Final report

1.1 Project details

Project title	Full scale demonstration of an active flap system for wind turbines
Project identification (program abbrev. and file)	EUDP-2015–I, J.nr. 64015-0069
Name of the programme which has funded the project	Energiteknologisk Udviklings- og Demonstrations Program (EUDP 2015-I)
Project managing company/institution (name and address)	Technical University of Denmark, Department of Wind Energy Frederiksborgvej 399, Campus Risø, DK 4000 Roskilde
Project partners	DTU, Siemens Wind Power A/S, Rehau A/S
CVR (central business register)	30060946
Date for submission	31st of March, 2019

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1.2 Short description of project objective and results

English

The overall objective of the project is to demonstrate the system integration, the functioning, the performance and the value of an active flap system by full scale turbine tests. During the first part of the project more than 20 concepts were briefly explored. Based on a consistent evaluation of these proposals, two flap designs were selected for detailed design and testing. One concept is a so-called add-on type that can be mounted on existing blades. After laboratory and wind tunnel tests the flap design was afterwards tested in the real environment, first on a so-called rotating test rig and finally on a Siemens 4 MW turbine. The full scale tests confirmed overall the simulated performance. It is therefore expected that the flap technology can provide an increase of 8% in AEP/Loads ratio for offshore platforms with negligible increase in CapEx.

Danish

Projektets overordnede formål er at demonstrere systemintegration, funktionalitet, performance og værdi af et aktivt flapsystem ved afprøvning på en fuldskalamølle. Gennem den første del af projektet blev mere end 20 koncepter foreslået og lettere undersøgt. Ud fra en grundig og konsistent evaluering af disse koncepter blev to designs udvalgt for grundigere videreudvikling og afprøvning. Et af de to designs er et såkaldt add-on koncept som betyder, at det monteres på eksisterende vinger. Efter laboratorie- og vindtunnelafprøvning blev dette design efterfølgende afprøvet under realistiske forhold, først på en såkaldt roterende test stand og efterfølgende på en Siemens 4 MW vindmølle. Overordnet bekræftede fuldskalaafprøvningen den beregnede effektivitet. Det forventes derfor, at den udviklede flapteknologi kan forøge AEP/last forholdet med 8% for offshore møller med kun ubetydelig forøgelse af CapEx.

1.3 Executive summary

In the summary we will make references to the material worked out during the project and therefor the material is listed at this stage in the report. It comprises internal reports (all confidential), public conference papers and presentations and journal articles:

WP1:

[1] Alejandro Gomez Gonzalez, ″Induflap 2 WP1 Final report″, Release 03, 2019.03.15, SGRE OF TE TD BL ROP.

[2] Alejandro Gomez Gonzalez , "Induflap2 Active flap – Fast Track Product Requirement Specification", Document ID: WP LPD B ROP-60-00255-9217-00/ revision 2019.03.15.

WP2:

[3] Thanasis Barlas, "Flap structural design and simulation in the INDUFLAP2 project". DTU Wind Energy, March 2019, DTU Vindenergi-I-0874(EN).

WP3

[4] Tom Løgstrup Andersen, Helge Aagaard Madsen, Thanasis Barlas, "INDUFLAP2 Investigation of Active Flaps for control of Aerodynamic Loads", DTU Wind Energy-I-0872(EN), March 2019.

[5] Tom Løgstrup Andersen, Helge Aagaard Madsen, Thanasis Barlas, "INDUFLAP2 NA08-2111 Blade Section for Rotating Test Rig", DTU Wind Energy, March 2019.

[6] Anders S. Olsen, Thanasis K. Barlas, Helge A. Madsen, Andreas Fischer, Georg Pirrung, "Flap testing on the rotating test rig in the INDUFLAP2 project", March 2019, DTU Vindenergi-I-0876(EN).

[7] Thanasis K. Barlas, "Flap aeroelastic loads and field testing in the INDUFLAP2 project, DTU Vindenergi-I-xx(EN), March 2019.

[8] Jörg Goldstein, Santiago Pardos, ″Aschlussbericht Project title: EUDP 15-I, Fuldskala demonstration af et aktivt flapsystem for vindmøller Project no.: J.nr. 64015-0069.″. 20.03.19.

WP4

[9] Alejandro Gomez Gonzalez and Peder Enevoldsen, "Field test of active flap FT008rev09 - Prototype preparation and installation", Presentation at 10th project meeting, November 22nd, 2017.

WP5

[10] Alejandro Gomez Gonzalez , "Design FMEA - Failure Mode and Effect Analysis", revision -22-03-2019.

[11] Alejandro Gomez Gonzalez , "Active flaps – Business Case", Document ID: WP TE TD B ROP-60-00255-B179-02, 2018.09.28.

Conference papers and articles

[12] Barlas, Thanasis K., Carlo Tibaldi, Frederik Zahle, and Helge Madsen. 2016. "Aeroelastic Optimization of a 10 MW Wind Turbine Blade with Active Trailing

Edge Flaps." 34th Wind Energy Symposium. AIAA - American Institute of Aeronautics and Astronautics, 1–11.

[13] Pettas, Vasilis, Athanasios Barlas, Drew Patrick Gertz, and Helge Aagaard Madsen. 2016. "Power Performance Optimization and Loads Alleviation with Active Flaps Using Individual Flap Control." Journal of Physics: Conference Series (Online) 749 (1). Institute of Physics Publishing: 012010. doi:10.1088/1742-6596/749/1/012010.

[14] Barlas, Athanasios, Vasilis Pettas, Drew Patrick Gertz, and Helge Aagaard Madsen. 2016. "Extreme Load Alleviation Using Industrial Implementation of Active Trailing Edge Flaps in a Full Design Load Basis." Journal of Physics: Conference Series (Online) 753 (4). Institute of Physics Publishing: 042001. doi:10.1088/1742-6596/753/4/042001.

[15] Barlas, Athanasios, Yu-Huan Lin, and Helge Aagaard Madsen. "Structural Design Optimization of a Morphing Trailing Edge Flap for Wind Turbine Blades." (2017). VIII ECCOMAS Thematic Conference on Smart Structures and Materials SMART 2017.

[16] Barlas, Athanasios, and Busra Akay. 2018. "Optimization of Morphing Flaps Based on Fluid Structure Interaction Modeling." 2018 Wind Energy Symposium, no. 210029. American Institute of Aeronautics and Astronautics Inc, AIAA. doi:10.2514/6.2018-0998.

[17] Gomez Gonzalez, A., Enevoldsen, P. B., Akay, B., Barlas, T. K., Fischer, A., & Aa Madsen, H. (2018). Experimental and numerical validation of active flaps for wind turbine blades. Journal of Physics: Conference Series, 1037(2), [022039]. DOI: 10.1088/1742-6596/1037/2/022039.

[18] McWilliam, M., Barlas, A., Aagaard Madsen , H., & Zahle, F. (2018). Aeroelastic Wind Turbine Design with Active Flaps for AEP Maximization. Wind Energy Science, 3(1), 231-241. DOI: 10.5194/wes-3-231-2018.

Presentations

[19] M.Sc. presentation by Yu-Huan Lin, DTU, "Thesis Presentation: Structural Design Optimization of the Controllable Rubber Trailing Edge Flap (CRTEF)". June 7, 2016, DTU Wind Energy.

[20] Peder Enevoldsen "Active trailing edge flaps in turbine design– a mature technology?". IQPC Blade workshop, April 6, 2017

[21] Thanasis Barlas, Yu-Huan Lin, Helge Madsen "Structural design optimization of a morphing trailing edge flap for wind turbine blades", IEA Wind, Smart Blade, Technical Expert Meeting - 27 April 2017

[22] Peder Enevoldsen Active trailing edge flaps in turbine design – a mature technology? IEA Wind, Smart Blade, Technical Expert Meeting - 27 April 2017

[23] H Aa Madsen "Wind Turbine Flap Technology Development – from laboratory to full scale", Sandia Blade Workshop, August 28-29, 2018, Lubbock, Texas

[24] A. Gomez Gonzalez, T. K. Barlas, P. Enevoldsen and H.Aa.Madsen, "Field test of an active flap system on a multi-MW wind turbine", To be presented at the Wind Energy Science Conference, 17-20th of June, Cork, Ireland.

