Smart Rotor Research at DTU Wind

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The vision with the SMART blade technology
Overview of major activities in the past

ADAPWING I initiated in 2003
- initial investigations of using adaptive trailing edge geometry on an airfoil to alleviate loads

ADAPWING II
- comprised the first wind tunnel experiment on a blade section with flaps

ATEF Adaptive Trailing Edge Flaps
- full scale experiment on the V27 turbine

Several Msc projects

Two PhD projects:

- 2007-2010: Advanced Load Alleviation for Wind Turbines using Adaptive Trailing Edge Flaps: Sensoring and Control by Peter Bjoern Andersen
- 2010-2013: Adaptive Trailing Edge Flaps for Active Load Alleviation in a Smart Rotor Configuration by Leonardo Bergami
ADAPWING I and II

First wind tunnel tests in 2007 with piezzo electric actuators

FIGURE C.2 THE TEST SECTION WITH THE TEST STAND AND THE WAKE RAKE DOWNSTREAM OF THE AIRFOIL SECTION.
ATEF - Adaptive Trailing Edge Flaps - first full scale experiment on the V27

An average of 14% load reduction was measured, and a 20% reduction of the amplitude of the 1P loads was observed.
For realization of the potentials of the SMART blade as seen from simulations

What technology to use for:

- flaps ?
- actuators ?
- sensors ?
The Controllable Rubber Trailing Edge Flap CRTEF development

Development work started in 2006

Main objective: Develop a robust, simple controllable trailing edge flap

The CRTEF design:
A TE flap in an elastic material with a number of reinforced voids that can be pressurized giving a deflection of the flap
The Controllable Rubber Trailing Edge Flap CRTEF
Two basic different types: spanwise or chordwise voids
Some milestones in the CRTEF development

- In 2007 a 1m long prototype rubber trailing edge flap was tested – problems with its robustness

- In autumn 2008 promising results with a 30 cm prototype with chordwise voids

- December 2009 wind tunnel testing of 2m long flap section

- March 2011 the project “Industrial adaptation of a prototype flap system for wind turbines – INDUFLAP”
The Controllable Rubber Trailing Edge Flap CRTEF – test of prototype in 2008
Wind tunnel experiment Dec. 2009

two different inflow sensors
Lift changes integrated from pressure measurements

Derived time constant about 100ms
New project on the CRTEF development

The 3½ years project Industrial adaptation of a prototype flap system for wind turbines –INDUFLAP was initiated in March 2011

Start of project  
Prototype CRTEF tested in laboratory

Project

End of project  
Prototype ready for test on MW turbine

Participants:
DTU Elektro  
DTU AED  
DTU Fiberlab

Industrial partners:
Rehau A/S  
Hydratech Industries Wind Power  
Dansk Gummi Industri A/S
Results from four parts of the INDUFLAP project to be presented here

- Feed forward flap control using inflow data
- The flap design and integration in blade
- A novel rotating test rig
- Lightning protection – a PhD study
Ideal control signals – inflow data in the form of inflow angle and relative velocity

Inflow data from a five hole pitot tube

Inflow data from a small sensor airfoil

Wind tunnel test of flaps and inflow sensors
Control by inflow signals – aero normal force loading considered

\[ F_N = \frac{1}{2} \rho V_r^2 C_N(\alpha)c \]

\[ f_c = K_\alpha (\alpha - \bar{\alpha}) + \left( \frac{V_r^2 - \bar{V}_r^2}{V_r^2} \right) K_{V_r} \]

where \( \bar{\alpha}, \bar{V}_r \) are exclude band filtered from 0.1 to 1Hz and \( f_c \) is the control signal

\( K_\alpha \) and \( K_{V_r} \) are constants determined in order to maximize load reduction
Control by inflow signals – aero force loading along the blade

Flap control: $f_c \rightarrow \text{Flap aerodynamics + flap actuator dynamics} \rightarrow F_{Nc}$

$F_{Nc}$ is controlled aerodynamic force normal to chord (flapwise).

