Consolidated results of the laboratory and full scale field validation of an active flap system

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Abstract. This article presents the consolidated results of a comprehensive validation campaign of a pneumatic active flap system (AFS) developed within the scope of the Induflap2 project \cite{1} in a collaboration effort between Siemens Gamesa Renewable Energy A/S (SGRE), the Technical University of Denmark (DTU), and Rehau GmbH. The validation results presented herein include wind tunnel measurements, measurements in a rotating test rig under free atmospheric conditions, as well as the validation at full scale on a 4MW wind turbine with 130m rotor diameter (SWT-4.0-130). This article is of a summarizing character and the reader is referred to further literature where applicable. During the course of the project, several revisions of the AFS were developed and tested at different levels of fidelity. Along with the different variations of the AFS, the impact of variations of the geometric and material related design parameters were studied. Two of the latest revisions of the AFS were tested at full scale on a wind turbine. The measurements presented herein focus solely on the latest revision of the AFS (internally referred to as the FT008rev10 concept). The different tests and measurements were performed in the period from 2016 to 2019. During the full scale measurements, a wind speed dependent load impact between 5\% and 10\% was measured for the blade root flapwise bending moments, demonstrating thus a large potential for turbine loading adjustments to perform active load control on modern wind turbines.

1. State of the art

Active devices for load control of wind turbine rotors have been extensively studied in the past decades and it is not the purpose of this article to give an exhaustive review of literature in this field. For this purpose, the reader is referred to \cite{2, 3, 4}, which in combination, give a very good overview of the variety of concepts for wind turbine active and passive load control including active flaps, microtabs, as well as diverse mechanisms for boundary layer (BL) control such as BL suction and blowing, plasma actuators, or synthetic jets. Most of the research groups active within active flap systems for rotor blades (including the authors) participated with short technical and scientific contributions to the technical expert meeting nr. 87 of the IEA Task 11 \cite{5} (only available to members), making this document a good compendium of the current state of affairs with regards to research and development within the Smart Blades community.

The amount of literature and studies available for system level full scale experimental validation of active control strategies and devices is rather limited. Recent tests were performed by Sandia Laboratories \cite{6, 7} within the scope of the SMART Rotor Project on a 9m long blade, where the outer 20\% of the blade span included a hinged flap section covering the aft 20\% of...
the chord. The flap was actuated in a mechanical fashion with means of motors embedded in the structure of the blade. The characterization of the system was performed mainly via on-off actuation of the flap as well as sinusoidal actuation. A summary of the results of the project is given in [8]. A further full scale test was documented during the period from 2010 to 2014 through a series of publications [9, 10] describing the test of a flap system as well as the controller strategy [11, 12] of a Vestas V27-225 kW (13m long blade) equipped with a 70cm long trailing edge flap. During these tests, the turbine was operated with and without flap control in intervals of 2 minutes. Recently, a shape conforming active flap (morphing trailing edge) developed within the framework of the EU INNWind project was tested under atmospheric conditions on the rotating test rig at the Risoe Campus of DTU [13, 14, 15]. Parts of the text matrix included flap actuation steps, periodic feed-forward control based on azimuth position, as well as feed-forward control based on inflow angle. The flap step actuation is performed with cycles of 10s over a test period of 5 minutes, repeating this procedure for different pitch angles of the flap. From the flap steps, a range of variation of lift coefficient delta ranging from +0.2 down to -0.25 was measured. Azimuth and inflow based feed forward control showed an average reduction of the standard deviation of the bending moment at the base of the rotating rig boom of 12% and 11%, respectively. Previous work on morphing flaps carried out within the framework of the Induflap1 project [1] includes testing under atmospheric conditions in the rotating test rig as well [16, 17]. The bending moment measurements using this flap (of 15% chord coverage) as described in [16] showed that a 5 deg flap actuation has a similar response as 1 deg blade pitch actuation, which is an interesting proxy for comparison of flap control authority. The work reported in [17] mentions a flap actuation in the range of -5 to +5 deg corresponding roughly to a pitch actuation of 3 deg for the full blade section.