[25] A. S. Olsen, T. K. Barlas, H. A. Madsen, A. Fischer, T. L. Andersen and B. Akay, "Measuring drag on an airfoil section in atmospheric flow with a wake rake". To be presented at the Wind Energy Science Conference, 17-20th of June, Cork, Ireland.

Miscellaneous

[26] Topical Expert Meeting #87 on Smart blades IEA Wind Task 11- Topical expert meeting on smart blades, April 27-28, 2017, DTU, Roskilde, Denmark

The background for the present project is that a number of numerical and experimental studies over the last more than 10 years have shown that active flap systems can provide an interesting option for control of aerodynamic loads on wind turbine blades. In the state of the art technology this is done by pitching the blades and by variable rotor speed. With an active flap system a third control option is possible which has the big advantage that the load control can be different along the blade which can increase AEP and reduce loads and noise

The overall objective of the project is to demonstrate the system integration, the functioning, the performance and the value of an active flap system on a full scale turbine combined with a detailed risk assessment of the system and a well described business case for the application of the system.

The project builds upon the results of the EUDP 2010-II project "Industrial adaptation of a prototype flap system for wind turbines" where a flap system was developed from a laboratory stage to an industry level as concerns manufacturing and testing. Another important basis for the project is the considerable experiences by Siemens in using passive add-on´s like gurney flaps and serrated trailing edges (dino tais). Siemens has also looked at different active flap concepts that will be explored in the present project.

The project work is organized in five work packages. In WP1 "System integration", WP2 "Simulation", WP3 "Validation", WP4 "Full system design" and WP5 "Managing and product design analysis".

At the beginning of the project it was decided to work within two main design tracks: 1) a so-called fast track (FT) for development of an add-on type flap which means it can be mounted on an existing wind turbine blade, see Figure 1 and left sketch in Figure 2 and; 2) a mid-term (MT) track where the flap design to be

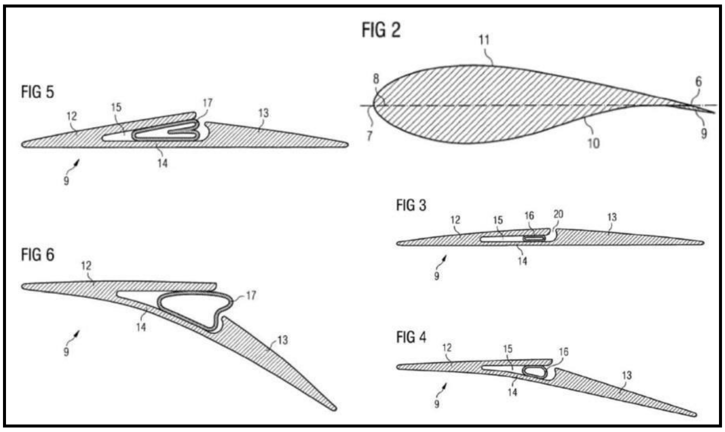


Figure 1 The add-on flap principle and design patented by Siemens.

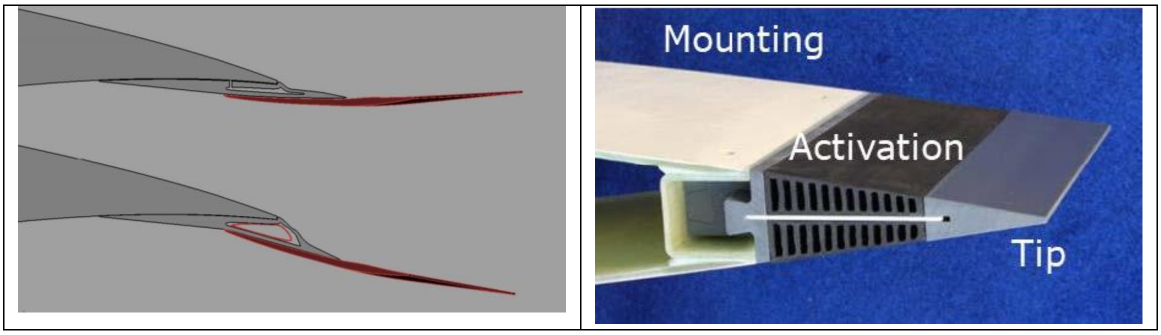
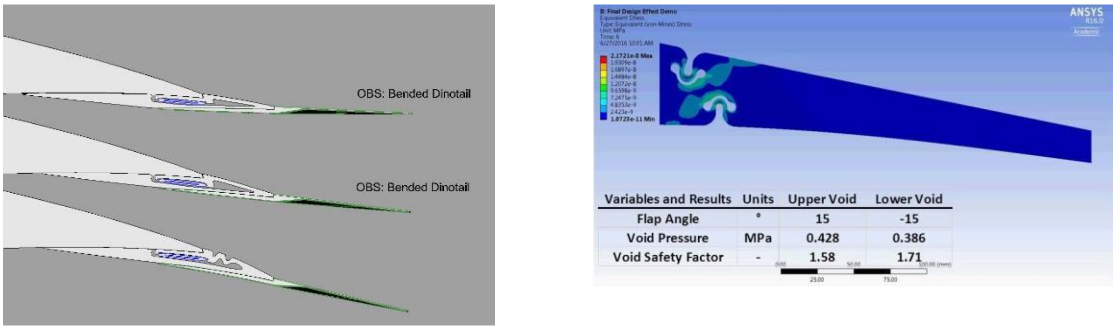


Figure 2 To the left is shown an add-on flap design (FT) that can be mounted on an existing blade with a sharp trailing edge. To the right a so-called MT design which requires a blade that is manufactured without the sharp trailing edge and have a spar where the flap can be attached to.

mounted on the blade requires a blade where the trailing edge region is designed with a finite thickness of the trailing edge, see right illustration in Figure 2.

During the first 6-9 months of the project more than 20 different flap designs were briefly explored [1]. The basic design idea which is the foundation of the INDUFlap2 project as well as the previous INDUFLAP project is that; 1) the actuation shall be pneumatic and 2) the flap shall be manufactured in elastic materials without any metal parts. These basic design requirements were considered to be necessary for development of a robust and cheap flap technology.

Product requirement specifications were defined [2] and afterwards a consistent evaluation of the designs was carried out in order to select 1-2 designs for detailed exploration and design.



Variables and Results	Units	Upper Void	Lower Void
Flap Angle	°	15	-15
Void Pressure	MPa	0.428	0.386
Void Safety Factor	-	1.58	1.71

Figure 3 The selected two draft designs for detailed development of the design.

We selected the two draft designs shown in Figure 3 although also FT013 and MT004 were investigated further to some extent. To the left in Figure 3 is shown the FT08 design and to the right the MT10 design.

The selected designs were now developed in much more details based on Finite Element (FEM) simulations [3], laboratory performance and fatigue testing [4], and wind tunnel testing [1].

Major subjects in this development have been; 1) choice of materials and 2) bonding issues and their interaction with the actual design. It turned out that the material Santoprene which also was the preferred material in the previous INDUFLAP project is an ideal material in relation to many of the material requirements for the flap manufacturing. However, it is very difficult to glue to other materials, e.g. when gluing the flap onto the blade. A solution to this is manufacturing with co-extrusion where the different materials are bonded during the ex-trusion process [8]. However, the co-extrusion manufacturing process requires expensive tools and also considerable time in adjusting all the parameters in the manufacturing of the first prototype. Therefore it is not a manufacturing process that can be widely used in investigating different prototypes. In the present project it is only used for manufacturing the latest MT design.

