INTERNATIONAL ENERGY AGENCY

**Implementing Agreement for Co-operation in the Research,
Development and Deployment of Wind Turbine Systems
Task 11**

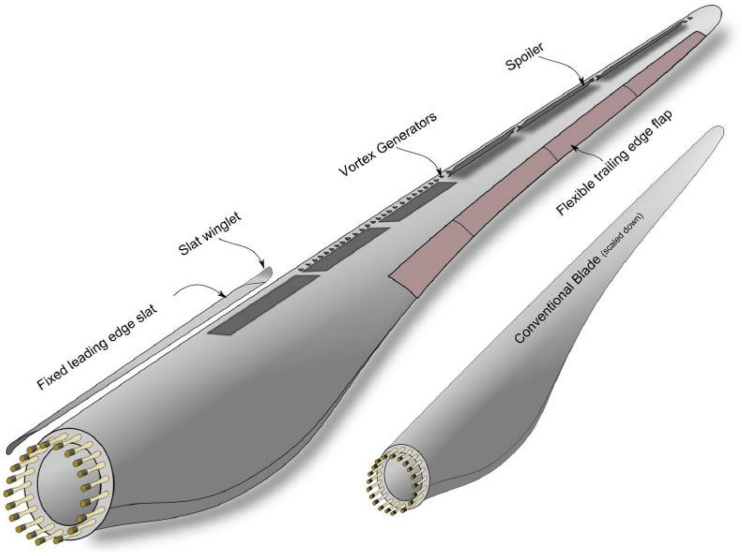
Topical Expert Meeting #87 on

Smart blades

IEA Wind Task 11- Topical expert meeting on smart blades

April 27-28, 2017

DTU, Roskilde, Denmark



Host:
Helge Aagaard Madsen and Thanasis Barlas
DTU Risø Campus
Frederiksborgvej 399, 4000 Roskilde
Denmark

Operating Agent:
Davy Marcel, Planair SA
Rue Galilée 6, 1400 Yverdon-les-Bains
Switzerland

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After one year the proceedings can be distributed to all countries, that is May 2018

Copies of this document can be obtained from:
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For more information about the IEA Wind TCP see www.ieawind.org

International Energy Agency Implement Agreement for Co-operation in the Research, Development and Deployment of Wind Turbine Systems (IEA Wind)

The IEA international collaboration on energy technology and RD&D is organized under the legal structure of Implementing Agreements, in which Governments, or their delegated agents, participate as Contracting Parties and undertake Tasks identified in specific Annexes.

The IEA's Wind Implementing Agreement began in 1977, and is now called the Implementing Agreement for Co-operation in the Research, Development, and Deployment of Wind Energy Systems (IEA Wind). At present, 26 contracting parties from 22 countries, the European Commission, and Wind Europe, participate in IEA Wind. Austria, Belgium, Canada, Denmark, the European Commission, EWEA, France, Finland, Germany, Greece, Ireland, Italy (two contracting parties), Japan, Republic of China, Republic of Korea, Mexico, Netherlands, Norway (two contracting parties), Portugal, Spain, Sweden, Switzerland, United Kingdom and the United States are now members.

The development and maturing of wind energy technology over the past 30 years has been facilitated through vigorous national programs of research, development, demonstration, and financial incentives. In this process, IEA Wind has played a role by providing a flexible framework for cost-effective joint research projects and information exchange.

The mission of the IEA Wind Agreement continues to be to encourage and support the technological development and global deployment of wind energy technology. To do this, the contracting parties exchange information on their continuing and planned activities and participate in IEA Wind Tasks regarding cooperative research, development, and demonstration of wind systems.

Task 11 of the IEA Wind Agreement, Base Technology Information Exchange, has the objective to promote and disseminate knowledge through cooperative activities and information exchange on R&D topics of common interest to the Task members. These cooperative activities have been part of the Wind Implementing Agreement since 1978.

Task 11 is an important instrument of IEA Wind. It can react flexibly on new technical and scientific developments and information needs. It brings the latest knowledge to wind energy players in the member countries and collects information and recommendations for the work of the IEA Wind Agreement. Task 11 is also an important catalyst for starting new tasks within IEA Wind.

IEA Wind TASK 11: BASE TECHNOLOGY INFORMATION EXCHANGE

The objective of this Task is to promote disseminating knowledge through cooperative activities and information exchange on R&D topics of common interest. Four meetings on different topics are arranged every year, gathering active researchers and experts. These cooperative activities have been part of the Agreement since 1978.

Carballeira Wind Farm - Spain

Two Subtasks

The task includes two subtasks.

The objective of the first subtask is to develop recommended practices (RP). In 2013 were edited RPs on “Social Acceptance of Wind Energy Projects”, “Wind Integration Studies” and. “Ground-Based Vertically Profiling Remote Sensing for Wind Resource Assessment”.

The objective of the second subtask is to conduct topical expert meetings in research areas identified by the IEA R&D Wind Executive Committee. The Executive Committee designates topics in research areas of current interest, which requires an exchange of information. So far, Topical Expert Meetings are arranged four times a year.

Documentation

Since these activities were initiated in 1978, more than 70 volumes of proceedings have been published. In the series of Recommended Practices 16 documents were published and five of these have revised editions.

All documents produced under Task 11 and published by the Operating Agent are available to citizens of member countries participating in this Task.

Operating Agent

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COUNTRIES PRESENTLY PARTICIPATING IN THE TASK 11	
COUNTRY	**INSTITUTION**
Denmark	Danish Technical University (DTU) - Riso National Laboratory
Finland	Technical Research Centre of Finland - VTT Energy
Germany	Bundesministerium fur Umwelt, Naturschutz und Reaktorsicherheit -BMU
Ireland	Sustainable Energy Ireland - SEI
Italy	Ricerca sul sistema energetico, (RSE S.p.A.)
Japan	National Institute of Advanced Industrial Science and Technology AIST
Mexico	Instituto de Investigaciones Electricas - IEE
Netherlands	Rijksdient voor Ondernemend Nederland (RVO)
Norway	The Norwegian Water Resources and Energy Directorate - NVE
Republic of China	Chinese Wind Energy Association (CWEA)
Spain	Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas CIEMAT
Sweden	Energimyndigheten - Swedish Energy Agency
Switzerland	Swiss Federal Office of Energy - SFOE
United Kingdom	CATAPULT Offshore Renewable Energy
United States	The U.S Department of Energy -DOE

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PRESENTATIONS

1. INTRODUCTORY NOTE

(by Helge Aagaard Madsen and Athanasios Barlas)

Background

In the past, two TEM´s on the same topic have been held; in 2006 at Delft University with about 30 participants and in 2008 at Sandia Laboratories with 22 participants. Since 2008 there has been a considerable research activity within the field like the Smartblades project[1] in Germany led by DLR (2013-2016) and the INDUFLAP projects[2] (2011-2018) in Denmark coordinated by DTU Wind Energy.
By "smart structures" or "SMART blade " is meant a wide range of different technologies but with the overall aim to provide a distributed control of the aerodynamic loads along the blade span with the objective to reduce fatigue and ultimate loads and increase the power production of the rotor.
With the continuing upscaling of turbines the SMART blade technology is becoming even more attractive as the time varying loads along the blade span cannot be controlled efficiently by the present technology using the pitch as this gives the same control along the blade span. Upscaling has also had the impact that the pitch bearing design has become even more challenging caused by the huge blade root bending moments.
Due to this continuing research on the SMART blade technology and because the development has reached a stage that is close to the first industrial prototype testing it is an appropriate time for a new TEM on the topic.

[1] http://www.smartblades.info/News.html
[2] http://www.induflap.dk/

Objective of the meeting
The objective is to provide an overview and status of research and development activities on the SMART blade technology and discuss where new research initiatives are needed.

The research areas of the SMART blade technology
The SMART blade technology is highly interdisciplinary and comprises several disciplines:

Aerodynamics and design tools
- The principles of changing the lift and drag of an airfoil with control elements: TE flaps, microtabs, boundary layer suction or blowing or other means of modifying the camber or pitch of the airfoil
- Modelling aspects: How to incorporate the above aerodynamic options in our aerodynamic and aeroelastic models?

Actuation technology

- Wind turbine blades are huge and existing actuation technology used on airplanes and helicopters cannot just be transferred to wind turbine blades so robust actuation solutions for wind turbine blades of 100m span or more are required
- Morphing structure technology

Control

- Control algorithms adopted from the pitch control can be adopted for e.g. flap control but in order to utilize the option for distributed control along the blade span new control schemes targeted for this is needed
- Transition from advanced controllers to industrial application
- System identification and model based control

Sensors

- The distributed control that is possible the SMART blade technology requires that more detailed information than what normally is used for pitch control. Information about the detailed inflow to the rotor is one option but also detailed information about blade position and movements from e.g. accelerometers or GPS can be used for such controls

Integrated aerodynamic and structural blade design

- The distributed control option should be taken into account from the start of the blade design and requires an integrated aerodynamic and structural design optimization tool
- Passive systems (e.g. twist flap coupling) or combined active and passive systems are important and can be achieved indifferent ways by e.g. suitable fiber orientation in the blades or by blade sweep
- Aeroelastic simulations of wind turbines with smart blade features close to the industrial certification
- Cost modelling and estimation for SMART blade technology

Expected outcome

- Provide an overview SMART blade research activities
- Indication of the interest for a new IEA Annex on the SMART blade technology

Time and place of meeting

Thursday 27th and Friday 28th of April 2017 at DTU Wind Energy at Campus Risoe, Roskilde, Denmark.

2. AGENDA

Thursday, Apr. 27th, 2017

09:00 Registration and coffee
10:00 Welcome by host DTU – Helge Aa. Madsen (DTU)
10:10 Introduction of IEA Task 11 by Vice Chair of IEA Wind – Stephan Barth (ForWind)
and by Operating Agent of IEA Task 11 - Davy Marcel (PLANAIR)
10:25 Recognition of participants
10:45 Introduction to the meeting topic - Helge Aa. Madsen (DTU)

10:55:11:10 Coffee break

Session 1

11:10 SMART BLADE GmbH & HFI TU Berlin: 10 years of wind turbine smart rotor R&D overview – George Pechlivanoglou (Smart Blade)

11:30 Passive/active load alleviation – Flemming Rasmussen (DTU)
11:50 Advances in smart blades - Morphing flap design and aeroservoelastic simulations – Thanasis Barlas

(DTU)

12:15-13:15 Lunch break

Session 2

13:15 Smart but simple: load alleviation by passive technologies – Pietro Bortolotti (Technische Universität München)
13:35 Focus on blades with active trailing edges – Johannes Riemenschneider (DLR)
13:55 Experiences with passive and active controls in Aerospace, Automotive and wind field – Giuseppe Calise (Unina)
14:15 Sandia Smart Rotor project summary – Jonathan Berg (Sandia)
14:35 Prototype casting of flexible rubber trailing edge – Tom Andersen (DTU)

15:00-15:20 Coffee break

15:20 The rotating test rig and examples of measurement results – Anders Olsen (DTU)
15:40 Development of blade response measurements – Marcel Poodt (ECN)
16:00 Focus on blades with adaptive leading edges – Michael Hölling (ForWind)
16:20 Focus on passive technologies – Elia Daniele (Fraunhofer IWES)
16:40 Discussion - Round up

17:00 End of day 1

19:00 Dinner at Restaurant Snekken in Roskilde

Friday, Apr. 28th, 2017

09:00 Introduction by host – summary of day 1

Session 3

09:10 HAWC2 Near Wake modelling of flaps – Georg Pirrung (DTU)
09:30 Blade optimization/design of blades with flaps – Michael McWilliam (DTU)
9:50 Rotor design at Suzlon – Leonardo Bergami (Suzlon)
10:10 Smart Rotor Research using DBD plasma as flow control actuators: An overview of TUDelft's activities – Ricardo Pereira (TUDelft)

10:30 – 11:00 Group photo and Coffee break

11:00 Active trailing edge flaps in turbine design – a mature technology? - Peder Enevoldsen (Siemens Wind Power)
11:20 Integrated Design Optimization of Wind Turbines: Challenges, Methods, Applications - Carlo Botasso (Technical University of Munich)
11:40 The Poul la Cour Tunnnel – The Danish Aerodynamic and Acoustic Wind Tunnel - Anders S. Olsen (DTU)

12:00-13:00 Lunch break

13:00-13:30 Discussion and conclusions
13:30-13:45 Interest for new IEA Annex on SMART blade? – Davy Marcel (PLANAIR)

14:00 Closure of meeting

3. LIST OF PARTICIPANTS

The meeting was attended by 25 participants from 6 countries. Following, the lists of participants and their affiliations.

Ricardo Pereira	Delft University of Technology
Johannes Riemenschneider	DLR – German Aerospace Center
Jan Tessmer	DLR – German Aerospace Center
Georg Raimund Pirrung	DTU
Anders S. Olsen	DTU Wind Energy
Michael McWilliam	DTU Wind Energy
Tom Løgstrup Andersen	DTU Wind Energy
Helge Aagaard Madsen	DTU Wind Energy
Thanasis Barlas	DTU Wind Energy
Marcel Poodt	ECN
Michael Friedrich	Envision Energy
Kevin Standish	Envision Energy
Stephan Barth	IEA Wind (ForWind – Center for Wind Energy Research)
Michael Hölling	ForWind – Institute of physics, university of Oldenburg
Elia Daniele	Fraunhofer IWES
Davy Marcel	IEA Wind (Planair)
Claudio Balzani	Leibniz Universität Hannover, Institute for Wind Energy Systems
Jonathan Berg	Sandia National Laboratories
Peder Enevoldsen	Siemens Wind Power
Alejandro Gomez Gonzales	Siemens Wind Power
George Pechlivanoglou	Smart Blade GmbH
Leonardo Bergami	Suzlon
Pietro Bortolotti	Technical University of Munich
Carlo Botasso	Technical University of Munich
Giuseppe Calise	Unina - Dept. Industrial Engineering - Aerospace Division

4. SUMMARY

In brevity, the following topics were presented and discussed.

Helge Aagaard Madsen, Technical University of Denmark, “Welcome.”:
Why 9 years after the TEM about smart blades topic? The industry was not ready to take the risks by this time. The technology hugely developed since then, especially in terms of size. Could we setup regular meetings concerning this topic?

Davy Marcel, IEA Wind (Planair), “IEA Task 11 presentation”:
As consultant, we obtained the mandate of task 11 Operating Agent recently. Task 11 is special transverse task (potentially concerning any special technical area within power). Among our activities, we are co-organizing events such as this TEM. The higher goal of TEM is the emulation of international technical resources in order for further development of IEA wind (creation of new tasks etc.).

George Pechlivanoglou, Smart Blade GmbH, “10 Years Smart Blade Research & Development”:

- Lots of knowledge in old car industry (knowledge partially lost with electronics).
- Major limitation today: no guarantees for blades equipped with actuators.
- Topics recommended to consider for new task: Actuator and wind farm control.

Comment from Envision: there are two markets: Extreme loads Vs fatigue loads.

Flemming Rasmussen, Technical University of Denmark, “Perspectives in aeroelastic tailoring of blades”:

- With years, more design parameters appeared.
- Increasing length = increasing pre-bending
- Big challenges related to derating (e.g. a 50% derating leads to stability issues)

Thanasis K.Barlas, Technical University of Denmark, “Advances in smart blades”:
Looking back, several challenges raised 10 years ago have been managed. Everybody profited of industrial practices (robustness improved).

Carlo L.Botasso, Technical University Munich, “Smart but Simple: Load Mitigation by Passive Technologies”:
No notes

Johannes Riemenschneider, DLR, “Progress on Blades with Active Trailing Edges”:
What should be our research drivers? What can we sell to the industry (lifetime, fatigue, tip deflection etc.)? Siemens answer: Bigger rotors!

Giuseppe Calise, Unina, “Experiences with passive and active controls in Aerospace, Automative and wind field":

- consortium Seapower has a more than 20 years of experience in the field of applied research in renewable energies (wind, tidal and wave) and in the wind field, Seapower experience is mainly related to small/medium wind turbine (up to 60kW). Activities in design: loads prediction according to IEC 61400-1 requirements, manufacturing, installation and field testing.
- During the last 25 years, different wind turbine design approaches have been employed: upwind, downwind, stall and pitch controlled, furling, fixed and variable speed.
- experience in using active and passive flow control (unsteady blowing and synthetic jets) for streamlined and bluff bodies employing both numerical and experimental techniques.
- UniNa Smart Structure Laboratory (SSL), belonging to the same University, has developed several aircraft morphing structures within several European projects, achieving NASA technology readiness level equal to 6.

Jonathan Berg, Sandia National Laboratories, "Smart Rotor Project Summary":
Around 15 people are working on wind, over nearly 10'000employees in Sandia,
Opinion: Blades tip defection is a design driver, rather than fatigue.

Tom Løgstrup Andersen, Technical University of Denmark, "Prototype casting of flexible rubber trailing":
Today we see more a mix between glass and carbon fiber in the blades (e.g. the LM world longest blade).