The flap control is numerically simulated by the aeroelastic code HAWC2 where the flap aerodynamics and flap actuator dynamics are modeled.
Load reduction of load input on the 5MW reference turbine

Figure 28. Reduction of the fatigue loads of the blade sectional normal force by control with inflow measured at radial position \( r = 54.59 \, m \), varying inflow turbulence intensity. The control band width includes 1p, 2p and 3p.
Example of an 80m rotor with inflow sensors

Normal force measured at four radial positions by pressure holes

Four 5 hole pitot tubes installed on a NM80 turbine with an 80m rotor

Experiment carried out within the DAN-AERO project from 2007-2010: LM, Vestas, Siemens, DONG Energy and Risø DTU
NM80 turbine – control of FN at R=30m from inflow measurement

Red curve is simulated flap controlled normal force using measured inflow

Fatt. Red. 35.6%
Reduce the pitch activity and alleviate the loads using the same sensors as for the pitch system.

Christensen LC, Bergami L and Ander PB "A Model Based Control methodology combining Blade Pitch and Adaptive Trailing Edge Flaps in a common framework" Presented at EWEA2013 in Vienna, 4-7 February 2013.

Fatigue Damage Equivalent Loads (DEL) alleviation at the blade root flapwise bending compared to the baseline NREL 5 MW turbine, Wöhler curve exponent of 10.
Feed forward flap control using inflow data

The flap design and integration in blade

A novel rotating test rig

Phd on lightning protection
Two different designs have been investigated during the INDUFLAP project.
Designs with chordwise voids

"Old" design

New design

Reinforcement of voids a major problem
The chosen flap design for testing on a 2m span blade section
The flap design for testing on a 2m span blade section
Integration in the blade

Perspectives:

Design of trailing edge

Realized on 2m blade section for lightning test

Mounting of trailing edge:
- easy to realize
- better fit
- easy to mount
Integration in the blade
Overall concept for blade with flaps

- Main blade is designed and manufactured without the trailing edge part (10-15% of chord)
- A spar is inserted at the TE with an attachment component for the flap
- From the region where flat back airfoils ends flaps are used along the whole span out to the tip
- A combination of passive flaps (3D mold manufactured) and 2D active flaps manufactured by an extrusion process are used
Feed forward flap control using inflow data

The flap design and integration in blade

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Phd on lightning protection
The rotating test rig

- A facility for testing new blade technology such as flaps and inflow sensors under realistic conditions (atmospheric inflow, elastic suspension, realistic pitch control, rotating environment, Reynolds number)
- Intended to close the gap between wind tunnel testing and full scale testing
- A blade section (about 2m spanwise length and 1m chord) is rotated by a 10m boom mounted on the shaft of the Tellus 100kW turbine (standard rotor taken down)
- Detailed measurements of the aerodynamic loading on the blade section, inflow and structural response
- Establishment of test rig (rotating boom + testing) part of the EUDP funded INDUFLAP project
- Turbine upgraded (variable speed + new 100kW generator) based on internal funding
Rotating test rig for test of flap technology

Pressure measurements

Pitch actuator

Pitot tube
small wing

Accelerometer

CRTEF

Pitch sensor

Rotational speed sensor

Tower accelerometer

Strain gauge
Rotating test rig
Based on a 100 kW turbine platform
Blade section 2x1m with detailed instrumentation with pressure taps

Each pressure tube is connected with a rubber hose of equal length and fixated to the composite shell.

Good fit between wing section, side pods and hatches.

Assembly

Cutting of trailing edge

Field test at Risø Campus June 2014
Installation of boom in June 2014
Installation of boom in June 2014
Installation of boom in June 2014
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  Anna Candela Garolera at DTU Elektro
Material tests

Breakdown strength tests to determine the maximum electric field that the flap material can support.

Results of the tests:

- The breakdown strength of Santoprene material is comparable to GFRP (Santoprene: 69 kV/mm, GFRP: 50 kV/mm) and significantly better than other rubber materials (Silicone rubber, PUR, EDPM)
Material tests

Tracking resistance tests

Results of the tests:

- The Santoprene material has 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)
Validation of the INDUFLAP prototype

Swept channel attachment tests to the INDUFLAP prototype:

- Applicable to surfaces of a wind turbine blade that are exposed to initial leader attachment when the blade is rotating
- Flashover paths over non-conductive surfaces and possible puncture locations

![Diagram of swept channel attachment tests to the INDUFLAP prototype]
High voltage validation tests

Swept channel attachment tests to the INDUFLAP prototype:
Summary and outlook

- Successful industrial manufacturing of flap prototype
- Lightning tests with flap show same robustness as GFRP
- Rotating tests of 2m flap section ongoing on outdoor rotating test rig to determine performance of the flap
- One of the next steps will be to involve wind turbine OEMs for investigation of full scale tests
Acknowledgement

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Thank you for your attention!