Instead of co-extrusion we have made considerable use of printed prototypes, [1],[4] and [8]. This has been good for demonstrating design principles and flap deflection capability but a drawback is that the materials that can be used for printing do not have the same good properties e.g. strength and fatigue in comparison with the materials used in co-extrusion. This has resulted in failures during wind tunnel tests [1] and performance tests in the laboratory [4].

The FEM simulations [3] have been widely used in development and improving the designs. Observations made during wind tunnel tests or performance and fatigue tests in the laboratory have let to new modified designs where the FEM simulations of the new design then have given the first insight into the performance and stresses in the material from which a safety factor can be derived. Also interaction with the experts on the manufacturing process has led to required modification. An example on this will be shown later in this report. To illustrate the design iterations due to feedback from testing previous versions it can be mentioned that the latest FT version developed in the project has number 14, see Figure 14 on page 10 in [3].

For testing flap prototypes in the real environment and close to conditions on a full scale turbine we have also made considerable use of the so-called rotating test rig (RTR) developed and build in the previous INDUFLAP flap project. A new 2m long blade section with an airfoil cross section equal to the one on the 4MW Siemens turbine at Høvsøre used for the full scale testing was build and instrumented [5], see Figure 4. In the present project we enhanced the instrumentation with a wake rake so that also the airfoil drag can be measured in addition to the measurements of the lift based on the pressure taps in the blade section. The wake rake is closely spaced pitot tubes mounted behind the airfoil section, see right photo in Figure 4, which enables the measurement of the velocity deficit behind the trailing edge of the airfoil from which the drag can be extracted [6] [25]. We can thus measure the airfoil and flap performance in real atmospheric flow and compare with the same characteristics in wind tunnel flow.

Figure 4 To the left manufacturing of the blade section for the rotating test rig. To the right the blade section has been instrumented. The arrangement with the black poles holds a wake rake that is used for measurement of the drag of the blade section.

The blade section attached to a 10m long boom was afterwards mounted on the rotating test rig, Figure 5. Both an FT and an MT design were tested [6].

Full scale testing of a flap system is as mentioned above the overall objective of the project. Preparations by manufacturing of the flaps began in early autumn 2017. The flap revision was the FT008_rev09 and they were manufactured by extrusion in silicone [8]. The manufacturing was followed by a test installation on one blade on the ground in October 2017, Figure 6, and later in the autumn the flaps were installed on the Siemens 4MW turbine in Høvsøre, sees Figure 6.

Figure 5 The blade section installed on the rotating test rig test rig.

Figure 6 The left photo shows the blade on the ground with the installed FT_008_rev09 and the dino tails (saw teeth elements) mounted on top of the flaps. Later in the autumn 2017 the blade was installed on the 4MW Siemens turbine at Høvsøre – right photo.

The finishing of the installation with e.g. mounting hoses for pneumatic supply from the hub could first be finished in the spring 2018 due to low temperature during the winter time and the measurements started then in May. A clear capability of the flaps to change the aerodynamic loads on the blade was demonstrated by comparing the blade root moment of the blade with flaps with the root moment of the neighbouring blade without flaps. This was based on a simple on/off activation of the flap.

Unfortunately the blade with the flaps was hit by a lightning strike in June 2018 and was damaged so much that it had to be replaced with a new one. This also meant that new flaps had to be manufactured before the installation on the new blade then could begin during the autumn 2018. One advantage by installing a new set of flaps was that an improved version FT008_rev10 could be used.

The delays in full scale testing due to replacement of the blade had the impact that a project extension was applied for, first to the end of December 2018 and later another extension to the end of March 2019.

The measurements with the new flap installation conducted in the first months of 2019 confirm the improved load response of the new FT008_rev10 version as both predicted by simulations and also measured in the wind tunnel.

Besides the flap technology development and measurements described above another major part of the project is several different investigations on exploring the usage of the flaps in different configurations.

One business case of using the technology is to take an existing turbine platform and show that a new and bigger rotor can be installed on the same platform if the flap technology is used to bring the loads down to the level of the original rotor. Such a case has been explored using the DTU 10MW reference rotor. In the investigation the rotor size is up scaled with 5% and flaps are installed on 30% of the blade span. A flap response range of +- 15 degree is assumed and a chordwise length of 10%. It should be mentioned that the range of +-15 degree in flap response can probably only be achieved with a MT flap design that can deflect actively both up and down whereas a FT design only deflects to one side.

Aeroelastic simulations for a representative set of Design Load Cases (DLC)'s show that both fatigue loads [13] and extreme loads [14] can be brought down to a level close to the original loads of the base line rotor. An example for the fatigue loads is shown in Figure 7. In particular the flapwise blade root moments MxBR can be seen to be at the same level as the baseline whereas for other components the reductions are less, e.g. the tower bottom moment MxTB.

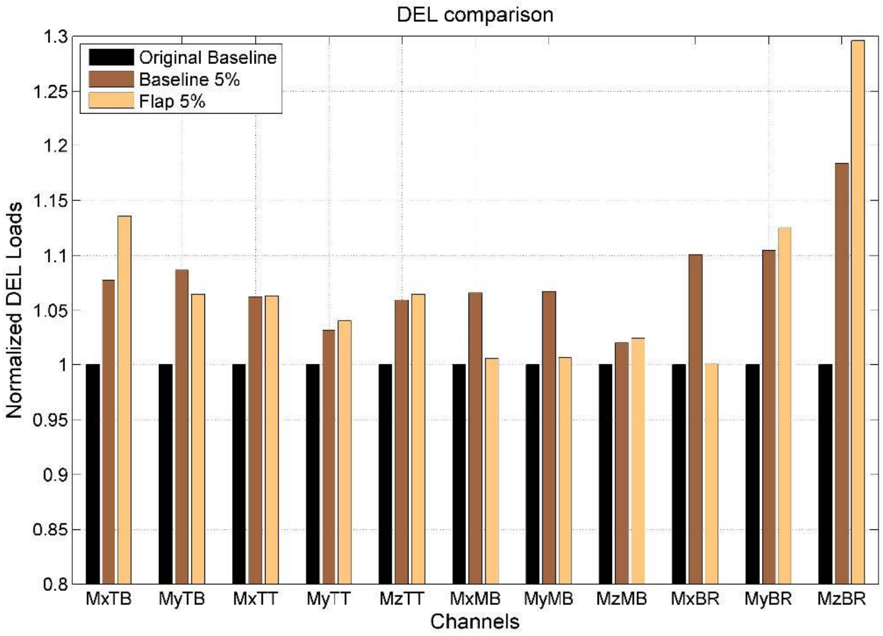


Figure 7 Figure from [13] showing how flaps can reduce fatigue loads for a 5% up scaled rotor down to a level close to the level of the baseline rotor for some components and in particular for the blades (e.g. flapwise blade root moment MxBR).

For the extreme load reduction the flaps are also efficient to bring down the blade flapwise moments. However, most important it might be that flaps are very efficient to increase the tip clearance which can be explained by the fact that they are used to control the loads on the outboard part of the blade. In the particular study in [14] it is shown that even for the 5% up scaled rotor with flaps the tip clearance is better that for the baseline.

Integration of flaps on a blade during the blade design will generally be more optimal than introducing the flaps on an extended baseline blade as shown above. The full integrated design of a blade with flaps considering both the aerodynamic and structural design has been explores in two cases in the project.