Helge Aagaard Madsen, "The Rotating Test Rig and Examples of Measurement Results":
Turbulence leads to various angle of attacks along the blade, so we use active slats for manipulating the angle of attack.

Marcel Poodt, ECN, "Development of blades response measurements":
No notes

Michael Hölling, Forwind, "Progress on Blades with Adaptive Leading Edges":
Turbulence leads to various angle of attacks along the blade, so we use active slats for manipulating the angle of attack.

Georg Pirrung, Technical University of Denmark, "HACW2 near wake modeling and application on rotors with flaps":
No notes

Michael Mc William, Technical University of Denmark, "Blade optimization/design of blades with flaps":

- Presented investigations of rotor design optimization with smart-blade technology.
- Demonstrated that smart blade technology can improve AEP without increasing loads
- Discussed how sensitivity analysis could help guide the development of smart blade

technology

Elia Daniele, IWES Fraunhofer, “Progress on Passive Blade Technologies”:

- Reduction of fatigue loads on the IWT-7.5-164 reference turbine more effective via geometrical bend twist coupling w.r.t. the structural one.
- Multivariable individual pitch control leads to effective reduction in terms of damage equivalent loads and duty actuator cycle.
- Multiscale testing at coupon level needs ad hoc design of grips for off-axis specimen.
- Direct roving placement would be soon tested for a blade segment production.

Leonardo Bergami, Suzlon, “Rotor Design in Suzlon”:

- Suzlon owns its own WTGs builts in blades, etc (vertical integrated)
- Within industry, it is not enough reducing the blades loads – you also need to translate it to a cost reduction
- To convince industry, solutions have to be simple and proven

Ricardo Pereira, TU Delft, “Smart Rotor Research using DBD Plasma as Flow Control Actuators: an Overview of TUDelft’s Efforts”:

- IBL method is quick
- Plasma is not problematic in relation with lightnings

Peder Enevoldsen, Siemens, “Active trailing edge flaps in turbine design – a mature technology?”:
No notes

Carlo L.Botasso, Technical University of Munich**,** “Integrated Design Optimization of Wind Turbines: Challenges, methods, applications”:

- Cost model difficult & case per case but mandatory for final result
- Main take away: increasing rotor size to decrease costs
- Various laminates materials tests ongoing (we have a relative freedom)
- The task 37 10MW WTG will be very similar to the DTU 10-MW WTG (the wtg reference data are public)

Conclusions:

- powerful tools, but we have to be careful how to use them
- A continuous sweep would not be fully realistic
- Tests various combination of tower heights with rotor sizes

Tom Logstrup, Technical University of Denmark, “The Poul la Cour Tunnel – The Danish Aerodynamic and Acoustic Wind Tunnel”:

- Brand new wind tunnel, inspired by state of the art wind tunnel (e.g. car industry), opening this year
- Open for services to any actor (e.g. manufacturers)

Final discussion and synthesis (led by **Thanasis K.Barlas**):

- There are still some open discussion about concept of actuator (we still need concrete comparisons)
- Simulation tools: how do we sell our services to companies?
- Consider a double research track : a fast track and a detailed track
- Consider assessing new technologies in failure situations?
- What the new task would focus on? It could be (1) all systems engineering items (not covered by task 37) (2) development of a universal tool, or about (3) testing the blade behaviour without bearings, or (4) design and behaviour of flaps (5) a combination of benchmarking and certification to support the industry (6) creation of a common platform in order to compare various concepts (further discussions needed to define the task perimeter)
- There has been many tests everywhere in the world but no common agreement about where we should start first (priorities definition, structured plan).

Take aways:

- We agree that Denmark, Germany, and Netherlands would be the three country involving resources for a new task project (Denmark/DTU would lead) (remark: Jonathan checks USA position).
- The interest for creating a new task shall be mentionned in the next Eco meeting and the request (similar to a business case) shall be prepared prior the second 2017 Exco meeting (expected november 2017).

Remarks:

- We need to do some EU lobbying as we tried to include smart blades subject in the call for 2020, but Bruxelles basically replies « mature technology so no need for support » (Stephan Barth input)
- Ignacio Marti is now head of structure and WTG design in DTU

5. PRESENTATION

Wellcome to participants of the IEA Wind Task 11 TEM meeting on

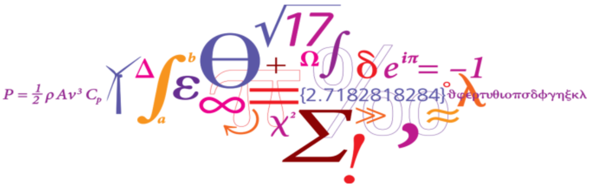
The Application of Smart Structures for Large Wind Turbine Rotor Blades

April 27-28, 2017
DTU Campus Risoe, Denmark

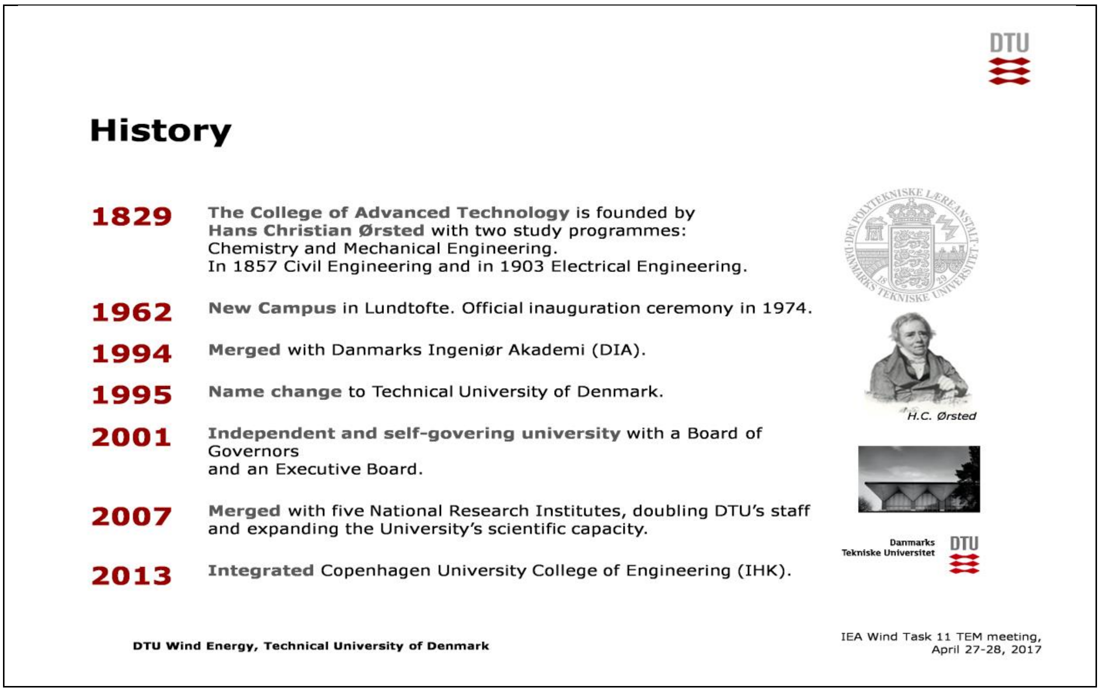
DTU Wind Energy
Department of Wind Energy

Introduction to DTU Wind Energy

Helge Aagaard Madsen
hama@dtu.dk



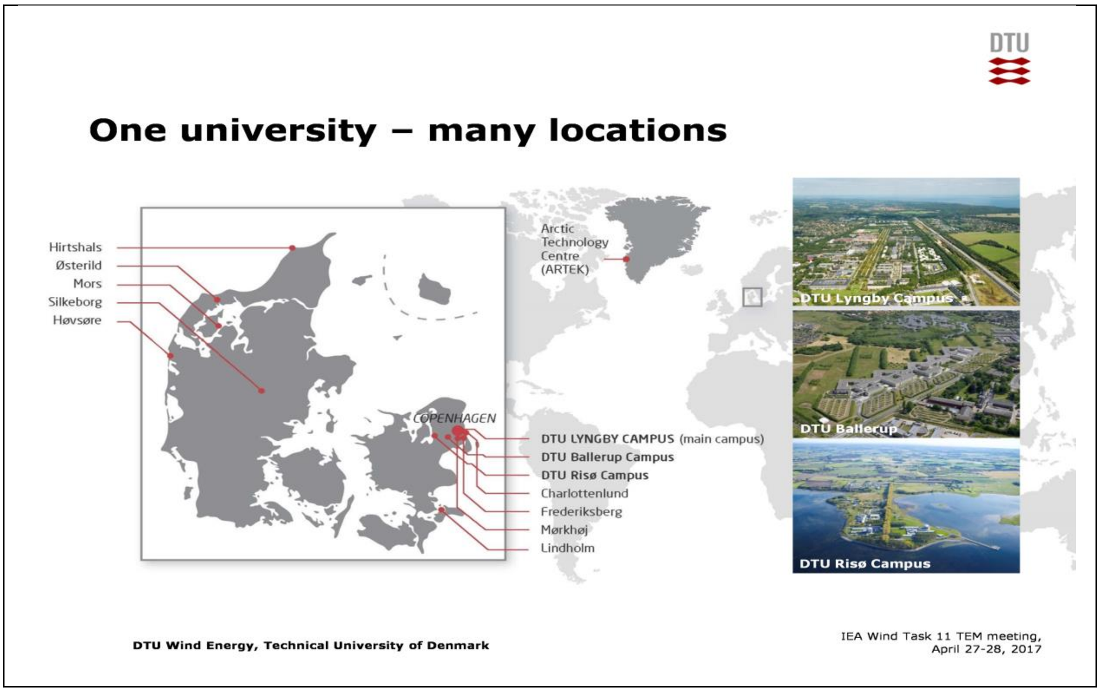
DTU Wind Energy
Department of Wind Energy



History

1829	**The College of Advanced Technology** is founded by **Hans Christian Ørsted** with two study programmes: Chemistry and Mechanical Engineering. In 1857 Civil Engineering and in 1903 Electrical Engineering.
1962	**New Campus** in Lundtofte. Official inauguration ceremony in 1974.
1994	**Merged** with Danmarks Ingeniør Akademi (DIA).
1995	**Name change** to Technical University of Denmark.
2001	**Independent and self-govering university** with a Board of Governors and an Executive Board.
2007	**Merged** with five National Research Institutes, doubling DTU's staff and expanding the University's scientific capacity.
2013	**Integrated** Copenhagen University College of Engineering (IHK).

H.C. Ørsted



One university – many locations

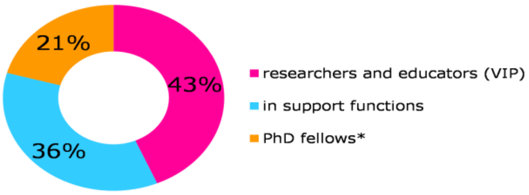
Staff and students

5,832

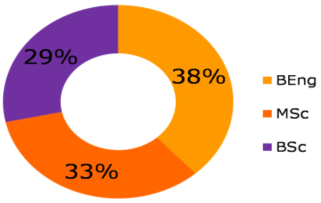
human resources (FTEs)

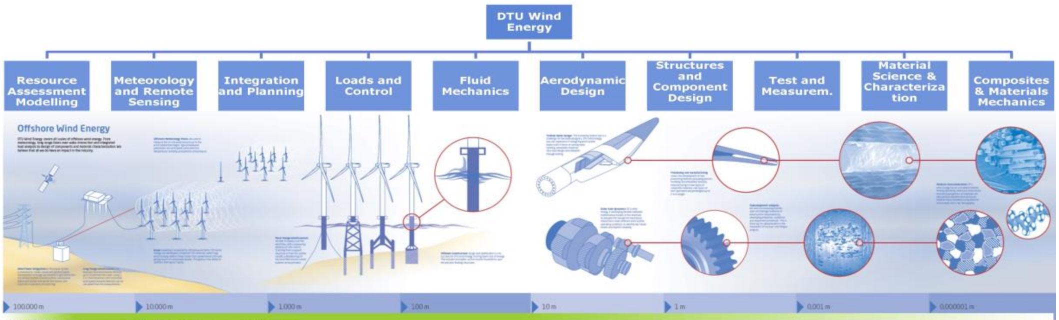
10,631

full-time students



*Employees only





DTU Wind Energy

- Resource Assessment Modelling
- Meteorology and Remote Sensing
- Integration and Planning
- Loads and Control
- Fluid Mechanics
- Aerodynamic Design
- Structures and Component Design
- Test and Measurem.
- Material Science & Characterization
- Composites & Materials Mechanics