At a smaller scale and under controlled wind tunnel conditions, the work described in [18] and in [19, 20] demonstrate the use of active trailing edge flaps on a 3m and 3.5m diameter model wind turbine model at the TU Berlin and the University of Waterloo, respectively. The investigations of Samara [20] focus mainly on the characterization of the flap system, benchmarking it against the pitch system of the turbine. For this purpose, an active flap segment of 20% chord and 22% span coverage was installed on the model test blades. The work concludes that the control authority of the active flap system and the blade pitch are similar. A close look at the results reveals that a flap angle actuation in the -20 to +20 deg is similar in terms of load impact to a pitch actuation in the range from 0 to 9 deg.

In recent years, experimental, computational and theoretical work related to active trailing edge flaps has been carried out by different groups and at different levels of fidelity. The reader is referred to the final report of the Innwind.eu project [21], in particular deliverables 2.23 and 2.33. In parts of this project, the active flap technology was explored both from an aerodynamic as well as from a control perspective with the focus of LCOE reduction. It is shown that the combination of individual flap control strategies with individual pitch control can lead to significant blade flapwise fatigue load reduction with some penalty on tower loading. The potential of AEP increase by flap scheduling at low wind speeds is also discussed and estimated to be approx. 0.5% (calculated at a mean wind speed of 10m/s). Similar results are presented in [22], where the AEP potential is estimated between 0.5% and 1.0% depending on the type of rotor design (cp optimized vs. low induction rotors).

Older references to active flow control in wind turbines date back to the early 1980’s, where plain hydraulically activated hinged flaps and ailerons were studied both for load and power control within the frame of the MOD-5A research and development program [23]. These active flow control technologies were mostly based on a direct knowledge transfer from the aeronautical industry.
2. Objectives
The main objective of the Induflap2 project is to design and subsequently perform a comprehensive characterization of an active flap system. The design of the active flap system shall comply with industrial requirements and be characterized at full scale level striving for a high technology readiness level. Furthermore, it has also been an objective of the project to perform the characterization of the AFS in a stepwise approach, increasing the fidelity level of validation in a systematic manner starting with tests under controlled conditions in a wind tunnel, continuing to testing under atmospheric flow in a rotating test rig and finally on a full scale wind turbine. An important task accompanying these measurements is the simulation of the sub-systems with tools such as CFD, as well as aeroelastic simulations of the full system.

3. Test methodology and selected results
This section describes the measurement setup for the AFS at different levels of fidelity and gives some exemplary results for each of the characterization steps listed below. As mentioned in the previous section, an important objective of the project is to develop the active flap technology in a systematic step-wise approach, where each step brings important aspects for the full system characterization. The logical sequence for this is as shown below.

- Wind tunnel measurement
- Rotating test rig measurements
- Full-scale validation

The main purpose of the wind tunnel measurements is to provide input for aeroelastic models in terms of aerodynamic polars at different flap settings, but also to test the AFS behaviour as sub-system from a fluid-structure interaction perspective, i.e. how ”aerodynamically stiff” the system is. The AFS as designed within this project is not equipped with position feedback control to counteract any deflection changes due to external loading. Therefore, although the flap position is driven mainly by the input pneumatic pressure to the system, there will also be a weak coupling to the external aerodynamic loading. A wind tunnel test is well suited for this purpose.

The next step in validation is to move away from a controlled flow environment and step closer to free atmospheric conditions. This is achieved by testing the system on an airfoil section mounted on an outdoor rotating test rig as will be described below. Besides the aerodynamic testing of the AFS (measurement of pressure distributions, \(C_n\), \(C_t\), etc.), the rotating test rig is also interesting in order to study the stability of the AFS as such. Due to the intrinsic flexibility of the flap, there is a risk that the flap is not aeroelastically stable, e.g. in particular high frequency flutter of the flap. This is an effect which for this flap is quite difficult to simulate, as the mass distribution and damping parameters are not easily quantified. Therefore a test of this type provides at least an indication of the stability of the flap during normal operation. This information is partially provided as well by the wind tunnel tests at specific wind and inflow angle conditions, but the rotating test rig includes a natural variation of the forcing frequency spectrum due to the high turbulence content in the air at low heights.

The final validation step in the project was in the form of a full scale test on a SWT-4.0-130 offshore turbine (on a test prototype installed onshore). The aim of this test was to verify the expected load impact of the flap at full scale. This is done by long duration step flap actuations at a wide range of atmospheric conditions. Furthermore, this validation step provides very useful input for other development tracks such as installation procedures, pressure supply equipment, own power consumption, effects of weather and environmental exposure, etc.