In the one study the DTU 10MW reference wind turbine is again the baseline [12]. Now a new blade is designed but with the same length as the baseline. As in the example above the flaps are covering 30% of the blade span and positioned at the outboard part of the blade. With constraints on loads and tip clearance it is shown that a considerable weight reduction in the range of 15-20% can be achieved and at the same time an increase in AEP in the range of 0.5 – 1.0%.

In another study a new blade is also designed for the DTU 10MW turbine and allowed to be longer than the baseline [18]. However, now a very simple flap control is used where the flap angle is just assumed to vary as function of mean wind speed. It means that the flap system will be much more simple and robust as compared with the above case where there continuously is a high flap activity. The overall result of the study is that the co-design taking into account the flaps during the whole blade optimization might add 0.5% increase in AEP compared with the case of optimizing first the blade and then adding the flaps.

Finally, an even simpler flap control is demonstrated in a case where a flap installation on the SWT-4.0-130, which is the turbine used for the present full scale demonstration of the flap technology. The focus of the work is on the extreme loads above rated with either 8 deg positive or negative flap deflection. The simulations show that the minus 8 deg flap deflection leads to a reduction of extreme loads on most components with a few % and 6% increase in tip clearance.

Based on the different studies mentioned above a final business case is described in [11]. The basic assumption is that it is a flap system with a simple control with flap variation as function of mean wind speed and a system that can detect if the turbulence intensity is high or low. For such a system it is concluded that:

- A conservative estimate of the increase of AEP/Loads ratio for a combination of the flap strategies mentioned above is therefore around 1.005/0.93 = 1.08 (0.5% AEP increase and 7% load reduction). It is therefore expected that the flap technology can provide an increase of 8% in AEP/Loads ratio for offshore platforms.
- An increase of CapEx for a full turbine installation is expected to be in the order of magnitude of 40 kEUR. The OpEx has not been evaluated at this stage. The expected power consumption of the system is below 10 kW (comparable to other auxiliaries such as cooling fans or drive motors). Therefore, the CapEx and own consumption are negligible in comparison to the baseline cost and own consumption of the turbine.

This interesting business case is the motivation for the project group to work on further development of the technology towards commercialization. An EUDP application was sent in the first of March 2019. The proposed project builds heavily on the present project but now with focus on the full system integration. The following section from the application gives an overview of and introduction to the proposed new work:

*"The project VIAs (**V**alidation of **A**ctive **A**erodynamic **A**dd-ons) aims at demonstrating and validating the full scale system integration of active flow control devices for the performance enhancement of wind turbines. In particular, the successfully developed active flap system for rotor blades (within the scope of the Induflap2 project, j. nr. 64015-0069) together with spoiler systems developed independently by Siemens Gamesa Renewable Energy A/S, will be integrated into a full scale multi-Megawatt wind turbine for demonstration of turbine performance enhancement and load control. This integration requires the maturing of peripheral subsystems to a technology readiness level (TRL) of 6, development of novel measurement instrumentation and techniques, demonstration of manufacturing concepts suitable for serial production, development of full-scale turbine servo control strategies, increasing the level of integration readiness level (IRL) to IRL6, as well as performing a thorough system characterization both at laboratory scale and field test level. The project partners Siemens Gamesa Renewable Energy A/S, DTU Wind Energy, and Rehau A/S bring with them a high degree of expertise, experience, and professionalism, all of them being world leading companies / institutions in their individual fields."*

1.4 Project objectives

The overall objective of the project is to demonstrate the system integration, the functioning, the performance and the value of an active flap system on a full scale turbine combined with a detailed risk assessment of the system and a well described business case for the application of the system.

As the main objective comprises development, manufacturing and demonstration of new technology where the tasks are shared between three project partners it requires close and frequent communication. It is also important to mention that it was agreed at the first project meeting to split the flap development up into two main tracks as described above: 1) a so-called fast track (FT) for development of an add-on type flap which means it can be mounted on an existing wind turbine blade; and 2) a mid-term (MT) track where the flap to be mounted on the blade requires a blade where the trailing edge region is designed with a finite thickness of the trailing edge. It was expected that the FT designs could be developed faster than the MT designs which also turned out to be the case. One consequence of that is that the fulfilment of the milestones will occur at different times for the two design tracks.

The project got a boost start with 5 project meetings within the first 7 months of the project. During this part of the project the overall work was within WP1 "System integration" supported by work in WP2 "Simulation" and with the objective to provide a wide range of flap concepts and designs. The selection of two FT designs for further detailed development was thus already carried out at the 3rd project meeting in December 2015 follow by selection of the MT design in September 2016. The detailed exploration of the selected designs could thus start early in the project with the first wind tunnel measurement campaign already in January 2016 on a printed FT_008_rev1 design [1], see Figure 8.

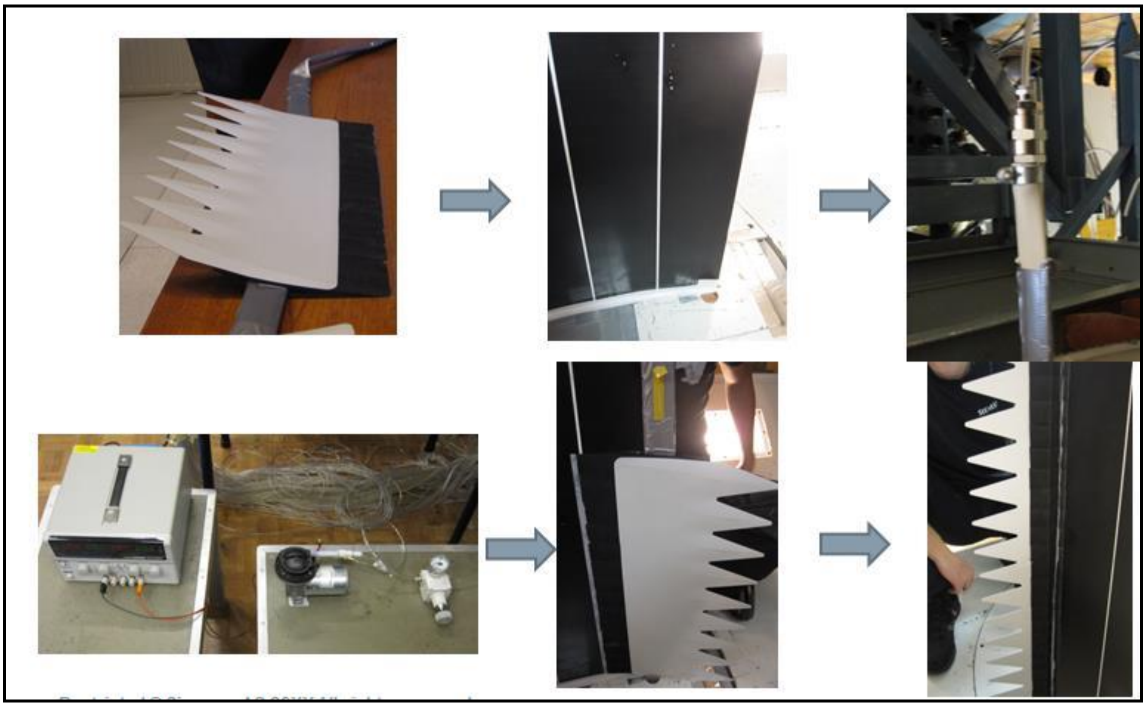


Figure 8 Main steps of wind tunnel setup for FT008_rev1. The flap was printed in sections with a spanwise length of 30 cm which then were positioned side by side to provide a full section fitting into the tunnel

The results from the first wind tunnel tests did not show a satisfactory aerodynamic response of the flap and also the flap material failed to some degree. Based on these results and performing new computations a second revision FT008_rev2 was designed and tested already in April 2016, [1]. Although this version had slightly better performance the capability to change lift was still much below the target of changing the lift coefficient with about 0.35 to 0.4.