Siting and integration

Offshore wind energy

Wind turbine technology

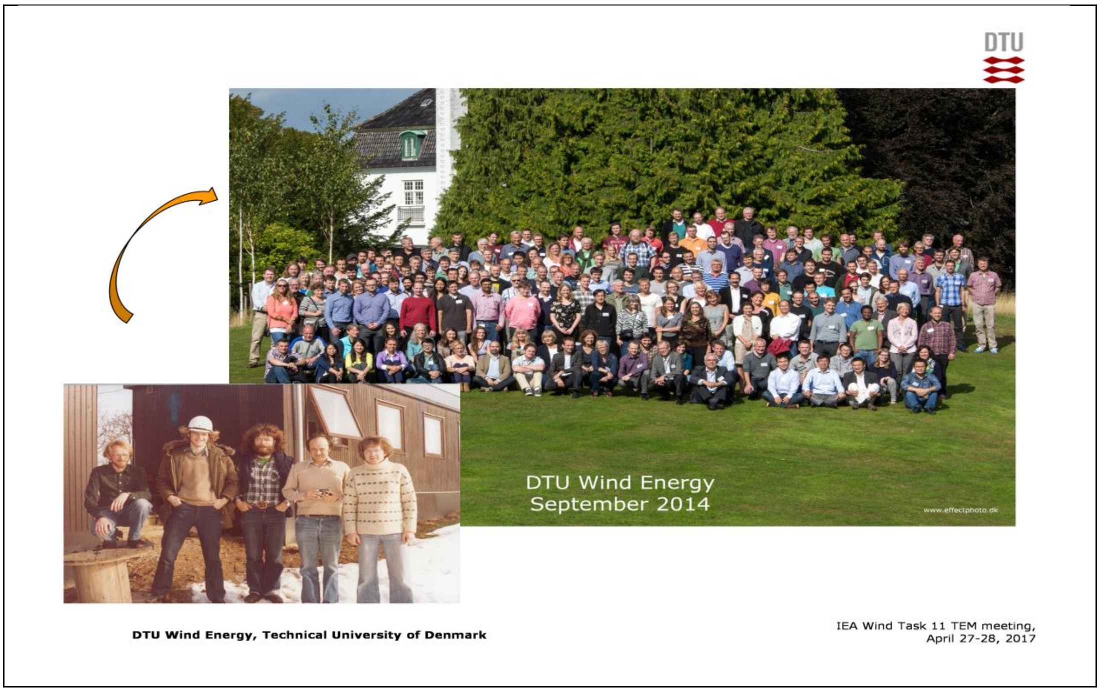
Education and teaching

Research based consultancy and tests

Changes during time

DTU Wind Energy, Technical University of Denmark

IEA Wind Task 11 TEM meeting,
April 27-28, 2017



DTU Wind Energy, Technical University of Denmark

IEA Wind Task 11 TEM meeting,
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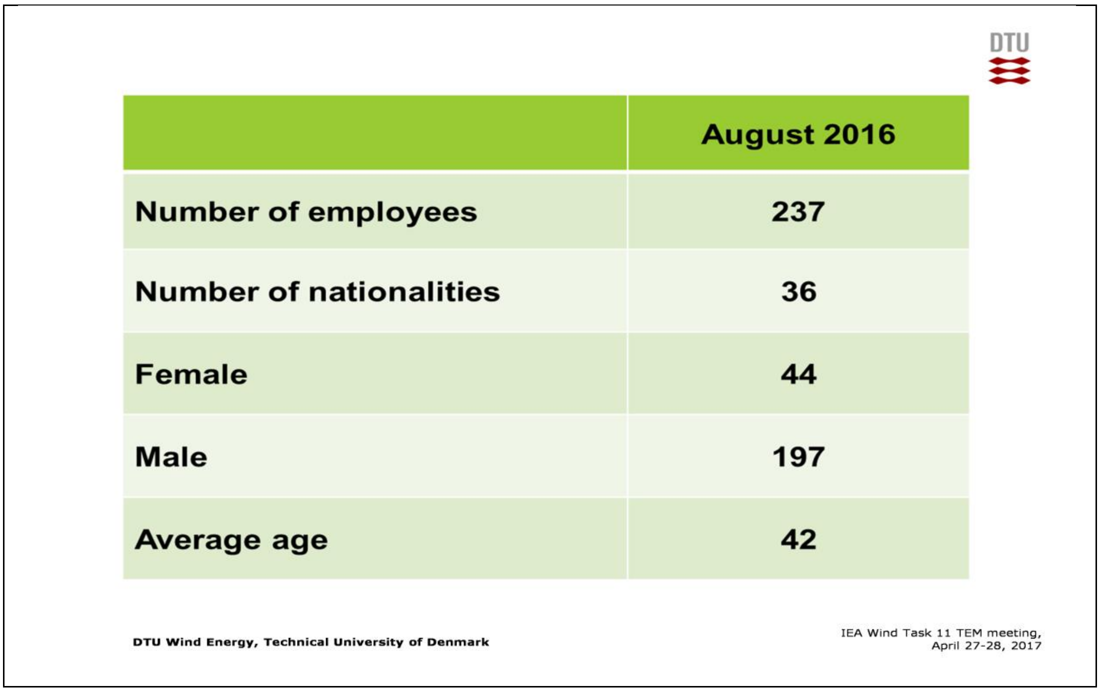
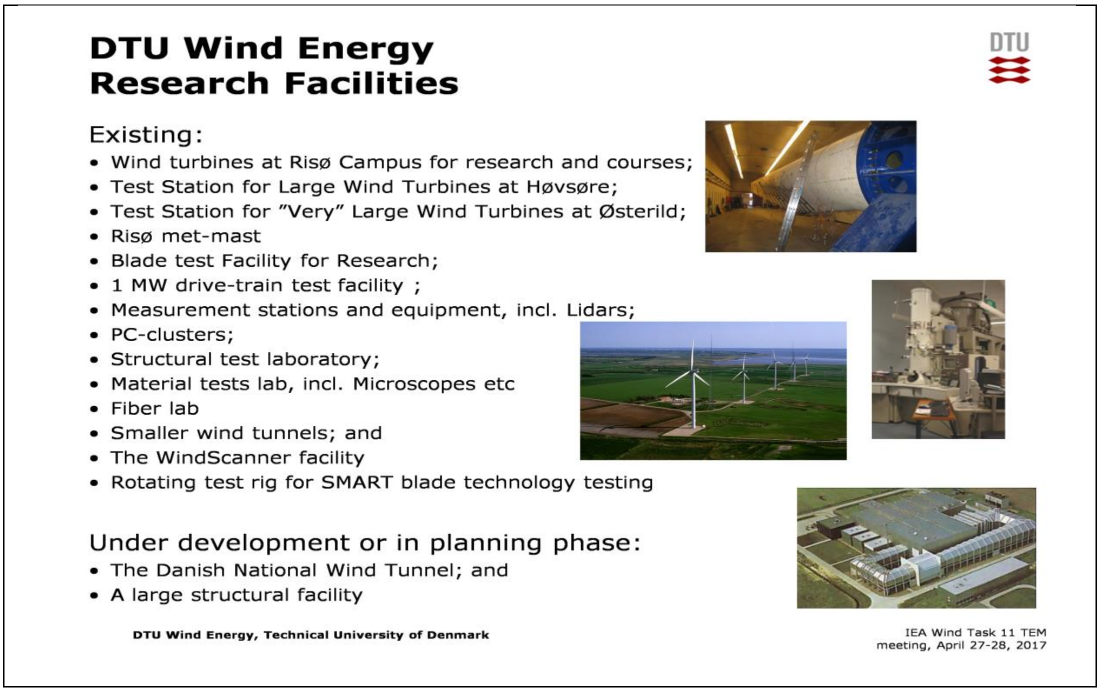


	August 2016
Number of employees	**237**
Number of nationalities	**36**
Female	**44**
Male	**197**
Average age	**42**

DTU Wind Energy, Technical University of Denmark

IEA Wind Task 11 TEM meeting,
April 27-28, 2017



DTU Wind Energy Research Facilities

Existing:

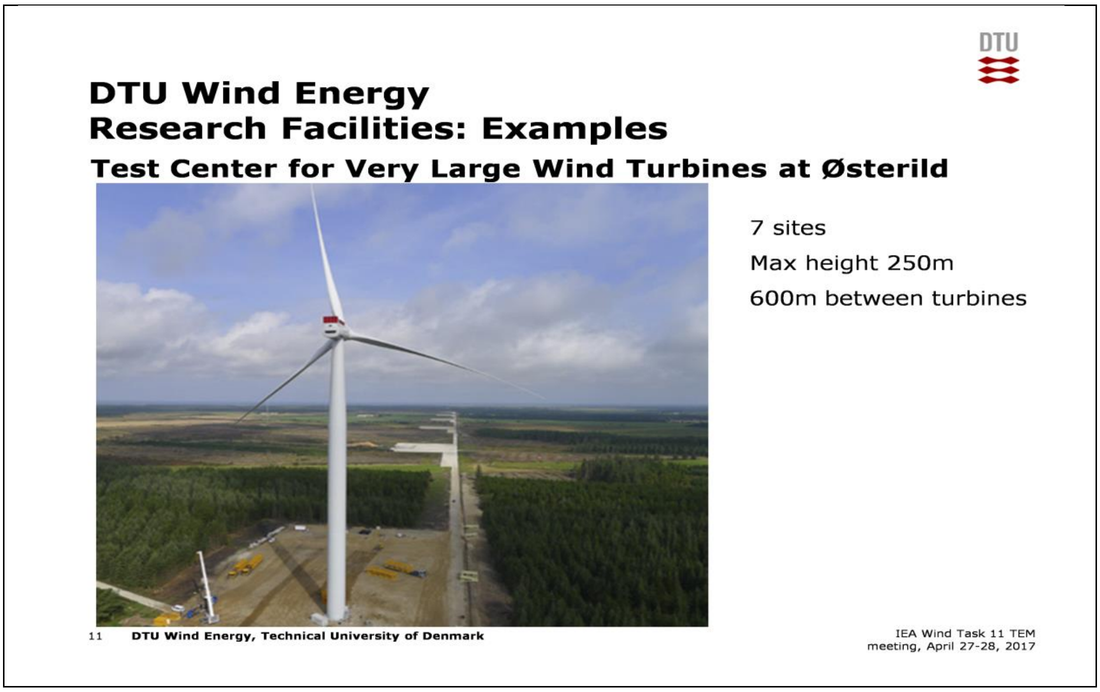
- Wind turbines at Risø Campus for research and courses;
- Test Station for Large Wind Turbines at Høvsøre;
- Test Station for ”Very” Large Wind Turbines at Østerild;
- Risø met-mast
- Blade test Facility for Research;
- 1 MW drive-train test facility ;
- Measurement stations and equipment, incl. Lidars;
- PC-clusters;
- Structural test laboratory;
- Material tests lab, incl. Microscopes etc
- Fiber lab
- Smaller wind tunnels; and
- The WindScanner facility
- Rotating test rig for SMART blade technology testing

Under development or in planning phase:

- The Danish National Wind Tunnel; and
- A large structural facility

DTU Wind Energy, Technical University of Denmark

IEA Wind Task 11 TEM
meeting, April 27-28, 2017



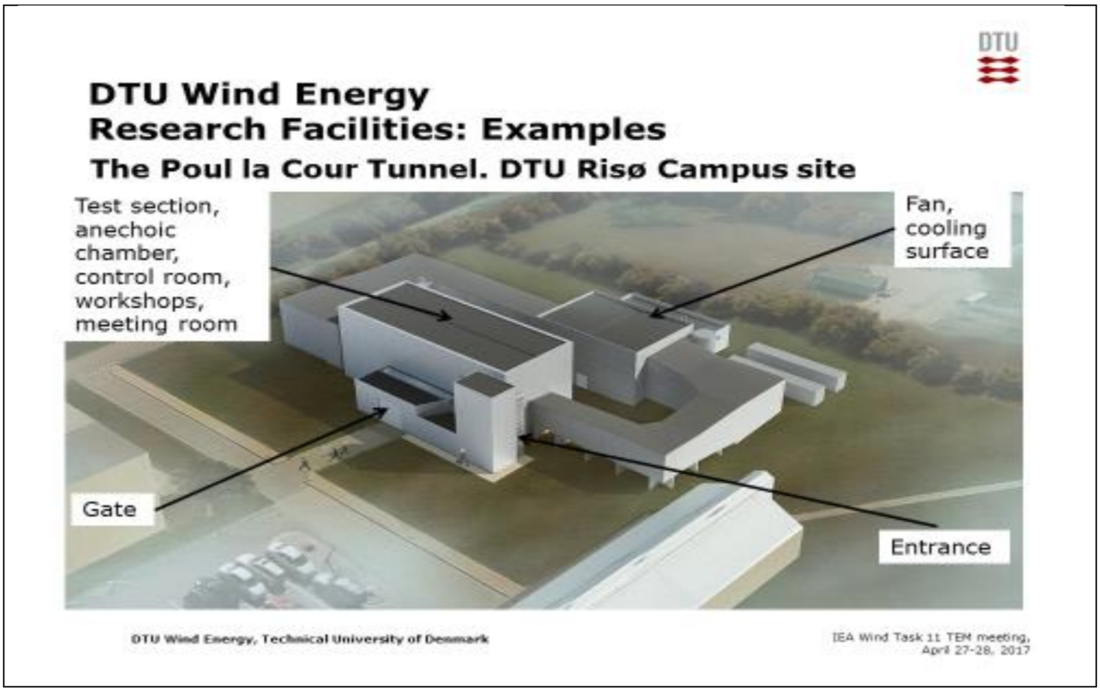
DTU Wind Energy
Research Facilities: Examples

Test Center for Very Large Wind Turbines at Østerild

7 sites

Max height 250m

600m between turbines



DTU Wind Energy
Research Facilities: Examples

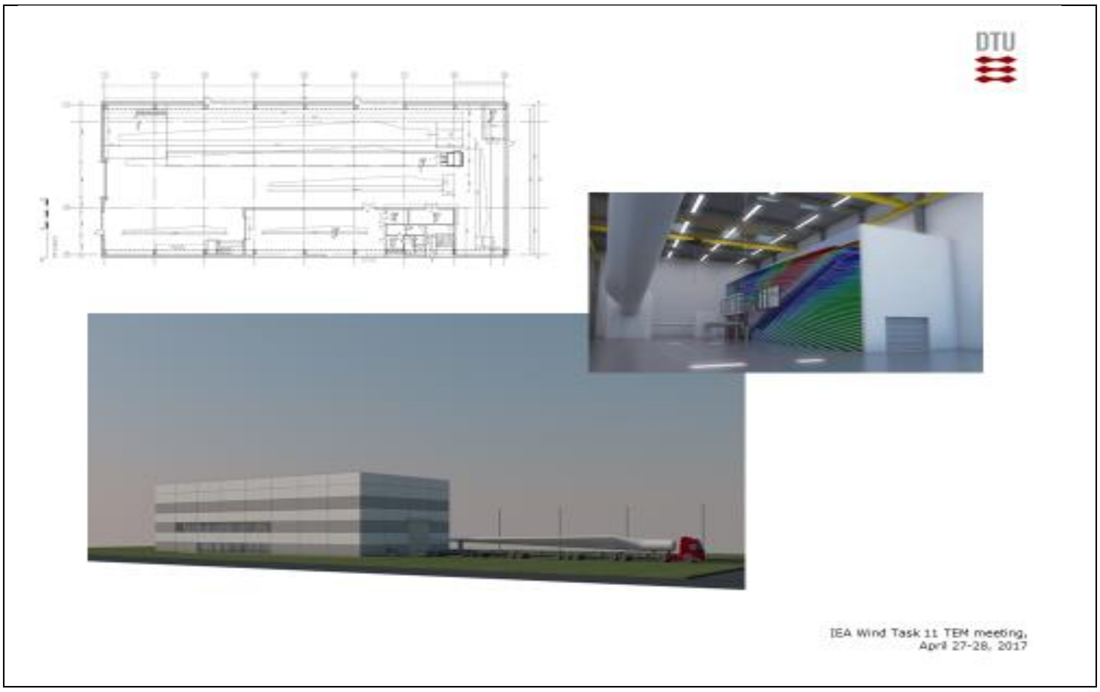
The Poul la Cour Tunnel. DTU Risø Campus site

Test section, anechoic chamber, control room, workshops, meeting room

Fan, cooling surface

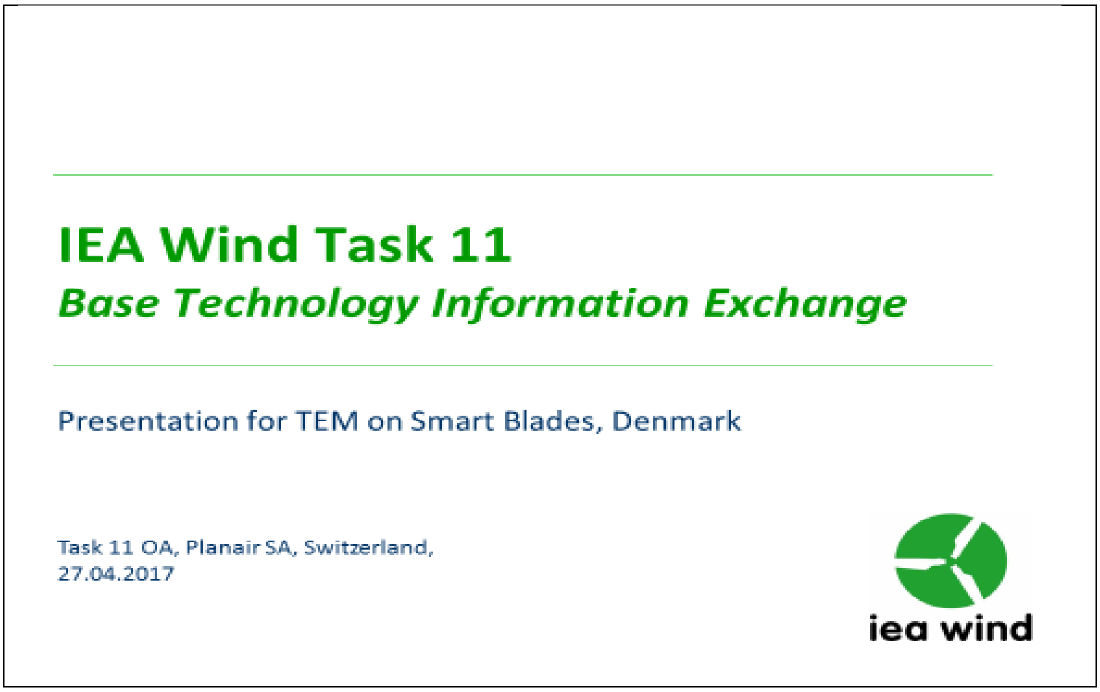
Gate

Entrance



DTU

IEA Wind Task 11 TEM meeting,
April 27-28, 2017



IEA Wind Task 11

Base Technology Information Exchange

Presentation for TEM on Smart Blades, Denmark

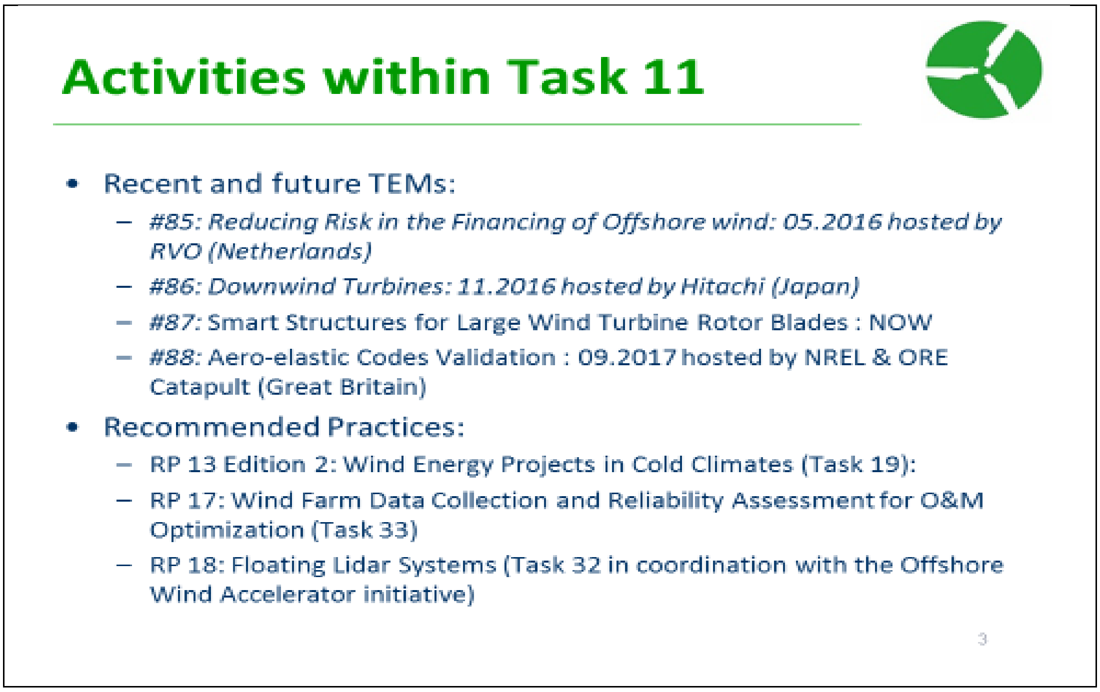
Task 11 OA, Planair SA, Switzerland,
27.04.2017

iea wind

Activities within Task 11

- Main objective : promote and disseminate knowledge on emerging wind energy topics
- Main activities :
  - Help identify new topics of interests
  - Organization of 4 topical experts meetings (TEM) a year on new topics of high interests
  - Coordination the approval process of Recommended Practices