These three fidelity validation levels support the goal of the Induflap2 project to increase the technology readiness level of the AFS towards industrialization.
3.1. Wind tunnel measurements

Wind tunnel (WT) measurements of the AFS mounted on an airfoil model of 900mm chord length (see example setup in figure 1) are performed in the Low Turbulence Tunnel of the Delft University of Technology in order to obtain the characteristic (steady state) aerodynamic behaviour of the flap as a function of input pressure to the system. The measurements are performed for steady flap deflections, i.e. the same flap deflection (linked to the pressure level) is kept throughout the full polar. The WT measurements and CFD simulations for one of the previous revision FT008rev09 of the AFS is described in [24] but not further discussed here. The results shown below are solely for wind tunnel measurements on the latest version of the AFS, the FT008rev10.

The impact of the AFS on the lift coefficient for different pressure levels is shown in figure 2 for a measurement performed at a Reynolds number of 4 million. The AFS was mounted on the pressure side of the airfoil model and supplied externally with pressurized air at different discrete levels. Due to the mounting of the AFS covering the aft pressure taps of the model, the measurement of the lift coefficient was based on pressure taps mounted on the tunnel walls, and not on the airfoil model. The drag coefficient of the airfoil is measured with help of a traversing wake rake behind the airfoil. The measurements for the AFS in the post stall range are performed at a Reynolds number of 2 million (shown as dotted lines). Wind tunnel measurements at high velocity (beyond approx. 70m/s) and high AoA (beyond stall) were not performed due to low-practical restrictions of the setup. One of the main design targets for the AFS design is to obtain a high impact on the lift level at the design angle of attack of the airfoil under consideration. For the AFS described here, the impact on lift coefficient is approx. 0.38 for angles of attack close to 6-7 deg, which is a quite considerable impact under the light of active flow control strategies. The design target lift coefficient variation range for the AFS was 0.4. Using a similar proxy for comparison for some of the flaps described in the state-of-the-art section, this AFS achieves the equivalent of an approximate pitching of 3 deg for the airfoil section (not to be confused with the pitching of the whole blade, as this depends on the span of coverage and the relative chord sizes of the blade).

Besides the polar coefficients, the wind tunnel measurements performed show a dynamically stable AFS, meaning that no sustained vibrations of the system have been observed for the tested ranges of wind speeds (up to approx 78m/s). The AFS is also "aerodynamically stiff", meaning that the deflection of the flap is driven by the actuation pressure, and the deflection impact due to the local aerodynamic forces is negligible for the main range of angles of attack.

The experimental input from wind tunnel measurements is used for full aeroelastic simulations and is described in [24, 25] using SGRE's in-house aeroelastic solver BHawC [27, 28] for a SWT-4.0-130 turbine. A very important aspect to the project was the direct validation (full scale measurement vs aeroelastic simulation) of the AFS mounted on the full scale turbine. Therefore, these wind tunnel measurements go directly as input to the aeroelastic simulations, in a fashion which at SGRE is normally referred to as one-2-one simulations, i.e. aeroelastic simulations where each individual 10-min measurement period is reproduced numerically as accurately as possible using all the atmospheric inflow information available (see some descriptions of the method in [26]). A discussion of these one-2-one simulations for the specific setup of this AFS is discussed in [25].

3.2. Rotating test rig measurements

As a second stage in the validation process of the AFS, an airfoil section including the AFS was mounted on the rotating test rig (RTR) at the DTU Risoe campus in order to conduct a preliminary characterization under atmospheric conditions. The RTR is advantageous as it allows testing at an intermediate level of complexity between wind tunnel and full-scale environments. In this test, a section corresponding to one of the master airfoils being used
in the SWT-4.0-130 was manufactured and the AFS FT008rev10 was mounted on it. The airfoil section has a chordwise and spanwise extension of 1m and 2m, respectively. The section was instrumented with two five-hole Pitot probes for inflow measurements, as well as pressure taps and a wake rake for measurements of the aerodynamic coefficients, reaching Re numbers of approx. 1-1.5 million. The setup showing the placement of the Pitot tubes and wake rake is shown in figures 3 and 4.