The improvement of the FT008_rev2 was then continued and supported by FEM simulations [3] and ended with FT008_rev9. It was manufactured by extrusion in two different materials TPU and Santoprene [8] and was also the version that was used in the first full scale tests (May-June 2018). This design was tested during a third wind tunnel campaign in April 2017 (one year and three month later than the first wind tunnel campaign in January 2016). Some of the problems observed in the previous tests were now overcome, e.g. the gluing problems. However, the aerodynamic response was still unsatisfactory.

Finally, the further development work led to the FT008_rev10. Besides differences in the geometry a major difference is that this flap is manufactured in silicone [8] which is a softer material than Santoprene. This design showed a very big increase in performance reaching a delta Cl (Cl is lift coefficient) of 0.38 with a target of 0.40 [1]. I should also be mentioned that this is the flap version used in the 2nd full scale test setup implemented on the new blade in the autumn 2018 after the lightning strike in June 2018.

The above description of the design iterations on development of the FT flap serves to illustrate that the work flow in the project became more circular than originally described in the Gantt diagram. By circular is meant that the continuous feed back from the testing and validation in WP3 "Validation" led to new design work, also requiring continuous input from WP2. So the overall plan with "concept exploration" during the first year; "proof of concept" during the second year and "design and validation" in the third project year became more overlapping, in particular between the activities in "proof of concept" and "design and validation".

In order to keep momentum during these continuous ongoing design iterations a biweekly telephone meeting was held between a few key persons from all three project partners during most of the project. This turned out to be very efficient for the progress in the project.

One minor change in the project content is that noise aspects have not really been considered. This is due to the merge between Siemens and Gamesa where the Danish part of the new merged company has focus on off-shore applications where noise is not an issue. However, the developed flap technology has probably the potential to be used for noise reduction as it can be used to control the angle of the dino tail on top of the flap which is known to be an important parameter for the noise reduction of a dino tail. Noise was part of the commercial milestone CM1: AEP/loads/noise certification review but due to the above mentioned change of focus of the project towards offshore application of the flap technology, no simulations of noise have been included.

As the main objective of the project is to demonstrate flap technology on a full scale turbine there are risks associated with this. One risk is to be able to get access to a turbine at the right time in the project. This has not caused major delays in the project as there has been good access to the prototype turbine SWT-4.0-130 in Høvsøre.

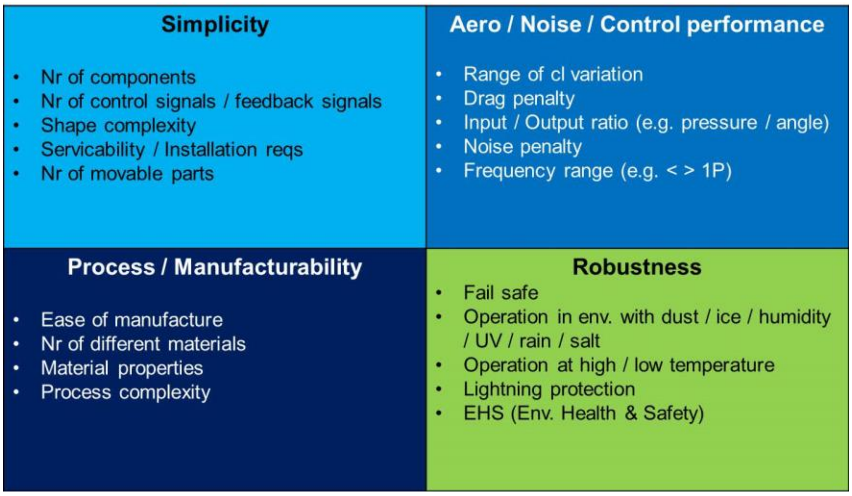
Another risk is associated with the weather and wind conditions as low wind and a certain positive temperature is crucial for being able to work from a lift and make installations on a blade. This has given quite some delays as the first full scale installation was initiated in the autumn 2017 but could not be finished before winter time where the temperature typically is too low, e.g. for gluing processes.

Finally, the lightning strike was of course unexpected and seemed not to be due to the flap installation on the blade. This caused a delay of around ½ year involving replacement of the blade; manufacturing of a new set of flaps and then going through the whole installation and instrumentation process again.

1.5 Project results and dissemination of results

As mentioned above there have been two main activities in the project; 1) development of an active flap technology towards a stage where a demonstration and measurement campaign on a full scale turbine can be carried out and; 2) explore by aeroelastic simulations different application scenarios of the flap technology in order to establish different business cases.

The development of the flap technology in the project was initiated through a brain storm process that resulted in more than 20 conceptual designs; 17 FT concepts and 10 MT concepts [1]. The FT concepts were afterwards scored by all project participants at a meeting in December 2015 according to the requirements listed in Figure 9. The result is shown in Figure 10 and it was then decided to proceed with the detailed design of FT008 and FT013.



Simplicity

- Nr of components
- Nr of control signals / feedback signals
- Shape complexity
- Servicability / Installation reqs
- Nr of movable parts

Aero / Noise / Control performance

- Range of cl variation
- Drag penalty
- Input / Output ratio (e.g. pressure / angle)
- Noise penalty
- Frequency range (e.g. < > 1P)

Process / Manufacturability

- Ease of manufacture
- Nr of different materials
- Material properties
- Process complexity

Robustness

- Fail safe
- Operation in env. with dust / ice / humidity / UV / rain / salt
- Operation at high / low temperature
- Lightning protection
- EHS (Env. Health & Safety)

Figure 9 The flap concepts were ranked based on these requirements.

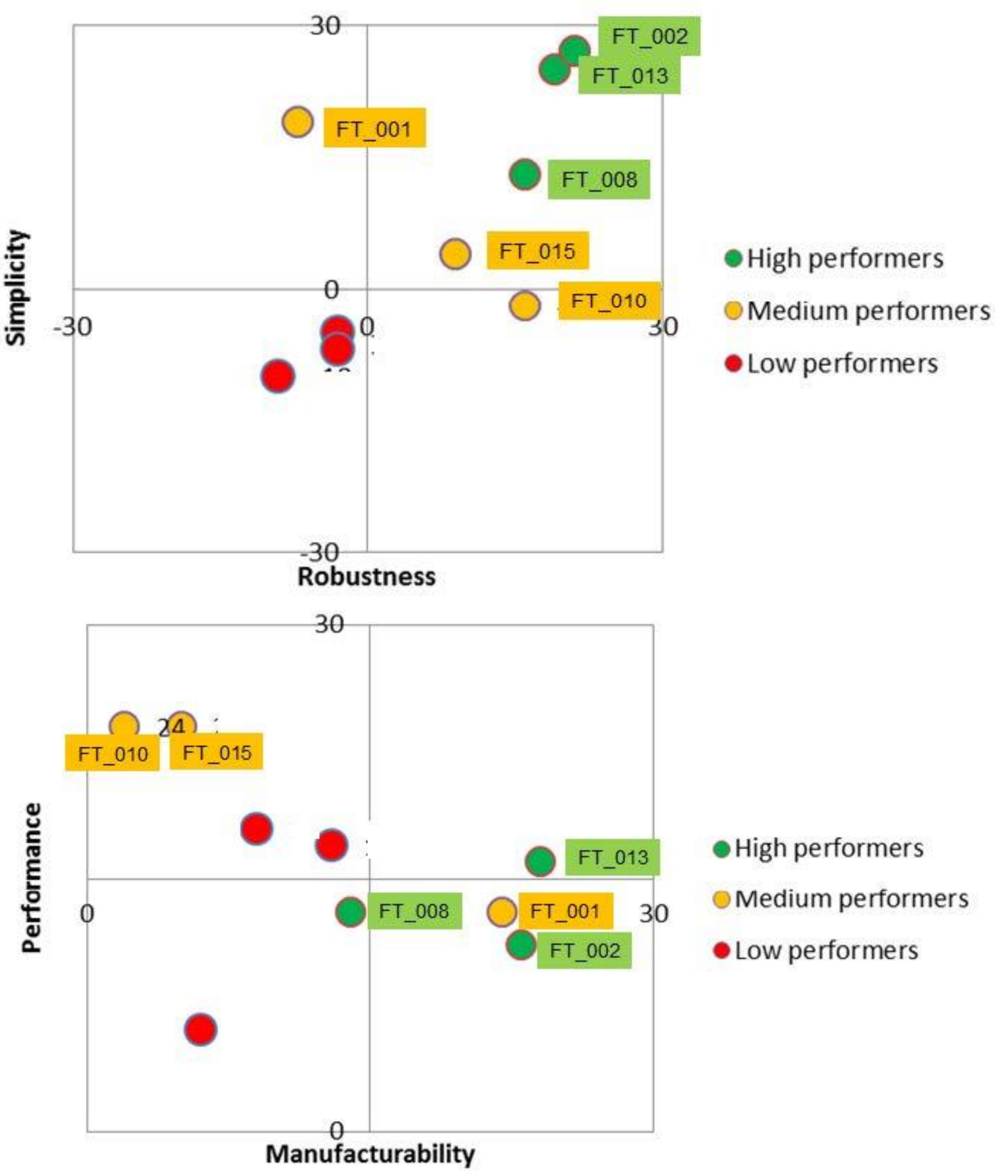
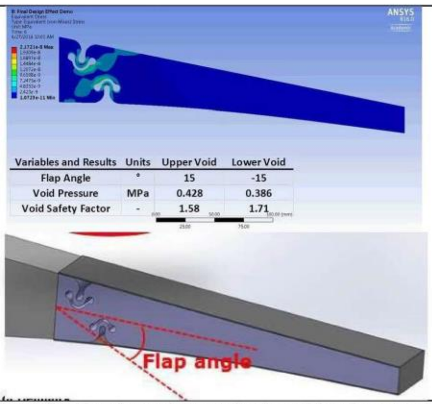