Participating countries
CWEA (China)
Denmark
Finland
Germany
Ireland
Italy
Japan
Mexico
Netherlands
Norway
Spain
Sweden
Switzerland
United Kingdom
United States



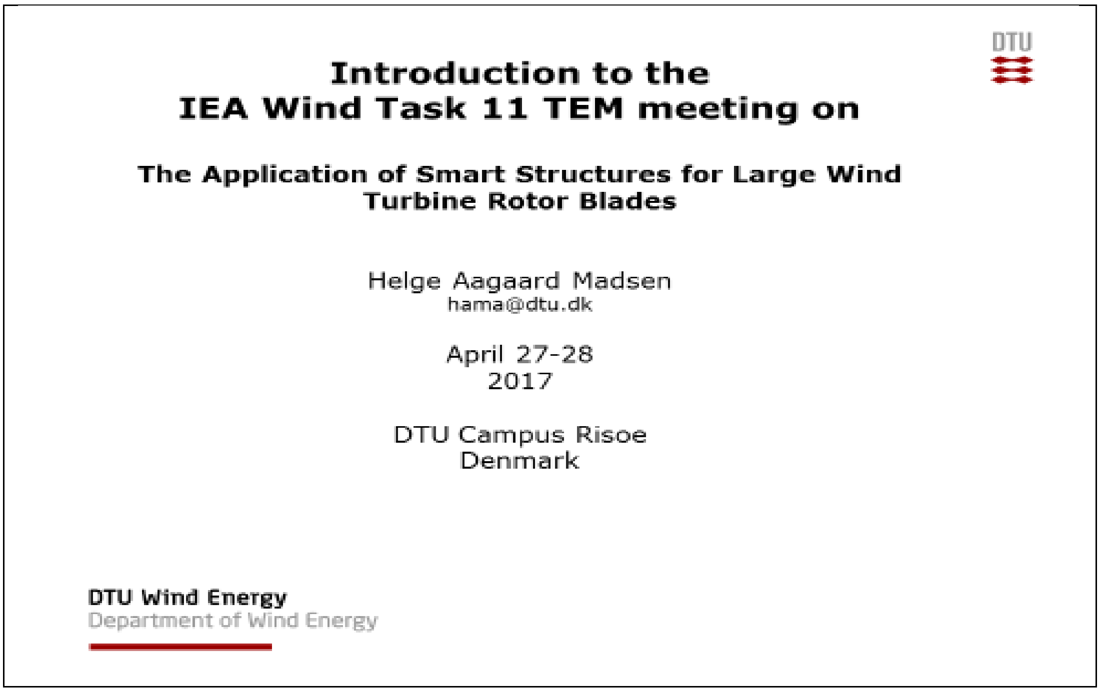
Activities within Task 11

- Recent and future TEMs:
  - *#85: Reducing Risk in the Financing of Offshore wind: 05.2016 hosted by RVO (Netherlands)*
  - *#86: Downwind Turbines: 11.2016 hosted by Hitachi (Japan)*
  - *#87:* Smart Structures for Large Wind Turbine Rotor Blades : NOW
  - *#88:* Aero-elastic Codes Validation : 09.2017 hosted by NREL & ORE Catapult (Great Britain)
- Recommended Practices:
  - RP 13 Edition 2: Wind Energy Projects in Cold Climates (Task 19):
  - RP 17: Wind Farm Data Collection and Reliability Assessment for O&M Optimization (Task 33)
  - RP 18: Floating Lidar Systems (Task 32 in coordination with the Offshore Wind Accelerator initiative)

New developments

- New operating agent since the beginning of 2017 : Planair SA from Switzerland
- Clarification of the organization processes for future TEMs
- Selection and implementation of an online community plateform with following objectives:
  - Give structure and substance to the wind energy expert community: where are the experts located, what are their expertise?
  - Facilitate exchange within the community: sharing events, news on progresses, relevant articles
  - Help identify new interesting topics that can lead to TEMs (and potentially new tasks)
  - Help organize meetings (TEM) around these new topics with a sufficient number of relevant experts attending

4



DTU

Introduction to the IEA Wind Task 11 TEM meeting on

The Application of Smart Structures for Large Wind Turbine Rotor Blades

Helge Aagaard Madsen
hama@dtu.dk

April 27-28
2017

DTU Campus Risoe
Denmark

DTU Wind Energy
Department of Wind Energy

Terminology

By "**smart structures**" or "**SMART blade** " is meant a wide range of different technologies but with the overall aim to provide a distributed control of the aerodynamic loads along the blade span with the objective to reduce fatigue and ultimate loads and increase the power production of the rotor.

Previous IEA TEM meetings on SMART blade

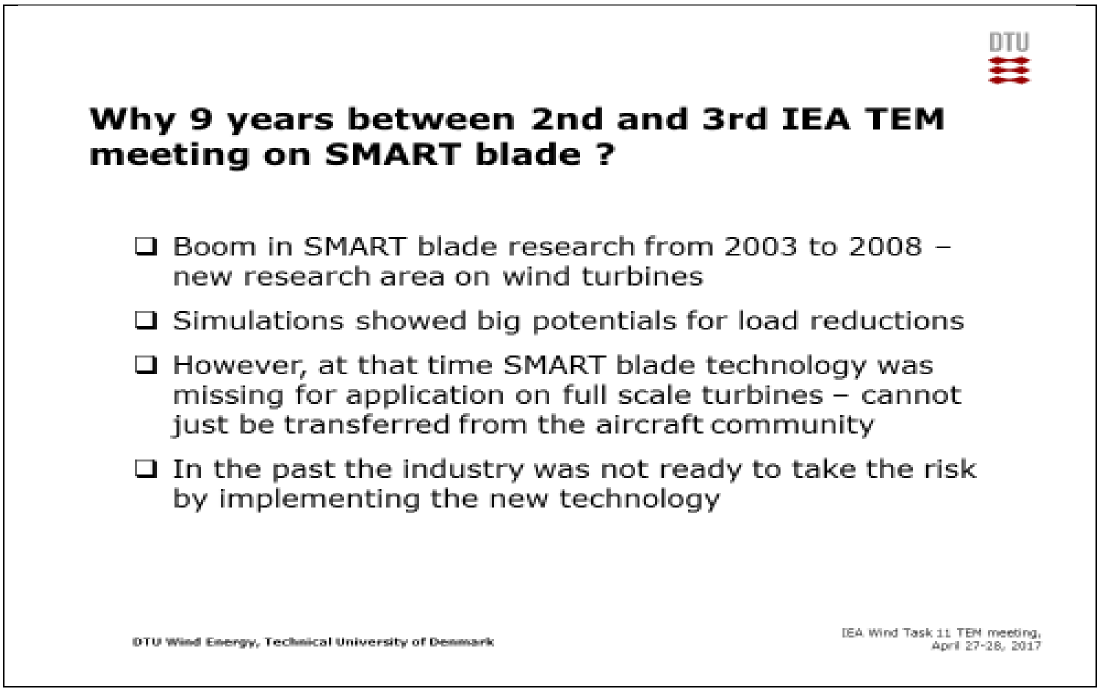
☐ **2006 at TU Delft with about 30 partcipants**

☐ **2008 at Sandia National Laboratories with 22 participants**

☐ **.**

☐ **.**

☐ **2017 at DTU with 27 participants**



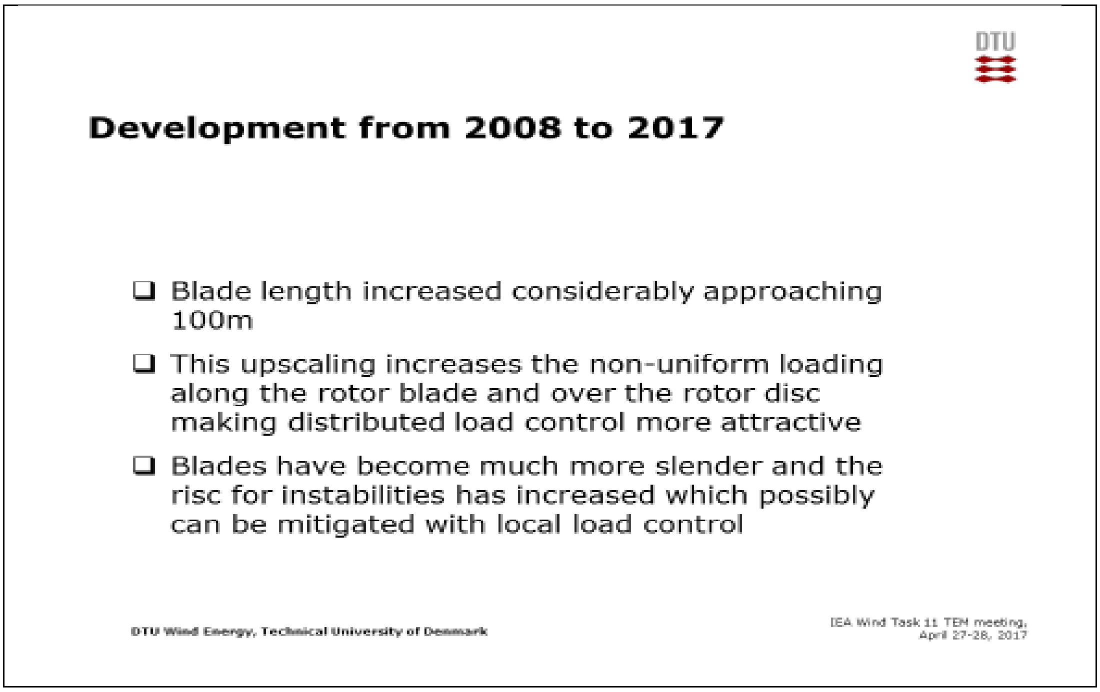
DTU

Why 9 years between 2nd and 3rd IEA TEM meeting on SMART blade ?

- Boom in SMART blade research from 2003 to 2008 – new research area on wind turbines
- Simulations showed big potentials for load reductions
- However, at that time SMART blade technology was missing for application on full scale turbines – cannot just be transferred from the aircraft community
- In the past the industry was not ready to take the risk by implementing the new technology

DTU Wind Energy, Technical University of Denmark

IEA Wind Task 11 TEM meeting,
April 27-28, 2017



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Development from 2008 to 2017

- Blade length increased considerably approaching 100m
- This upscaling increases the non-uniform loading along the rotor blade and over the rotor disc making distributed load control more attractive
- Blades have become much more slender and the risc for instabilities has increased which possibly can be mitigated with local load control

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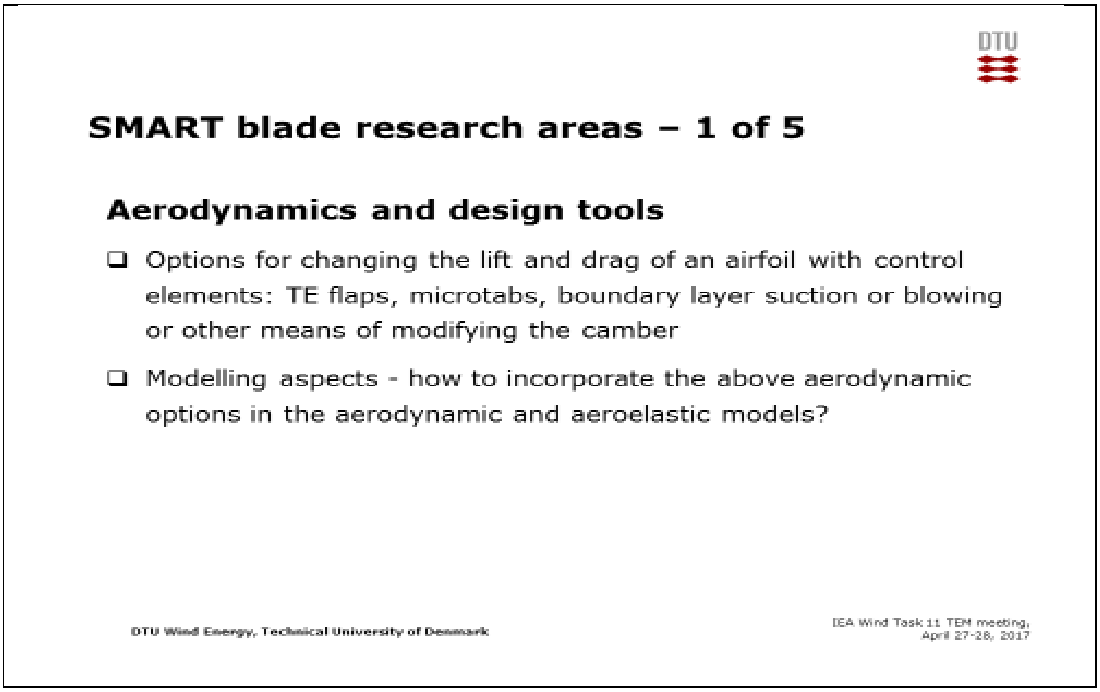
IEA Wind Task 11 TEM meeting,
April 27-28, 2017

Meeting objectives

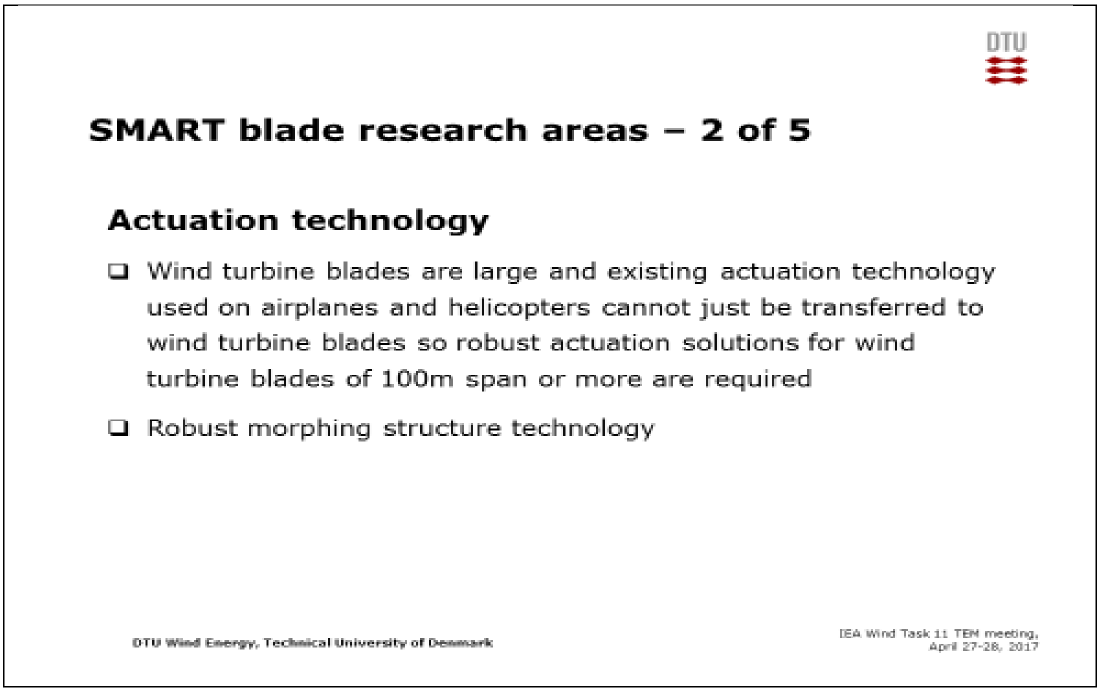
- To provide an overview and status of research and development activities on the SMART blade technology and discuss where new research initiatives are needed



SMART blade research areas – 1 of 5

Aerodynamics and design tools

- Options for changing the lift and drag of an airfoil with control elements: TE flaps, microtabs, boundary layer suction or blowing or other means of modifying the camber
- Modelling aspects - how to incorporate the above aerodynamic options in the aerodynamic and aeroelastic models?



