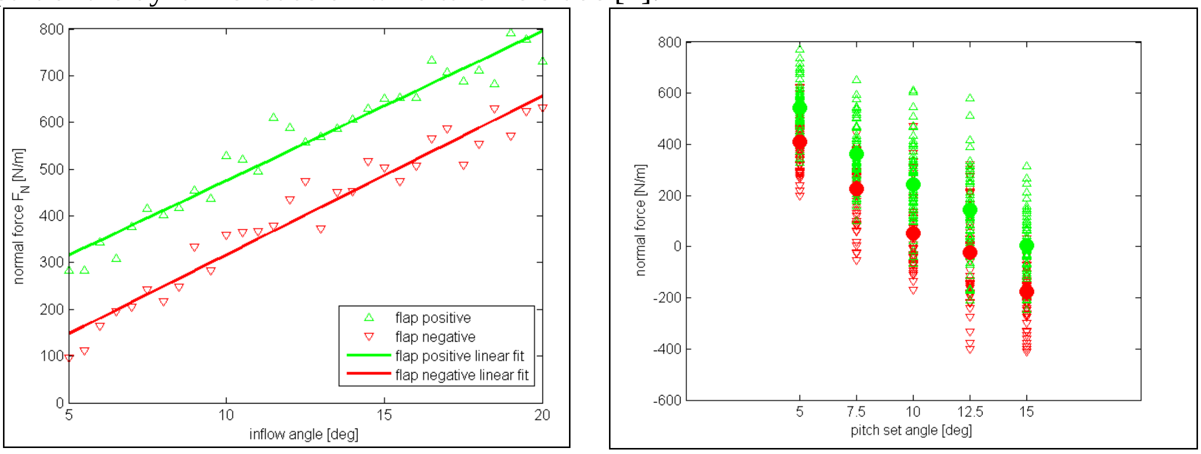


Figure 12: The graph to the left shows the normal force on the blade section as function of measured inflow angle for plus/minus 5 deg. flap angle. To the right is shown the normal force on the blade section for plus/minus 5 deg. flap angle as function of the pitch setting of the flap angle.

8 CONCLUSIONS

A morphing trailing edge (flap) for wind turbine blades has been developed over the last 10 years. The functioning of the flap system is simple as the movement of the flap is created by pressurizing voids in the flap that is manufactured in a flexible material. This means that the system is without any metal and mechanical parts that should ensure a robust system.

A dedicated outdoor rotating test rig has been developed for testing the flap system. The rig constitutes a testing that lies between wind tunnel testing and a full scale testing. The advantages are e.g. that it enables testing at a Reynolds number that is only slightly lower than what is present on a full scale turbine. Another major advantage is the real atmospheric inflow that makes it possible to test realistic flap control algorithms. Finally and not least the flap system are tested for g loadings that correspond to full scale turbine conditions.

The future steps will be further testing on the rotating test rig and corporation with wind turbine OEM´s for full scale testing of the flap system.

ACKNOWLEDGEMENTS

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