Figure 10 The result of scoring the different FT concepts according to: simplicity, performance, robustness and manufacturability.

For the MT designs the scoring was carried out at a project meeting in September 2016 and the MT_010 was chosen to proceed with, see Figure 11. By these concept selections for further exploration, the milestone **M1 "Conceptual design solutions"** were fulfilled in September 2016.

<table>
<tr>
<td colspan="2">
<table>
<tr><td>Reference name</td><td>MT_010</td></tr>
<tr><td>Add-on type</td><td>Midterm</td></tr>
<tr><td>TRL</td><td>1</td></tr>
<tr><td>Last updated</td><td>15-09-2016</td></tr>
</table>
</td>
<td>


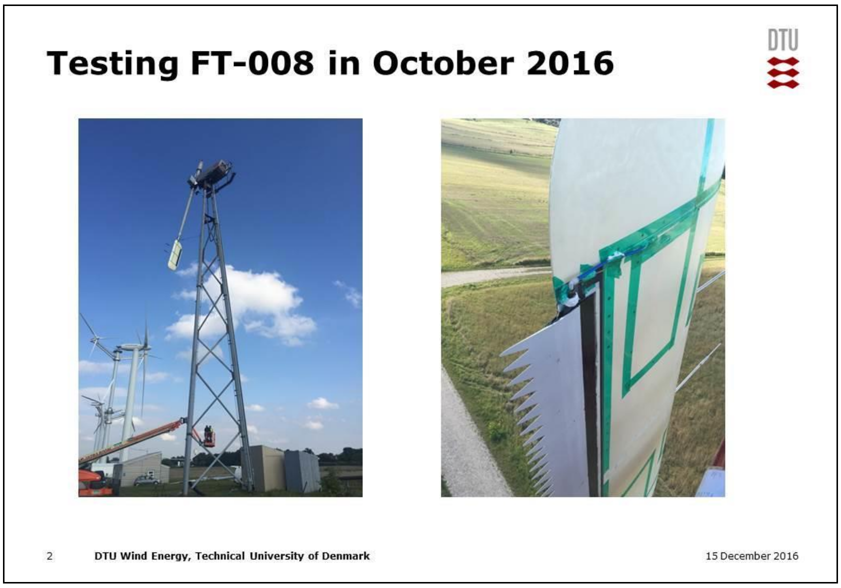
<table>
<tr><th>Variables and Results</th><th>Units</th><th>Upper Void</th><th>Lower Void</th></tr>
<tr><td>Flap Angle</td><td>°</td><td>15</td><td>-15</td></tr>
<tr><td>Void Pressure</td><td>MPa</td><td>0.428</td><td>0.386</td></tr>
<tr><td>Void Safety Factor</td><td>-</td><td>1.58</td><td>1.71</td></tr>
</table>
</td>
</tr>
<tr>
<td>Description</td>
<td colspan="2">Concept for add-on application based on a single void to be pressurized.

Flap where the geometrical elongation of an initially bend surface helps to give a big deflection (+-15 deg.) The initially bend surface can be covered with an elastic skin as shown in the lowest photo</td>
</tr>
<tr>
<td>Pro’s and Con’s</td>
<td colspan="2">Pros:
- High deflection to both sides
- Compact design

Cons:

- Present version requires high pressure (can be modified by the design)</td>
</tr>
<tr>
<td>Further actions and open questions</td>
<td colspan="2">-</td>
</tr>
</table>

Figure 11 The MT_010 was chosen as to proceed with.



Testing FT-008 in October 2016

2 **DTU Wind Energy, Technical University of Denmark** 15 December 2016

Figure 12 An early version of the FT_008 flap tested on the rotating test rig in the autumn 2016.

The development and validation of the designs in WP3 "Concept validation" started already in January 2016 with the first wind tunnel test of the FT_008_rev1. As described above the development of the FT_008 required several design iterations to reach a satisfactory performance of delta Cl of 0.38 obtained with FT_008_rev10. The investigations in the laboratory comprised tests of different flap materials, different type of actuation hoses inside the flap, position of hoses, fatigue tests and much more as described in [4]. An early version of the FT flap was also tested on the rotating test rig in the autumn 2016, see Figure 12.