SMART blade research areas – 2 of 5

Actuation technology

❑ Wind turbine blades are large and existing actuation technology used on airplanes and helicopters cannot just be transferred to wind turbine blades so robust actuation solutions for wind turbine blades of 100m span or more are required

❑ Robust morphing structure technology

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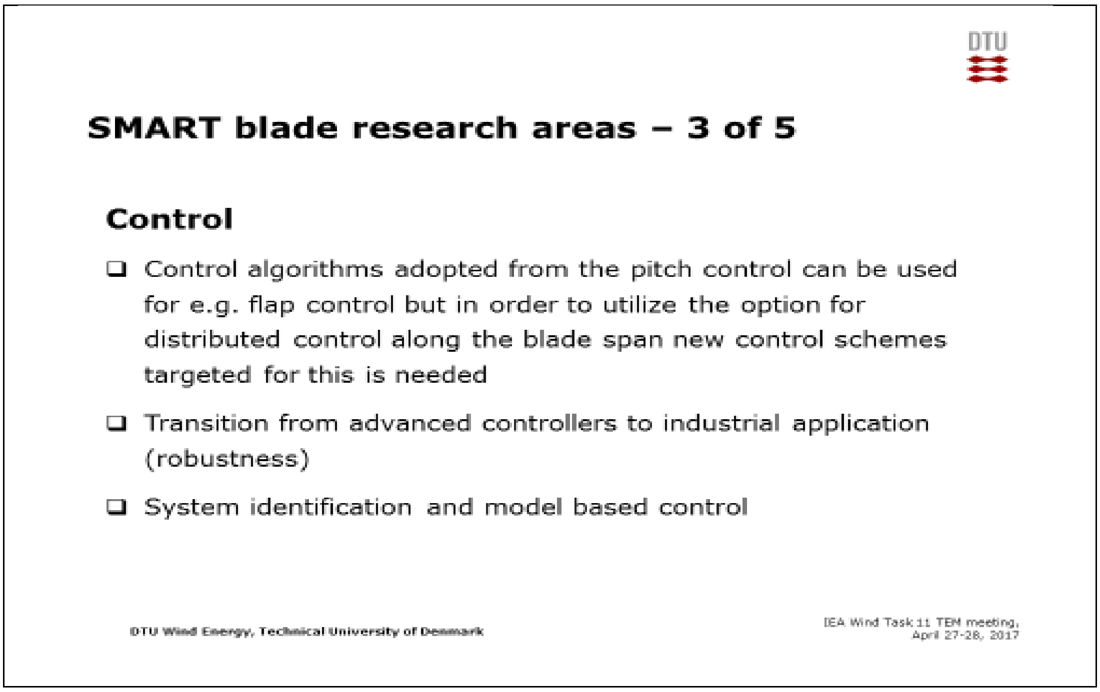
IEA Wind Task 11 TEM meeting,
April 27-28, 2017



SMART blade research areas – 3 of 5

Control

❑ Control algorithms adopted from the pitch control can be used for e.g. flap control but in order to utilize the option for distributed control along the blade span new control schemes targeted for this is needed

❑ Transition from advanced controllers to industrial application (robustness)

❑ System identification and model based control

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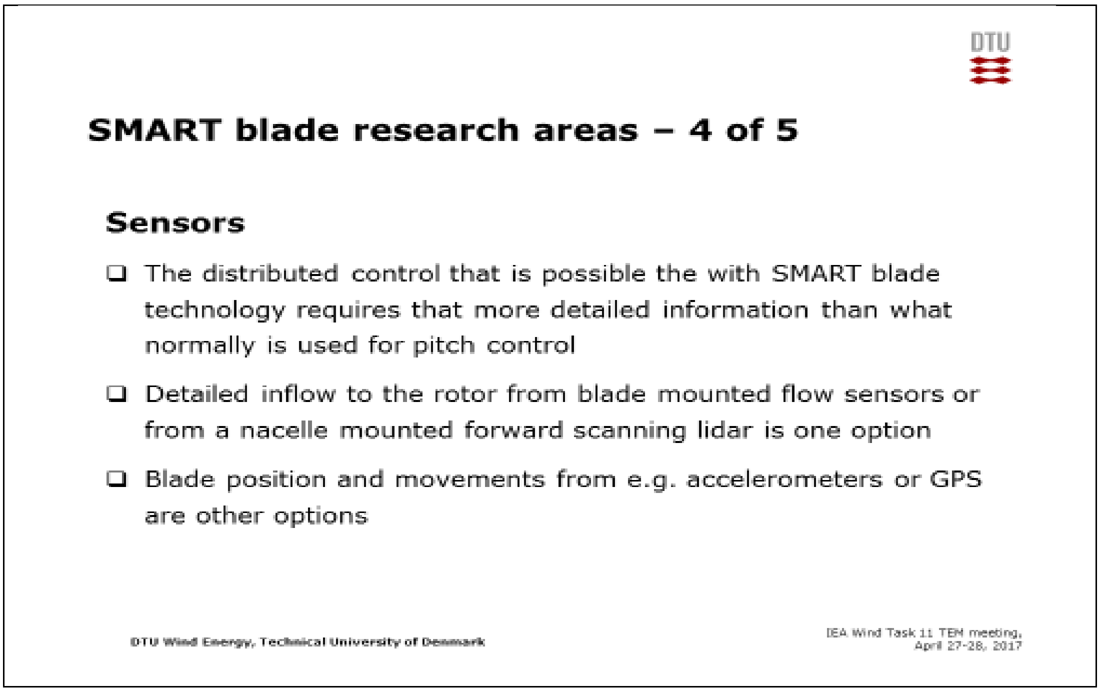
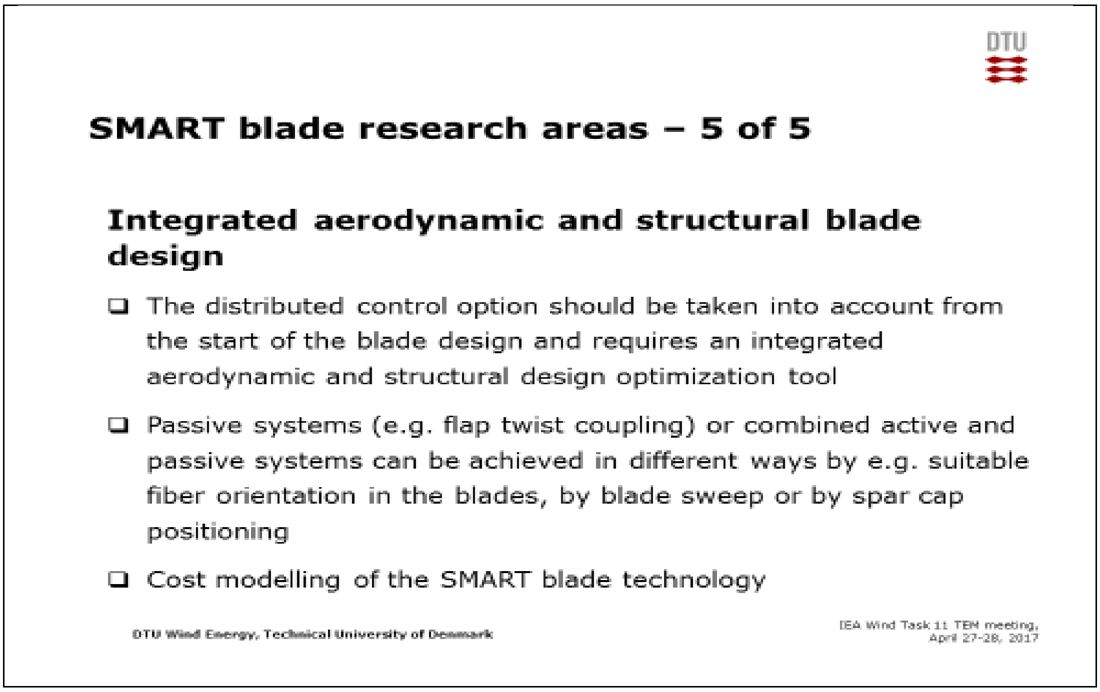
IEA Wind Task 11 TEM meeting,
April 27-28, 2017



SMART blade research areas – 4 of 5

Sensors

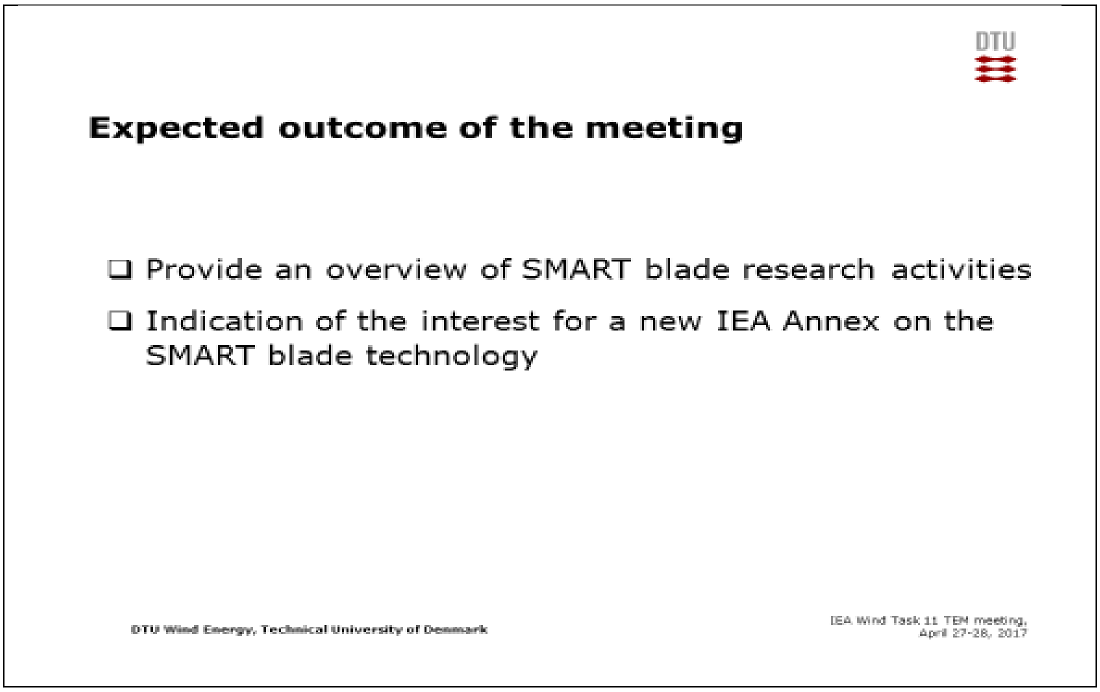
- The distributed control that is possible the with SMART blade technology requires that more detailed information than what normally is used for pitch control
- Detailed inflow to the rotor from blade mounted flow sensors or from a nacelle mounted forward scanning lidar is one option
- Blade position and movements from e.g. accelerometers or GPS are other options



SMART blade research areas – 5 of 5

Integrated aerodynamic and structural blade design

- The distributed control option should be taken into account from the start of the blade design and requires an integrated aerodynamic and structural design optimization tool
- Passive systems (e.g. flap twist coupling) or combined active and passive systems can be achieved in different ways by e.g. suitable fiber orientation in the blades, by blade sweep or by spar cap positioning
- Cost modelling of the SMART blade technology



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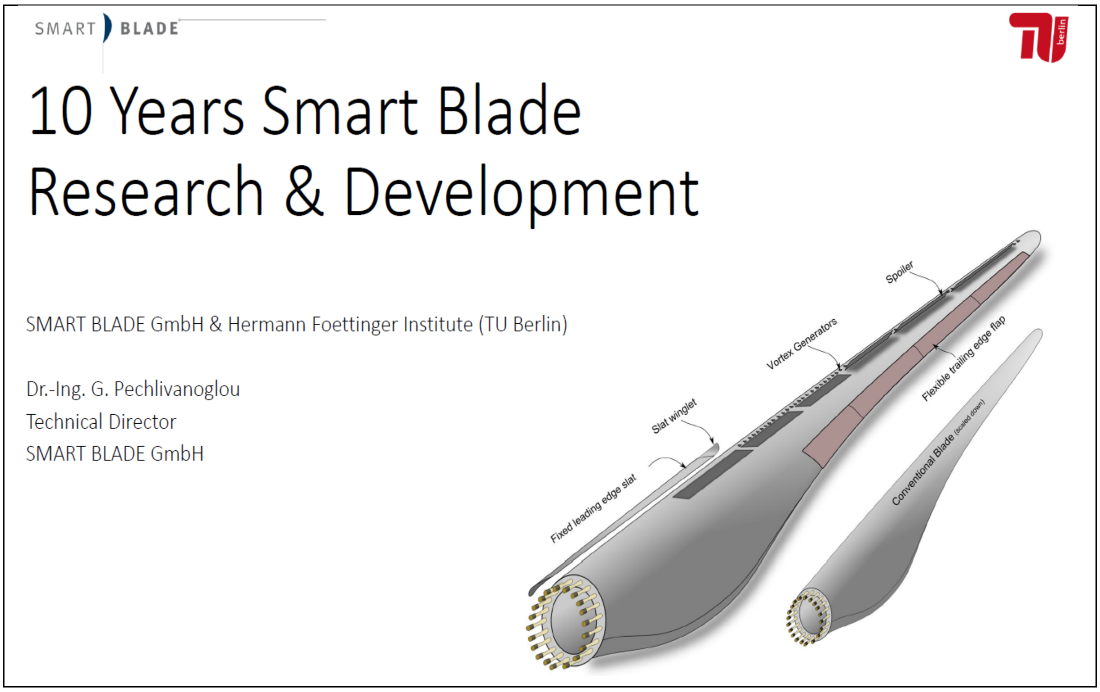
Expected outcome of the meeting

- ☐ Provide an overview of SMART blade research activities
- ☐ Indication of the interest for a new IEA Annex on the SMART blade technology

DTU Wind Energy, Technical University of Denmark

IEA Wind Task 11 TEM meeting,
April 27-28, 2017

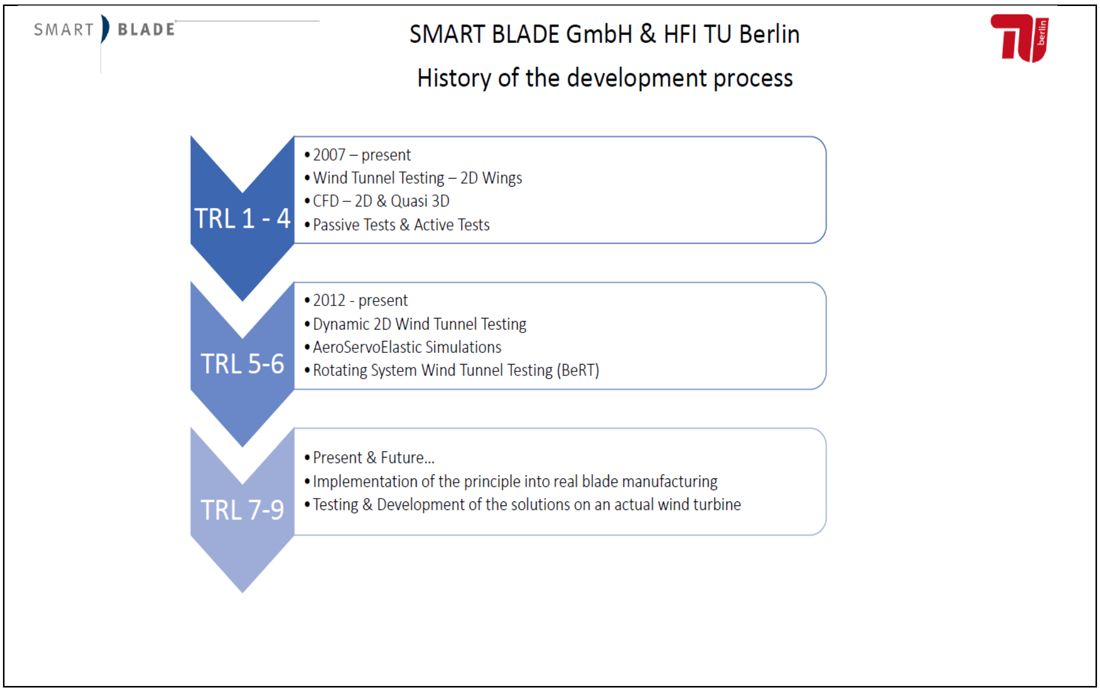


SMART BLADE

10 Years Smart Blade Research & Development

SMART BLADE GmbH & Hermann Foettinger Institute (TU Berlin)