A series of tests were performed with variations of both the pitch of the airfoil section and the flap pressure settings, and adding devices to cause small alterations of the baseline airfoil aerodynamic behaviour such as vortex generators and zig-zag tape. The full set of results of these tests has still not been published in a public manner. Nevertheless, the analysis of the data shows similar lift coefficient variations as measured in the wind tunnel, but with a lower lift slope for the full system due to a combination of edge effects (limited span) low Reynolds number and potentially flow transition induced by some of the measurement systems installed. The reader is referred to [29] for a description of some of these tests.

The pressure taps measurements enable a comparison between the data acquired in the RTR and in the wind tunnel (for the same airfoil section and AFS revision). The pressure distribution on the RTR was measured with a total of 59 pressure orifices distributed in the chordwise

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**Figure 1.** View of the AFS installed on the wind tunnel model

**Figure 2.** Wind tunnel results for FT008rev10 at different pressure levels. NOTE: the dotted region of the curve was measured at a Reynolds number of 2 million.

**Figure 3.** View of section as seen from rotation axis

**Figure 4.** View of the section from below
direction. Furthermore, in order to assess the 2-dimensionality of the flow, 16 pressure orifices were installed in the spanwise direction at a chordwise position of 15%.

For the actuation of the flap as well as the data acquisition in the rotating test environment, both the pressure supply control valves as well as the pressure sensors were mounted inside the test section as shown in figure 6. Furthermore, the actuation pressure of the AFS, the dynamic loading on the boom of the RTR (measured by means of strain gauges), as well as the operation parameters of the RTR (rotational speed, pitch, and azimuth position) were logged synchronously with all other pressure quantities for a total of approximately 200 individual channels.

An example of the total pressure deficit (the wake) measured behind the airfoil with the wake rake is shown in figure 5. A detailed description of the wake rake measurements is given in [29], where a good agreement between values measured at wind tunnel and RTR level is found, despite the differences in slope of lift curve mentioned. This type of comparisons are of high value for the future improvement of this intermediate fidelity test rig. The RTR proved to be very valuable in the validation process due to its ease of accessibility and low cost of testing in comparison to a full scale test.

3.3. Full scale measurements
The last step in this experimental validation chain is a long-term full-scale test of the AFS on a test wind turbine. For this test, only one blade is equipped with the AFS (see figures 8 and 9) which enables a direct blade-2-blade comparison against the other two reference blades, as
The AFS system, together with the auxiliary systems (pressure supply, control and electrical systems for valves and pumps, and measurement system) was installed during the summer of 2017. The system went then into operation during the autumn of the same year. The AFS is mounted externally on the outer portion of the 63m long blade (initially a 15m flap spanwise coverage as described in table 1, and subsequently upgraded to a 20m spanwise coverage). The pressurized air to the AFS is fed through a supply line which is installed "hidden" behind the trailing edge of the blade until a location close to the midspan section. At the midspan section, a hole was drilled in the blade and the pressure supply line was led along the web and until the hub connection. The supply line was then routed through the blade covers, making sure to allow for pitch rotation without interference. The supply lines were then connected to a series of valves for activation and deactivation of the system, which in turn were connected to an accumulator tank and a pump system. All items can be operated remotely and integrated with the main controller of the turbine.

The turbine is instrumented with strain gauges in the root of all three blades as well as at the tower top position. All operational parameters of the turbine such as pitch, rotor speed, and power are continuously logged. The atmospheric inflow is measured with a met-mast, with a nearby Lidar scanning 10 heights spanning across the full rotor extension, and with the nacelle anemometer simultaneously. Nevertheless, for the results presented in this article based on blade-to-blade comparisons, the wind speed is only required for filtering of low and high wind speed ranges, and for this purpose the nacelle anemometer was used. The pressure level of the AFS is logged synchronously with all other quantities. In addition, the blade is equipped with a remote surveillance camera in order to monitor the AFS (see exemplary view in figure 8). All quantities are logged continuously for the full measurement period with a sampling frequency of 25 Hz (except the Lidar signals, which are sampled with 1 Hz). A schematic representation of the system is shown in figure 7.

The measurements were performed during two phases as described in table 1. The AFS
FT008rev10 was tested during phase 2 during the spring and summer of 2019 at Hoevsoere Test Center in northern Denmark (see site layout in figure 10).

For the purpose of analysis of the load impact of the AFS, a blade-2-blade approach has been developed. This approach is described in detail in [25]. The governing principle of this approach is that when comparing two neighbouring blades, most of the uncertainty due to atmospheric influence is removed as both blades see the same flow simultaneously (except the azimuthal variations of shear and veer, which are averaged out during the measurement period). This approach leads to a high degree of correlation of the loads between blades, and because it is a relative comparison, even slight deviations in blade strain gauge calibration do not alter the results.