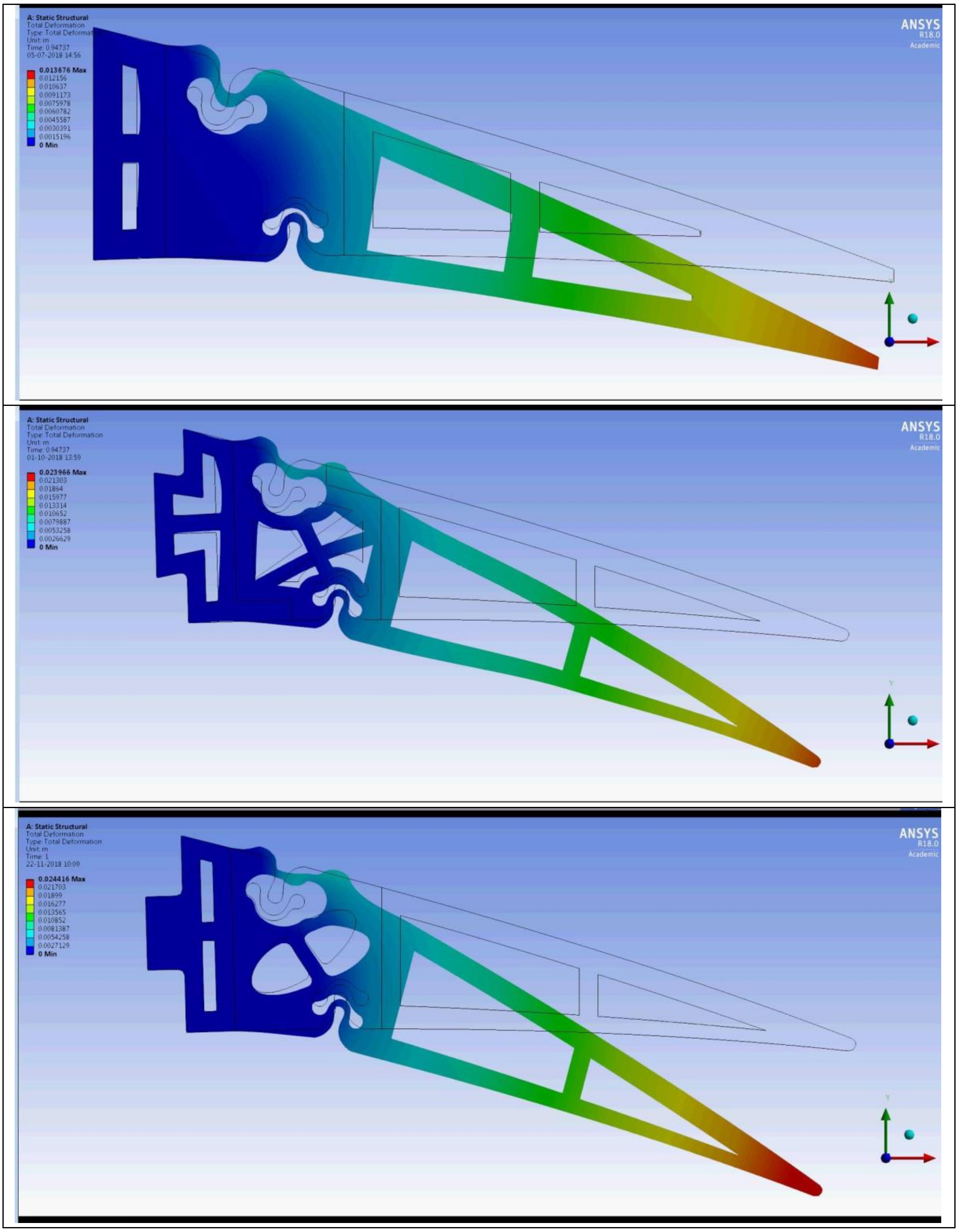
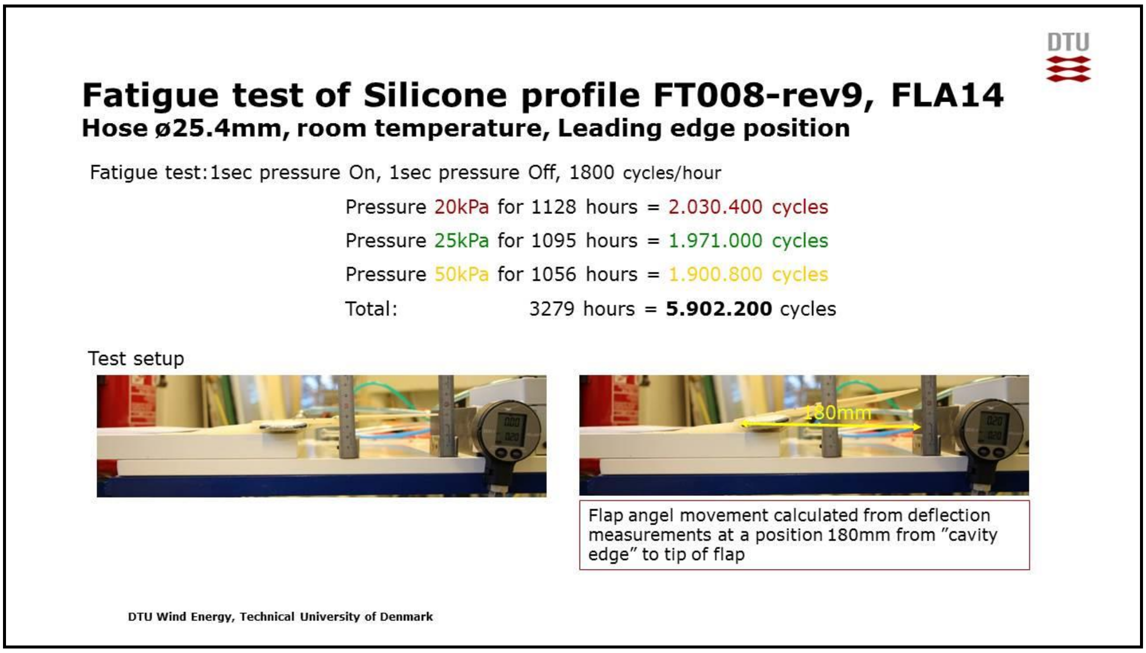


Figure 13 The development of the MT_010 flap. Upper version was initially proposed for manufacturing. Changes of design in the middle proposed by the manufacturing experts. Final design shown as the lowest sketch in the figure.

The development of the MT_010 design did also require quite some design iterations. This is illustrated in Figure 13 with three stages of the flap design. It should be mentioned that in this case the changes were not inferred due to low performance but due to concern from the manufacturing experts on the extrusion process [8]. The upper design in Figure 13 was first proposed. However, for extrusion the massive solid part is not easy to handle and the manufacturing people proposed the design in the middle of Figure 13. This was then modelled again with the FEM tool and based on the new simulations the final design in the lower part of Figure 13 was chosen.

An important part of the validation in WP3 has been fatigue test of the flaps. Recently one version, the FT_008_rev9 in silicone passed 5 mill using a test set-up in the laboratory shown in Figure 14 which confirms a satisfactory fatigue strength.



Fatigue test of Silicone profile FT008-rev9, FLA14

Hose ø25.4mm, room temperature, Leading edge position

Fatigue test:1sec pressure On, 1sec pressure Off, 1800 cycles/hour

Pressure 20kPa for 1128 hours = 2.030.400 cycles

Pressure 25kPa for 1095 hours = 1.971.000 cycles

Pressure 50kPa for 1056 hours = 1.900.800 cycles

Total: 3279 hours = **5.902.200** cycles

Test setup

Flap angel movement calculated from deflection measurements at a position 180mm from "cavity edge" to tip of flap

DTU Wind Energy, Technical University of Denmark

Figure 14 The fatigue test set-up in the laboratory at DTU.

With the validation activities described above and reported in reports [3], [4] and [6] the milestone **M3: "sub-component validation"** is fulfilled.

The integration of the flap system on a full scale turbine and the field testing is the objective of WP4 "Full system design". The FT_008_rev9 was manufactured at Rehau during the early autumn 2017. To develop and test the procedures of the installation of the flaps on the blade this was first performed on a blade on the ground at the Siemens manufacturing place in Brande [9]. Later in the autumn the installation was carried out on the turbine in Høvsøre. However, the installation could not be completed due to low temperatures at the end of 2017 and in the winter time. This was then done in late April 2018 and the measurement campaign started in May. A simple on/off control of the flap was used during these first measurements and the capability of the flap system to change the loading on the blade was done by comparing the blade root moment of the blade with the flaps with the blade root moment of the neighbouring blade without flaps. In this way a clear impact of the flaps can be measured [9].

Unfortunately the blade was hit by a lightning strike in June 2018 and the blade had to be replaced. This also meant that a new set of flaps had to be manufactured and installed on the blade. The only positive part of that accident is that a considerable improved flap, the FT__008_rev10 could be used for the re-installation.