Dr.-Ing. G. Pechlivanoglou
Technical Director
SMART BLADE GmbH



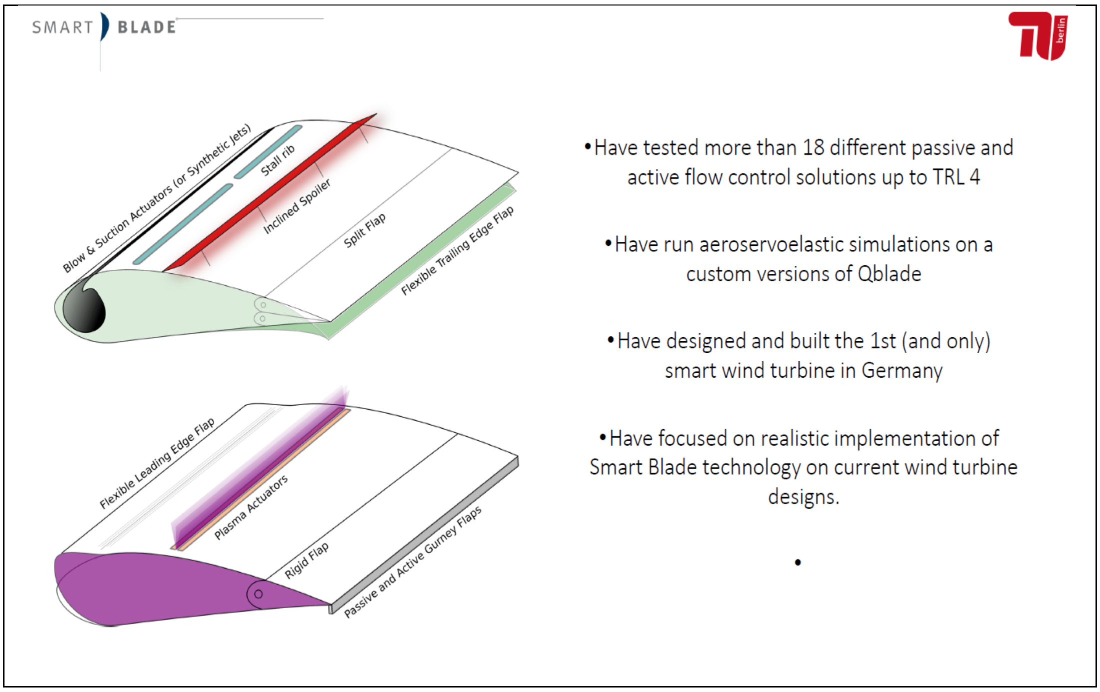
SMART BLADE GmbH & HFI TU Berlin

History of the development process

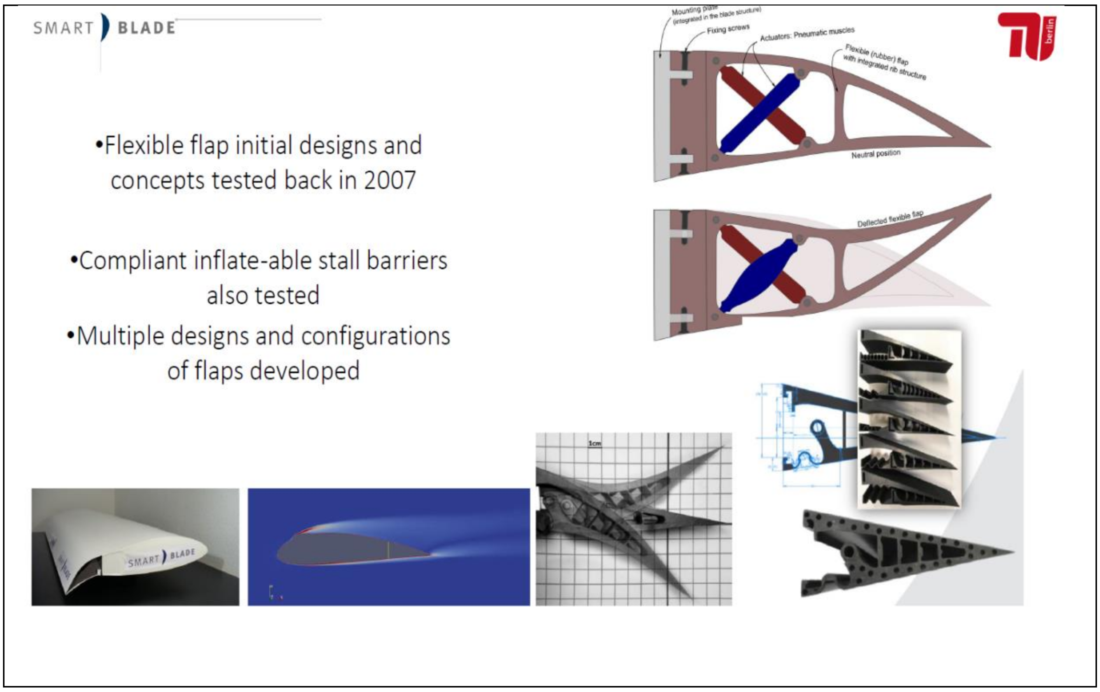
TRL 1 - 4
- 2007 – present
- Wind Tunnel Testing – 2D Wings
- CFD – 2D & Quasi 3D
- Passive Tests & Active Tests

TRL 5-6
- 2012 - present
- Dynamic 2D Wind Tunnel Testing
- AeroServoElastic Simulations
- Rotating System Wind Tunnel Testing (BeRT)

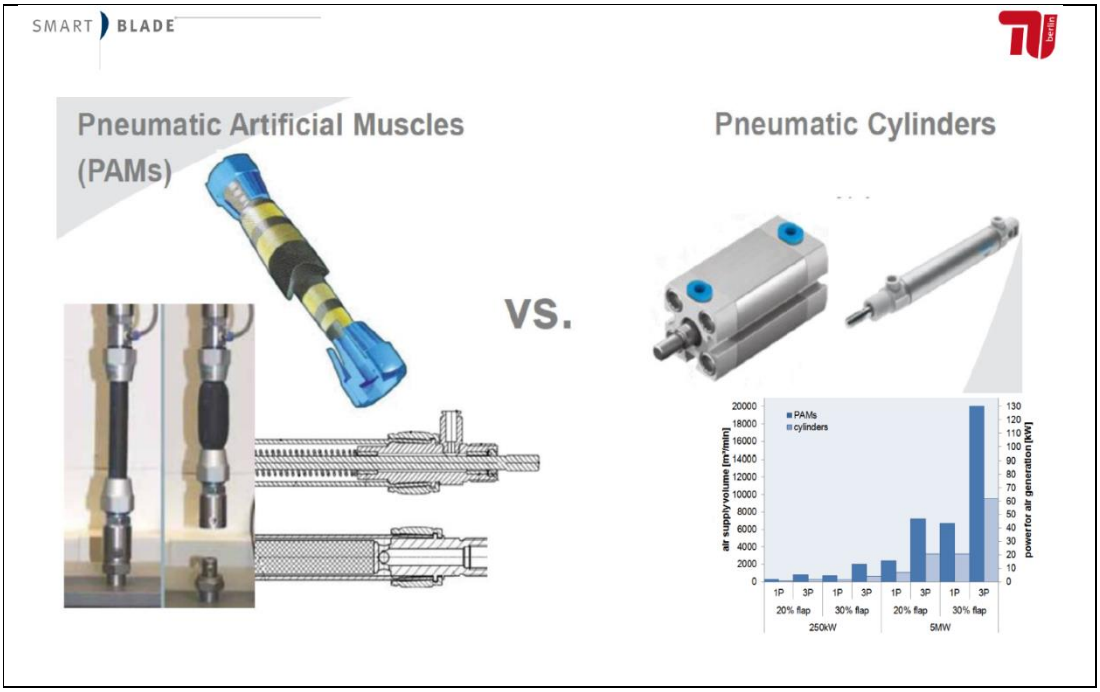
TRL 7-9
- Present & Future…
- Implementation of the principle into real blade manufacturing
- Testing & Development of the solutions on an actual wind turbine



- Have tested more than 18 different passive and active flow control solutions up to TRL 4
- Have run aeroservoelastic simulations on a custom versions of Qblade
- Have designed and built the 1st (and only) smart wind turbine in Germany
- Have focused on realistic implementation of Smart Blade technology on current wind turbine designs.



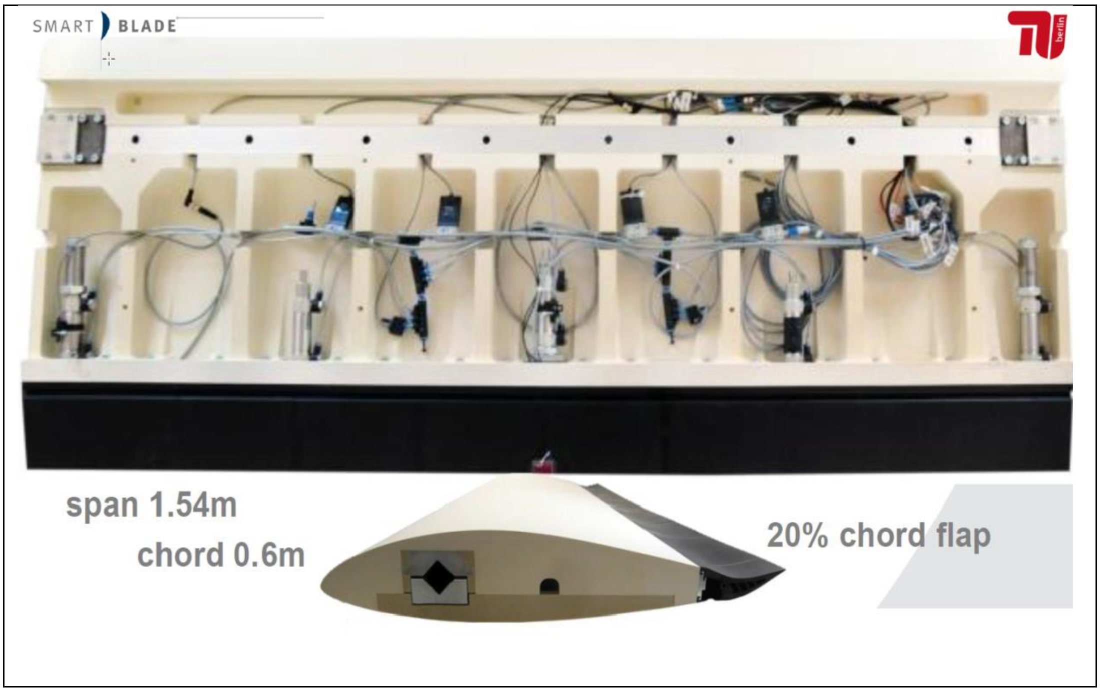
- Flexible flap initial designs and concepts tested back in 2007
- Compliant inflate-able stall barriers also tested
- Multiple designs and configurations of flaps developed



Pneumatic Artificial Muscles (PAMs)

vs.

Pneumatic Cylinders

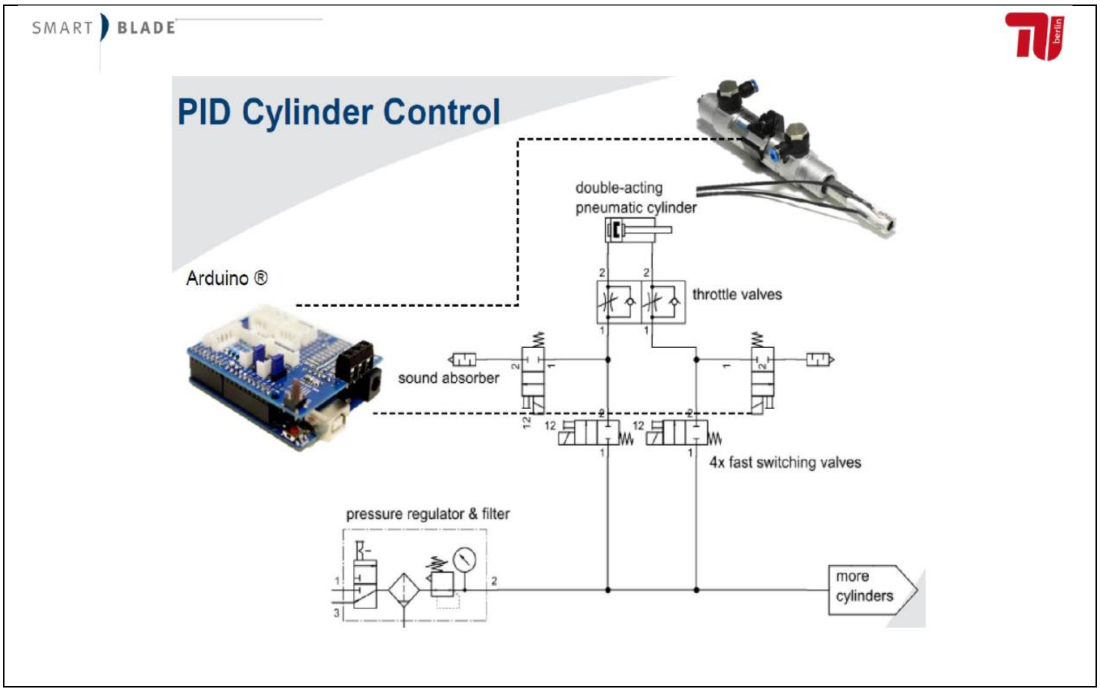


SMART BLADE

span 1.54m

chord 0.6m

20% chord flap



SMART BLADE

PID Cylinder Control

Arduino ®

double-acting pneumatic cylinder

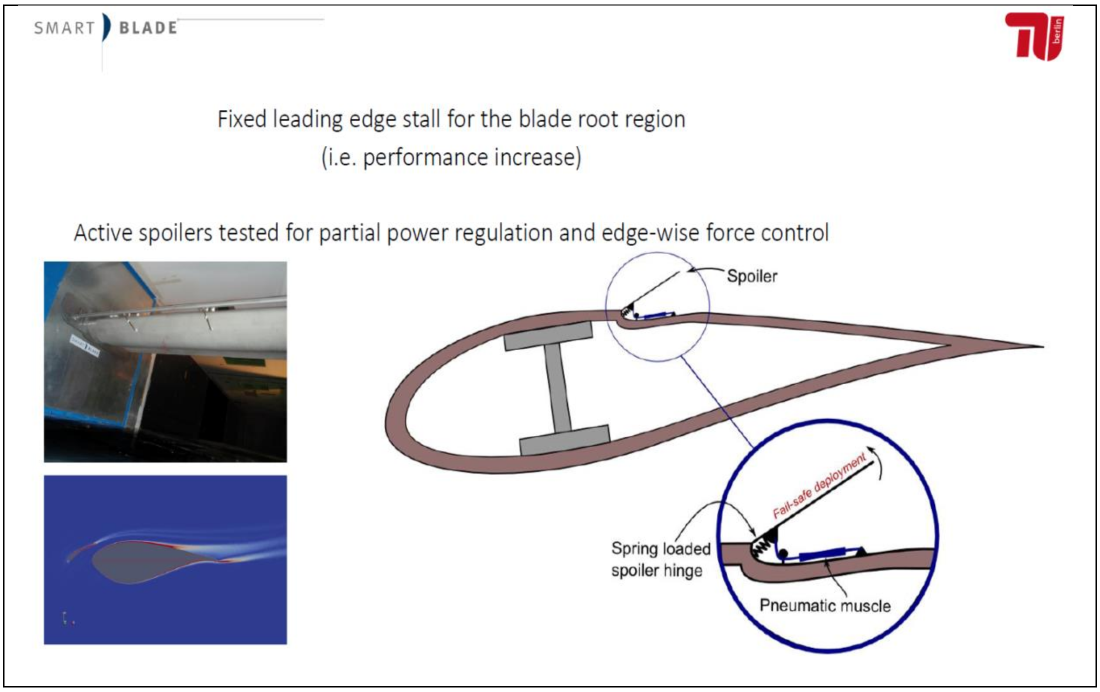
throttle valves

sound absorber

4x fast switching valves

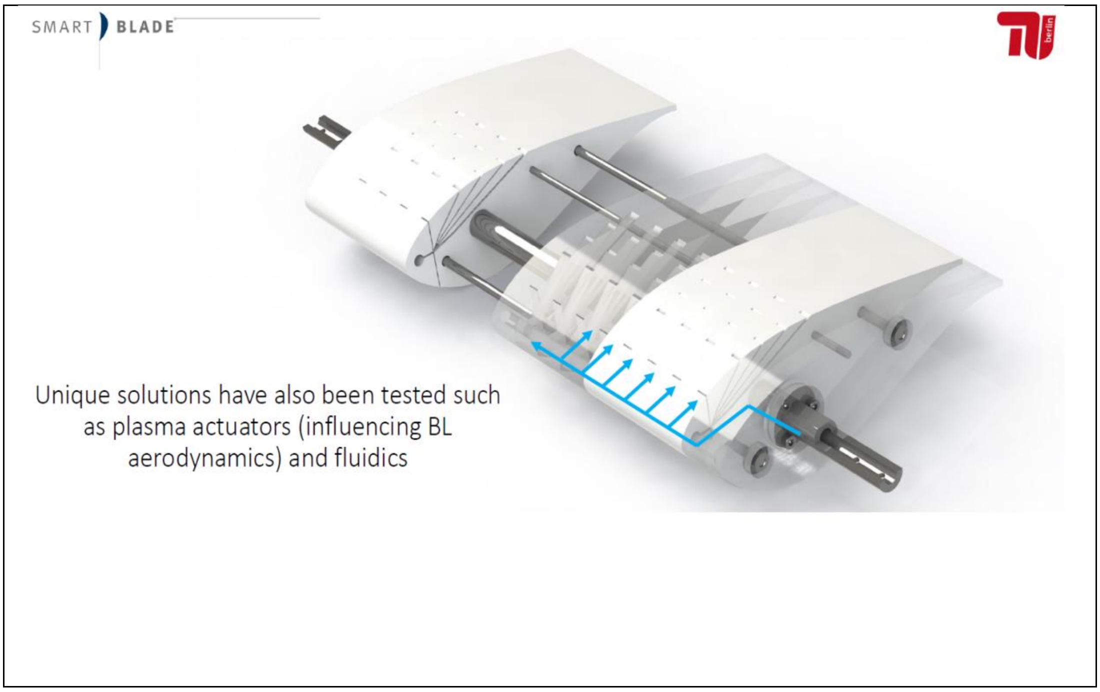
pressure regulator & filter

more cylinders

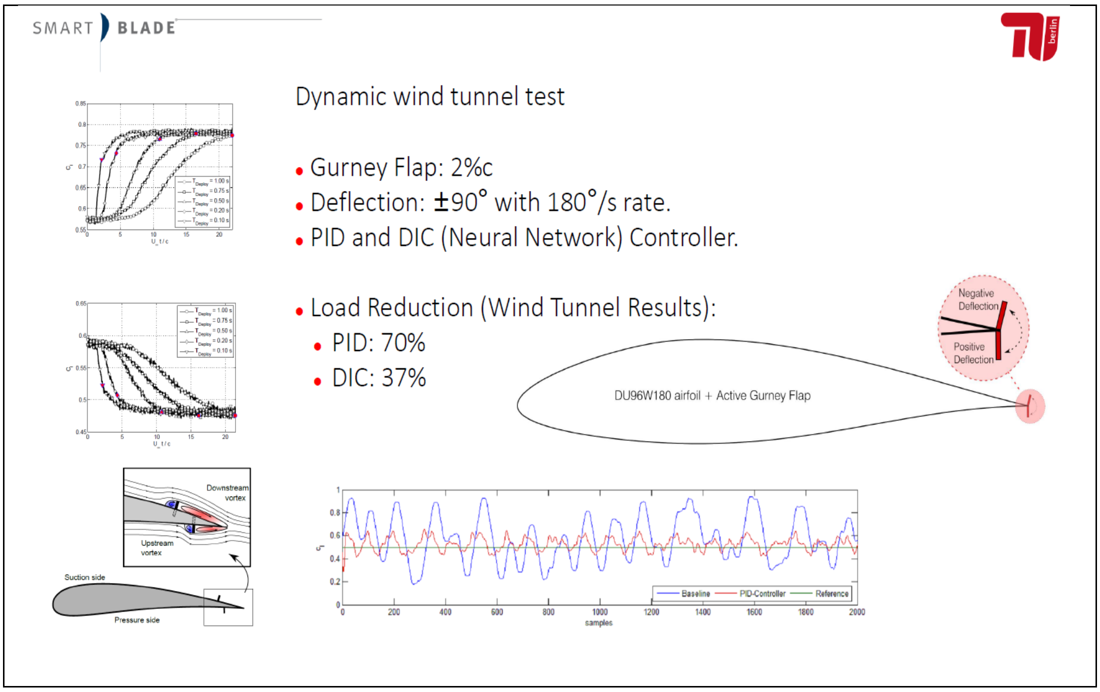


Fixed leading edge stall for the blade root region
(i.e. performance increase)