An example of a comparison of the load impact on the blade equipped with AFS vs one of the reference blades is shown in figures 11 and 12. These figures show exemplary the impact on flapwise loads for full flap activation, filtered for low and high wind speeds, below and above 9m/s, respectively. This wind speed has been chosen as it corresponds approximately with the peak of the blade bending moment curve before the blade starts pitching out. The reason for having to split the wind speed range into regions below and above rated, is due to the start of the pitch actuation above rated. The large difference in operation angles of attach below and above rated leads to different relative impacts on loading by the AFS (due to the operation in different regions of the lift polar), therefore, the transition from below to above rated power will look like a hysteresis curve on a blade-2-blade comparison curve, and the reduces the accuracy of the linear regression.

The plot in figure 11 shows the AFS impact at low wind speeds normalized by the peak value of the bending moment curve. A value of 1 in the abscissa (load of the baseline blade) in this curve corresponds therefore to peak flapwise bending moment of the turbine. For this wind speed range, the AFS is shown to have a load impact between 5% and 6%. The peak value of the flapwise bending moment curve was chosen because it is a good proxy for the level of turbine loading due to thrust related loads, which affect components such as the blade root, the bending of the hub, the tower top bending, as well as the bending of the main frame. Levels of 5% to 6% might sound low at a first glance, but they are actually quite significant for the design of a component such as the hub, the pitch bearing, or the blade, and is also directly related to the control authority on the tip deflection of the blades.

For high wind speeds, a reference value of 0.66 is chosen (representative of high wind operation around 17−20m/s). At high wind speeds, when the blades start pitching out and the induction
of the rotor is reduced, all thrust related loads are reduced. Experience shows that the level
of the thrust related loads at high speed are close to 65% of the peak values, therefore this
representative value of 2/3 was chosen. For this wind speed range, the AFS has a load impact
of 10% (see figure 12). Loads at high speeds are normally related to extreme loads in edgewise
direction, but also high asymmetric rotor loading. A 10% loading impact is quite a significant
one. Nevertheless, loads at these wind speed ranges are not always dominant in the full design
load basis.

The full-scale test shows the ability of the AFS system to significantly influence the loading
level of the platform. At the current stage of development however, the focus is not placed
on the time response of the system (this is strongly coupled to the dynamics of the pneumatic
system) and is therefore not mentioned here. The work presented in [25] discusses a method
to extract the time response of an AFS during normal operation under atmospheric turbulence
but still with high accuracy. In future work, the emphasis will be placed on the development of
peripheral systems which allow a fast flap deployment in order to be able to test different load
alleviation strategies at full-scale level.

4. Conclusions
A pneumatic active flap system was designed, manufactured, and successfully tested at different
levels of fidelity and complexity, starting with sub-system tests at wind tunnel level, and
finalizing with full scale validation on a SWT-4.0-130 turbine. Wind tunnel measurements
performed for the latest revision of the AFS show a lift impact levels of approx. 0.4 and provided
input for carrying out relevant aeroelastic simulations of the system. This level of variation of the lift coefficient is deemed to be significant in order to provide an active load control system with enough authority of control for adjusting the loading level of the wind turbine. Furthermore, a subjective validation of the stability of the AFS was performed by observing the dynamic behaviour during wind tunnel tests at different wind speeds and angles of attack.

Measurements of the AFS were performed in a rotating test rig, subjecting the system to free atmospheric flow. During this measurement campaign, preliminary validation systems such as an airfoil-mounted wake rake were developed. Inflow and aerodynamic quantities measured with the Pitot probes and airfoil pressure taps will be further analysed, leading to learnings on how to improve these type of mid-scale fidelity setups in the future.

During the full scale demonstration of the system, a load impact between 5% and 10% was measured for the blade root flapwise bending moments. The measurements were performed using a blade-to-blade approach, where a high level of accuracy is obtained due to the high inflow correlation between neighbouring blades, reducing thus significantly the level of scatter.

The Induflap2 project has advanced the active flap technology towards a higher technology readiness level. The full scale testing, building on top of measurements at wind tunnel and rotating test rig level, are very important steps towards this.

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