The measurements on the turbine have now been ongoing for almost two month and they confirm the higher performance of the new flaps. With these activities in WP4 the **M4: "full system field testing"** and the commercial mile stone **CM2: "TL7 design"** is fulfilled**.**

Besides the flap technology development and measurements described above another major and important part of the project is several different investigations on exploring the usage of the flaps in different configurations. This has mainly been carried out within WP2 using the aeroelastic code HAWC2 for simulation of Design Load Cases (DLC´s) inclusive turbines with flaps and the HAWTOpt2 optimization framework which is a Multi Disciplinary Multidisciplinary design optimization (MDO) tool developed by DTU Wind Energy.

These studies were presented in some details above under the section "Executive summary" and therefore only a summary of the results will be presented here.

In two studies it is illustrated how the DTU 10MW reference turbine can be up scaled with 5% in rotor radius which leads to an increase in AEP of 3.7%. Installing flaps on the outer 30% of the blade span can bring the loads on most of the components back to the level of the baseline turbine loads [13], [14]. This means that the value of a flap installation is an increase in AEP of more than 3%. In this case it is assumed that it is a fast responding flap system with a flap angle response of +-15 deg which only can be realized with an MT flap as it can deflect both up and down.

In another study the DTU 10MW reference wind turbine is again the baseline [12]. Now a new blade is designed, both the aerodynamic and structural design, but with the same length as the baseline. As in the example above the flaps are covering 30% of the blade spans and positioned at the outboard part of the blade. With constraints on loads and tip clearance being equal to the baseline it is shown that a considerable weight reduction of the blades in the range of 15-20% can be achieved and at the same time an increase in AEP in the range of 0.5 – 1.0%.

In a third study [18] the main result is that taking the flap installation into the loop when designing the blade it is possible to increase AEP with 0.5% compared with the case of optimizing first the blade and then adding the flaps.

Finally, an even simpler flap control is demonstrated in a case where a flap installation on the SWT-4.0-130, which is the turbine used for the present full scale demonstration of the flap technology [17]. The focus of the work is on the extreme loads above rated with either 8 deg positive or negative flap deflection. The simulations show that the minus 8 deg flap deflection leads to a reduction of extreme loads on most components with a few % and 6% increase in tip clearance.

With the above studies the commercial milestone **CM1: AEP/loads/noise certification review** is fulfilled, however noticing that noise studies have not been included as the project only has focussed on flap application for offshore turbines which is the branch of the Simens-Gamesa company in Denmark.

The above AEP/load studies on different ways of using the flap technology and in particular the case on the SWT-4.0-130 with the very simple flap control [17] has formed the basis for working out a final, full system business case as presented in [11]. From that report we cite:

- A conservative estimate of the increase of AEP/Loads ratio for a combination of the flap strategies mentioned above is therefore around 1.005/0.93 = 1.08 (0.5% AEP increase and 7% load reduction). It is therefore expected that the flap technology can provide an increase of 8% in AEP/Loads ratio for offshore platforms.
- An increase of CapEx for a full turbine installation is expected to be in the order of magnitude of 40 kEUR. The OpEx has not been evaluated at this stage. The expected power consumption of the system is below 10 kW (comparable to other auxiliaries such as cooling fans or drive motors). Therefore, the CapEx and own consumption are negligible in comparison to the baseline cost and own consumption of the turbine.

With this business case the last commercial milestone **CM3: full system business case** is fulfilled.

Based on the above overview of achievements and all the more detailed information in the reports and publications worked out in the project it can be concluded that the project did succeed in fulfilment of the objectives, not least the demonstration of an active flap system on a full scale turbine which probably is the first time on that size of turbine.

The new flap technology opens for a more detailed and distributed control of the aerodynamic loads along the blade which the present technology with pitch regulation cannot provide.

So far the project has only resulted in increased turnover directly from the project execution but there are expectations for increased turnover for the industrial partners over the next years as described below under **1.6 Utilization of project results**.

The project results have been presented at several conferences as most of the publications are conference proceedings where there also has been an oral presentation. However, there have been a few presentations without a paper like presentations at blade workshops like [20] at the IQPC Blade workshop, April 6, 2017 and [23] at the Sandia Blade Workshop, August 28-29, 2018, Lubbock, Texas. The blade workshop is a good forum for informing the industrial community about development of the new technology like the active flaps. Finally, it can be mentioned that DTU arranged a so-called IEA Technical Expert Meeting on SMART blade technology in April 2017 [26] and gave two presentations on the INDUFLAP2 project at that meeting [21], [22].

1.6 Utilization of project results

The project partners find that the results of the present project and the business case is so encouraging that the group will work on further development of the technology towards commercialization. An EUDP application was sent in the first of March 2019. The proposed project builds heavily on the present project but now with focus on the full system integration. The following section from the application gives an overview of and introduction to the proposed new work:

"*The project VIAs (**V**alidation of **A**ctive **A**erodynamic **A**dd-ons) aims at demonstrating and validating the full scale system integration of active flow control devices for the performance enhancement of wind turbines. In particular, the successfully developed active flap system for rotor blades (within the scope of the Induflap2 project, j. nr. 64015-0069) together with spoiler systems developed independently by Siemens Gamesa Renewable Energy A/S, will be integrated into a full scale multi-Megawatt wind turbine for demonstration of turbine performance enhancement and load control. This integration requires the maturing of peripheral subsystems to a technology readiness level (TRL) of 6, development of novel measurement instrumentation and techniques, demonstration of manufacturing concepts suitable for serial production, development of full-scale turbine servo control strategies, increasing the level of integration readiness level (IRL) to IRL6, as well as performing a thorough system characterization both at laboratory scale and field test level. The project partners Siemens Gamesa Renewable Energy A/S, DTU Wind Energy, and Rehau A/S bring with them a high degree of expertise, experience, and professionalism, all of them being world leading companies / institutions in their individual fields.*"

It is expected that a first prototype turbine can be tested 1-2 years after completion of the VIA´s project which could be around 2023. The marked plans are sketched in the business case document [11] from which we cite:

"*The expected volume of global offshore installation between 2016 and the prognose up to 2020 is shown in Figure 1. It shows an order of magnitude of yearly offshore installations of 5-6 GW in the years 2019-2020. Taking into consideration the offshore market share of SGRE of approximately 50%, and expectations of market growth, it is realistic to expect that offshore installations including active flap technology in the years 2022-2023 will be of the order of magnitude of 1GW, ramping up to 3-4GW within a period of 3 years primarily for the European market. These technologies are expected to greatly improve the competitiveness of the products offered through the reduction of LCOE.*

After market introduction and achievement of TRL8, it is expected that the technology has the potential to be extended to the full offshore fleet for new installations, reaching levels of approx. 6-15 GW yearly in the period 2025-2030."

1.7 Project conclusion and perspective

The INDUFLAP2 project has advanced the flap technology much closer to commercialization than at the starting point. The demonstration on a full scale turbine is a very important step towards this. The very good and open corporation between the project partners combined with the whole line of testing facilities from laboratory, wind tunnel, rotating test rig to full-scale have made it possible to carry out many design iterations during the project and improved the flap performance considerably. Important insight into choice of flap material and gluing issues has been provided. Also the first experience with co-extrusion has been achieved which is expected to be the manufacturing method for a mass production.

Also the exploration of different applications of the flap technology has shown that there is a variety of interesting business cases from advanced flap systems (delta Cl of around 0.8 and a fast responding system) that can provided a high load reduction to very simple systems that just vary the flap deflection as function of mean wind speed but still can reduce extreme loads and increase the tip clearance.

There seems thus to be a good possibility to get the first systems on the market within 3-5 years and this new technology will just be more and more competitive for the future upscaling of wind turbines.

Annex

The project has a public home page:

http://www.induflap.dk/

and a restricted share point site (EUDP representatives can get access – write to Helge Aagaard Madsen hama@dtu.dk):

https://share.dtu.dk/sites/INDUFLAPII_124750/SitePages/Home.aspx

The share point has been important for sharing a lot material between the partners and there is e.g. all the material presented at the 13 project meetings.

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