Active spoilers tested for partial power regulation and edge-wise force control



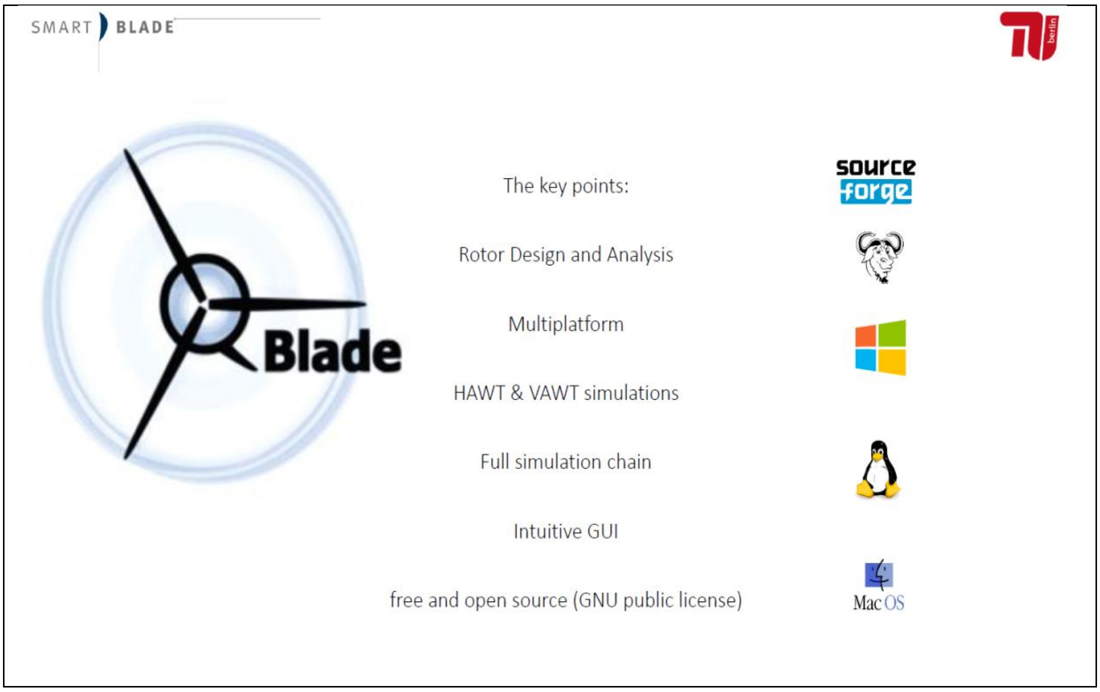
Unique solutions have also been tested such as plasma actuators (influencing BL aerodynamics) and fluidics



Dynamic wind tunnel test

- Gurney Flap: 2%c
- Deflection: ±90° with 180°/s rate.
- PID and DIC (Neural Network) Controller.

- Load Reduction (Wind Tunnel Results):
  - PID: 70%
  - DIC: 37%



The key points:

Rotor Design and Analysis

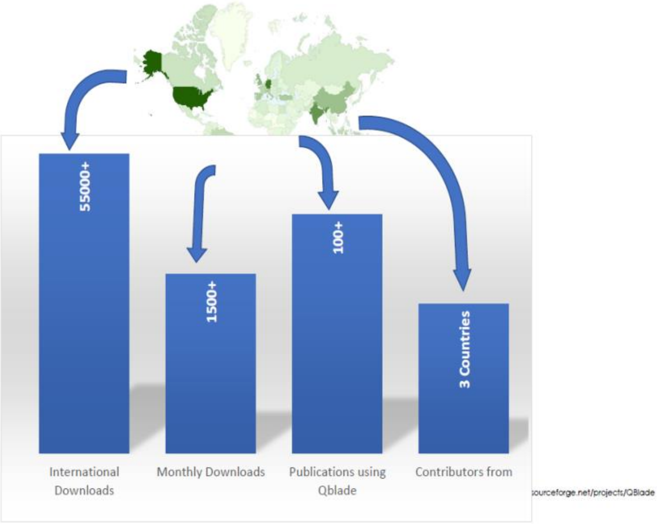
Multiplatform

HAWT & VAWT simulations

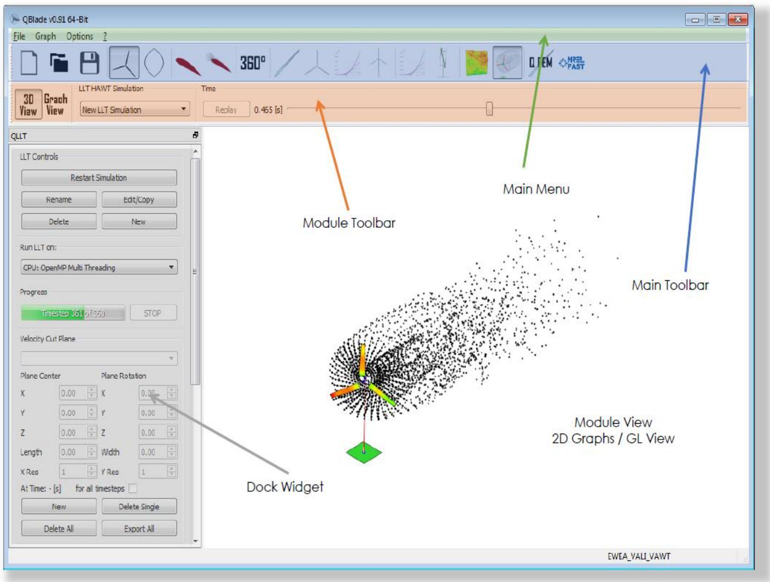
Full simulation chain

Intuitive GUI

free and open source (GNU public license)



sourceforge.net/projects/QBlade

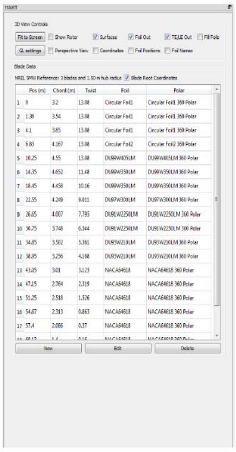

QBlade v0.91 64-Bit

LLT HAWT Simulation: New LLT Simulation

Time: 0.465 [s]

Run LLT on: CPU: OpenMP Multi Threading

Progress: Timestep 361 of 360


HAWT

3D View Controls

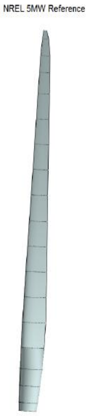
Fit to Screen ☐ Show Rotor ☑ Surfaces ☑ Foil Out ☑ TE/LE Out ☐ Fill Foils

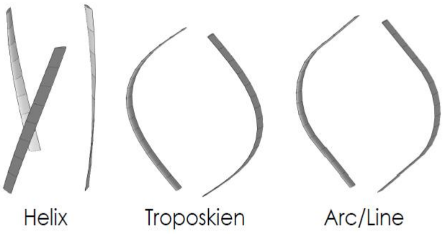
GL settings ☐ Perspective View ☐ Coordinates ☐ Foil Positions ☐ Foil Names

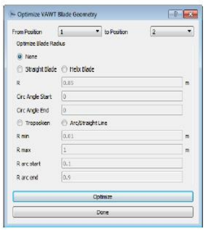
Blade Data

NREL 5MW Reference: 3 blades and 1.50 m hub radius ☑ Blade Root Coordinates

	Pos (m)	Chord (m)	Twist	Foil	Polar
1	0	3.2	13.08	Circular Foil1	Circular Foil1 360 Polar
2	1.36	3.54	13.08	Circular Foil1	Circular Foil1 360 Polar
3	4.1	3.85	13.08	Circular Foil1	Circular Foil1 360 Polar
4	6.83	4.167	13.08	Circular Foil2	Circular Foil2 360 Polar
5	10.25	4.55	13.08	DU99W405LM	DU99W405LM 360 Polar
6	14.35	4.652	11.48	DU99W350LM	DU99W350LM 360 Polar
7	18.45	4.458	10.16	DU99W350LM	DU99W350LM 360 Polar
8	22.55	4.249	9.011	DU97W300LM	DU97W300LM 360 Polar
9	26.65	4.007	7.795	DU91W2250LM	DU91W2250LM 360 Polar
10	30.75	3.748	6.544	DU91W2250LM	DU91W2250LM 360 Polar
11	34.85	3.502	5.361	DU93W210LM	DU93W210LM 360 Polar
12	38.95	3.256	4.188	DU93W210LM	DU93W210LM 360 Polar
13	43.05	3.01	3.125	NACA64618	NACA64618 360 Polar
14	47.15	2.764	2.319	NACA64618	NACA64618 360 Polar
15	51.25	2.518	1.526	NACA64618	NACA64618 360 Polar
16	54.67	2.313	0.863	NACA64618	NACA64618 360 Polar
17	57.4	2.086	0.37	NACA64618	NACA64618 360 Polar






Optimize VAWT Blade Geometry

From Position 1 to Position 2

Optimize Blade Radius

● None

○ Straight Blade ○ Helix Blade

R 0.85 m

Circ Angle Start 0

Circ Angle End 0

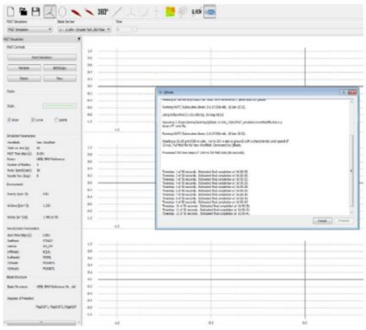
○ Troposkien ○ Arc/Straight Line

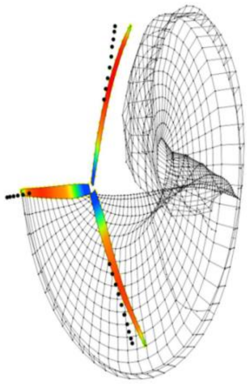
R min 0.01 m

R max 1 m

R arc start 0.1

R arc end 0.9

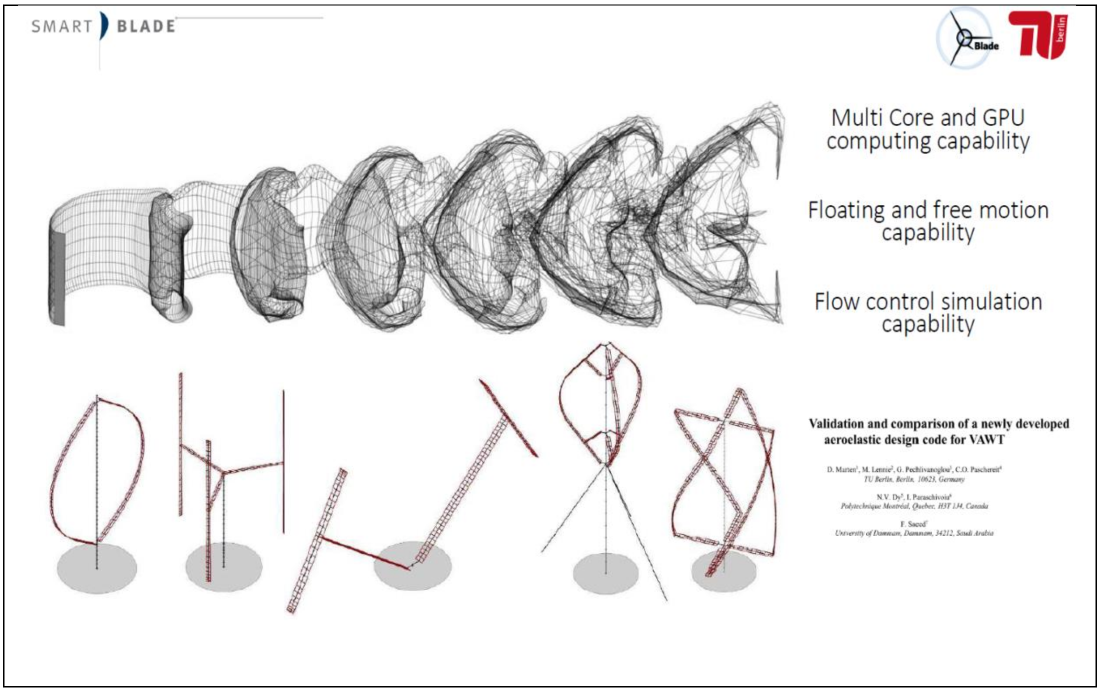




Advanced blade and wake aerodynamics

State of the art aeroelastic modeling (FAST v8)

Novel HAWT & VAWT multi-T. beam model (see next slide)



Multi Core and GPU computing capability

Floating and free motion capability

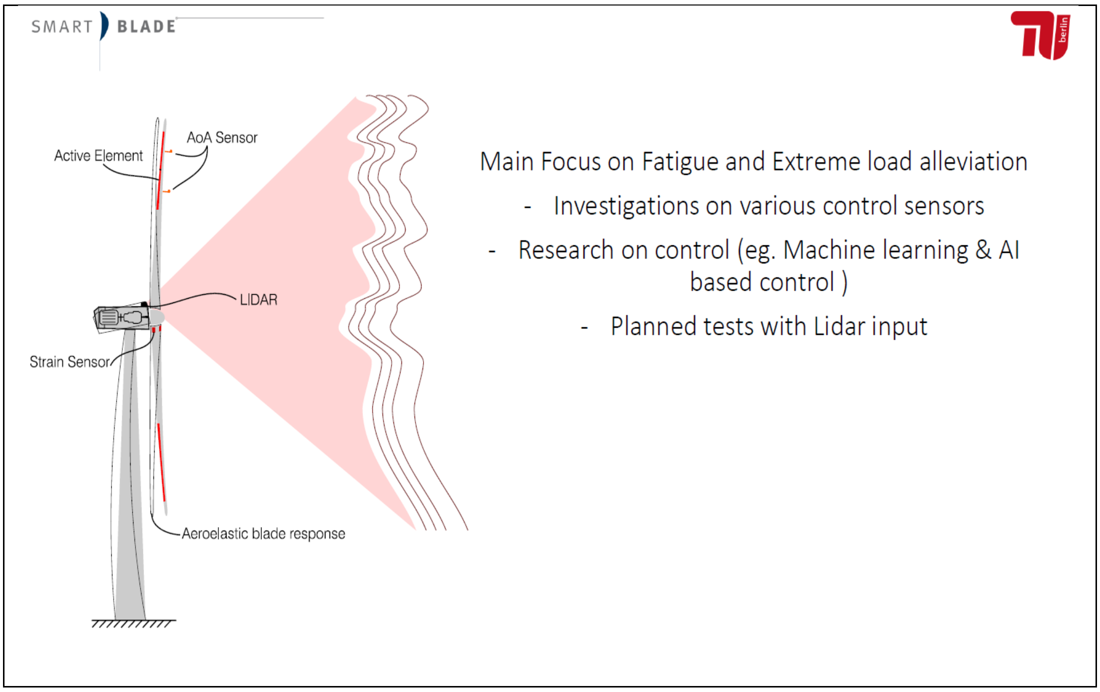
Flow control simulation capability

Validation and comparison of a newly developed aeroelastic design code for VAWT

D. Marten[1], M. Lennie[2], G. Pechlivanoglou[3], C.O. Paschereit[4]
TU Berlin, Berlin, 10623, Germany

N.V. Dy[5], I. Paraschivoiu[6]
Polytechnique Montréal, Quebec, H3T 1J4, Canada

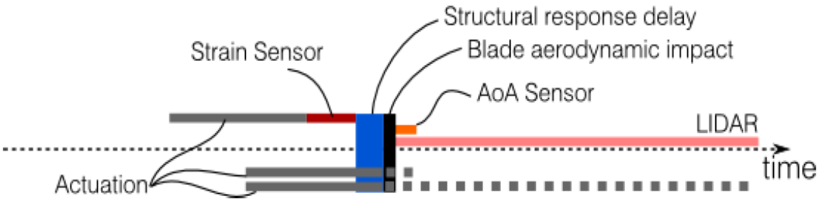
F. Saeed[7]
University of Dammam, Dammam, 34212, Saudi Arabia



Main Focus on Fatigue and Extreme load alleviation

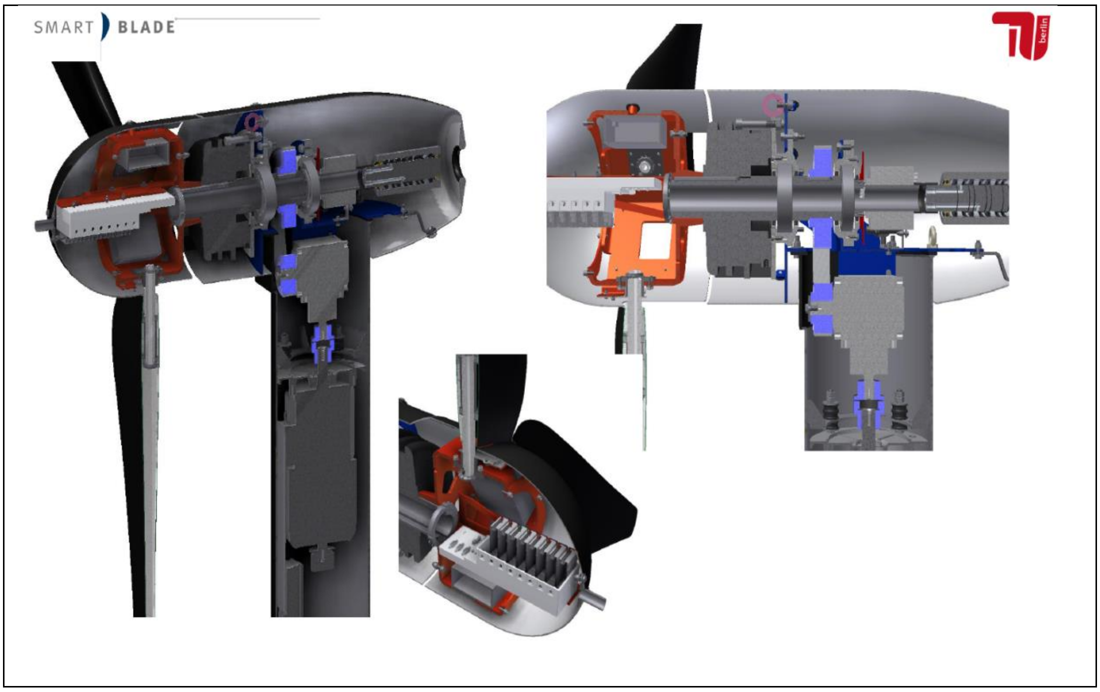
- Investigations on various control sensors
- Research on control (eg. Machine learning & AI based control)
- Planned tests with Lidar input

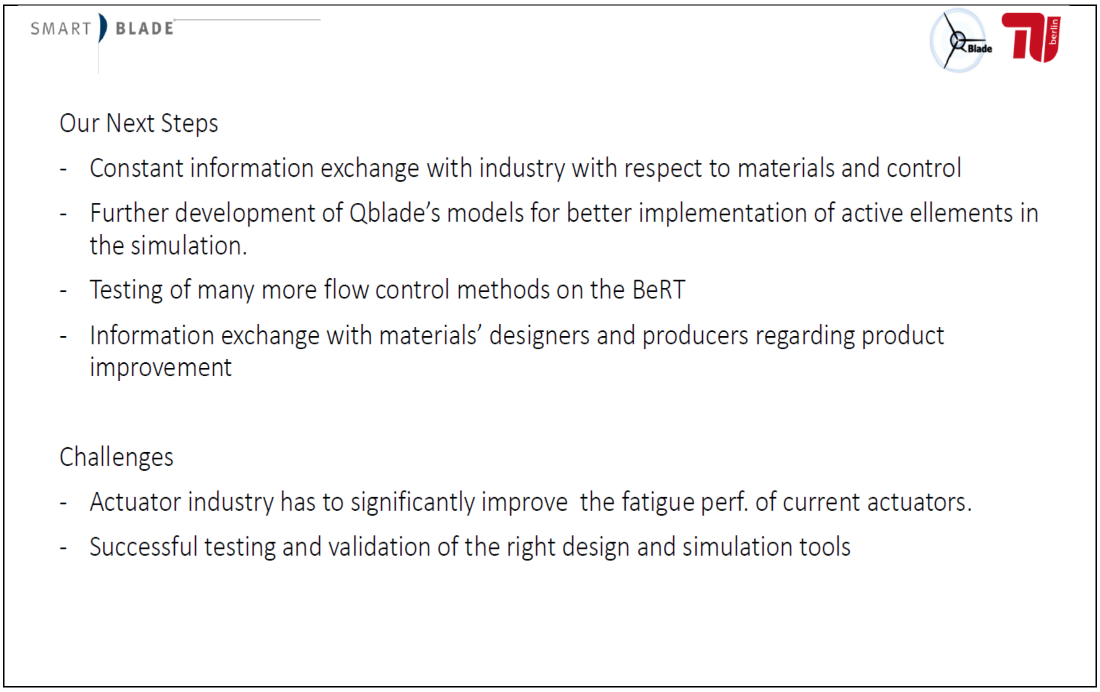
In-depth investigation of various actuators and sensors in order to identify delay sources and controller instability.



Design and development the 1st and only German SMART wind turbine. 3m rotor diameter, located at the settling chamber of the large wind tunnel of TU Berlin

Currently undergoing the 6th wind tunnel test with various control concepts currently being tested.



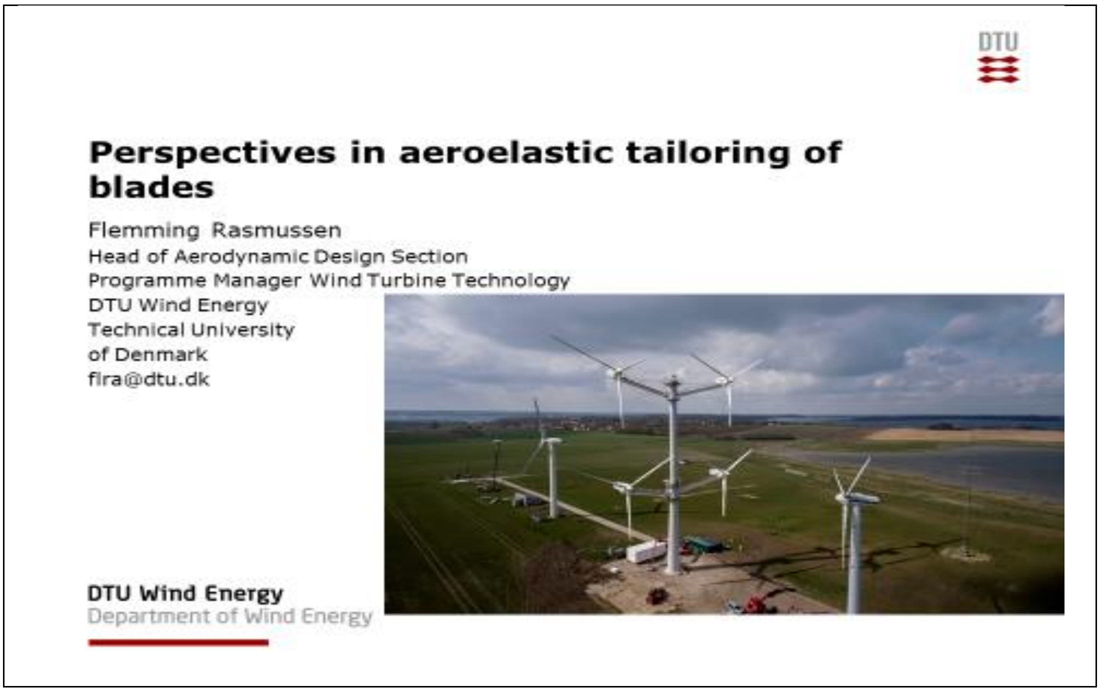


Our Next Steps

- Constant information exchange with industry with respect to materials and control
- Further development of Qblade's models for better implementation of active ellements in the simulation.
- Testing of many more flow control methods on the BeRT
- Information exchange with materials' designers and producers regarding product improvement

Challenges

- Actuator industry has to significantly improve the fatigue perf. of current actuators.
- Successful testing and validation of the right design and simulation tools



Perspectives in aeroelastic tailoring of blades

Flemming Rasmussen
Head of Aerodynamic Design Section
Programme Manager Wind Turbine Technology
DTU Wind Energy
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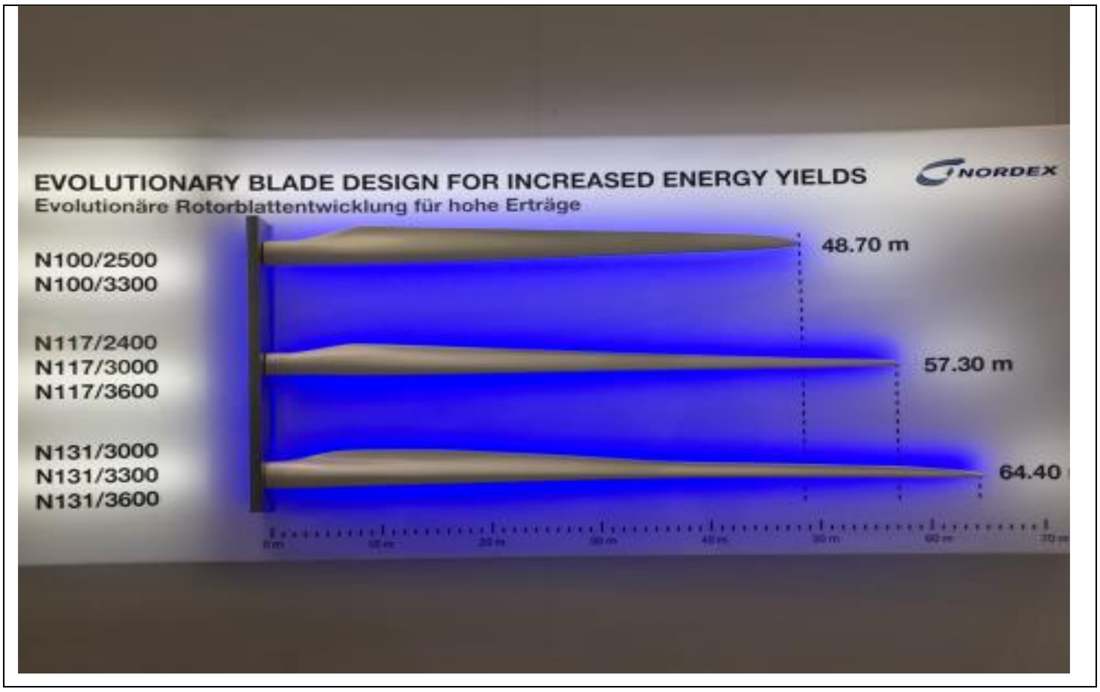
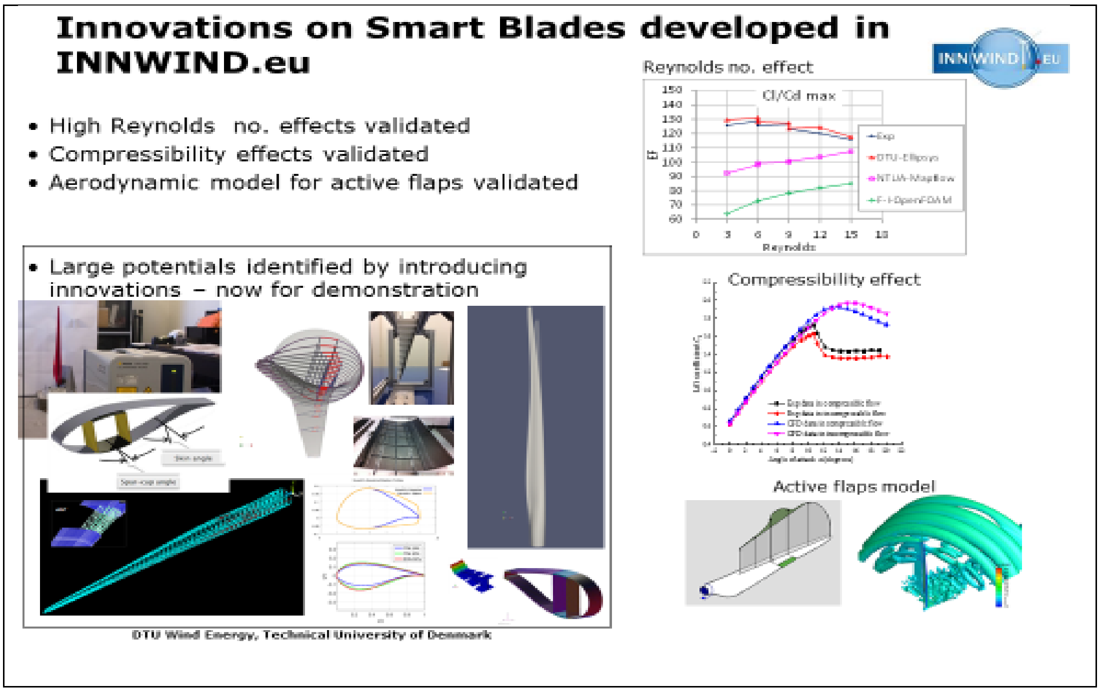
DTU Wind Energy
Department of Wind Energy



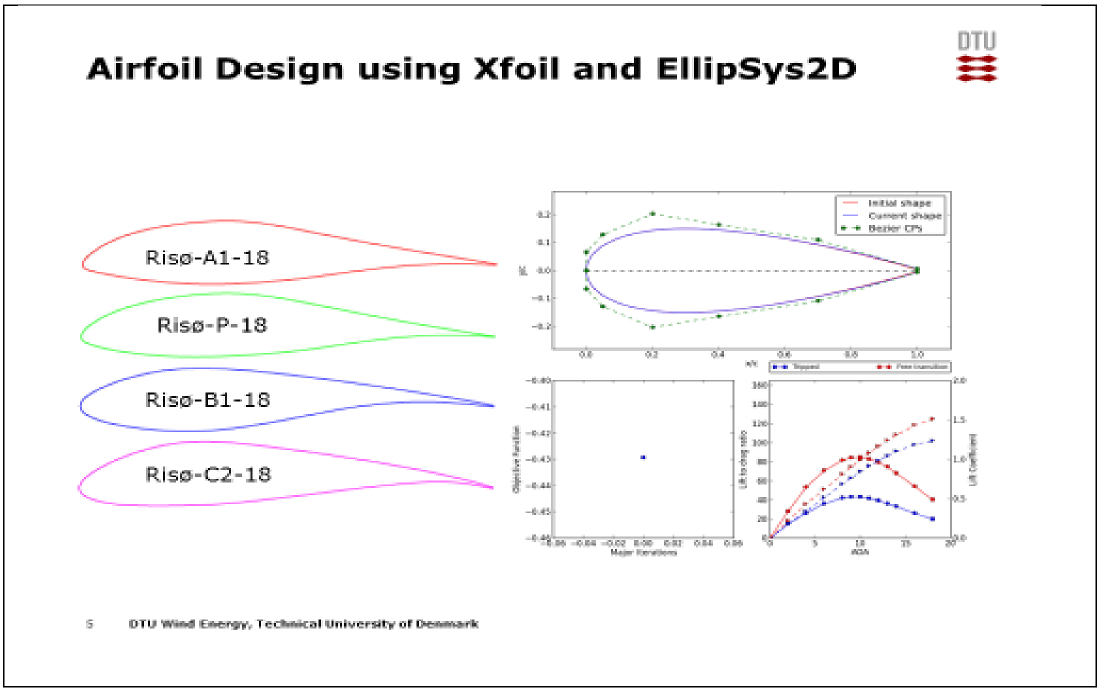


Innovations on Smart Blades developed in INNWIND.eu

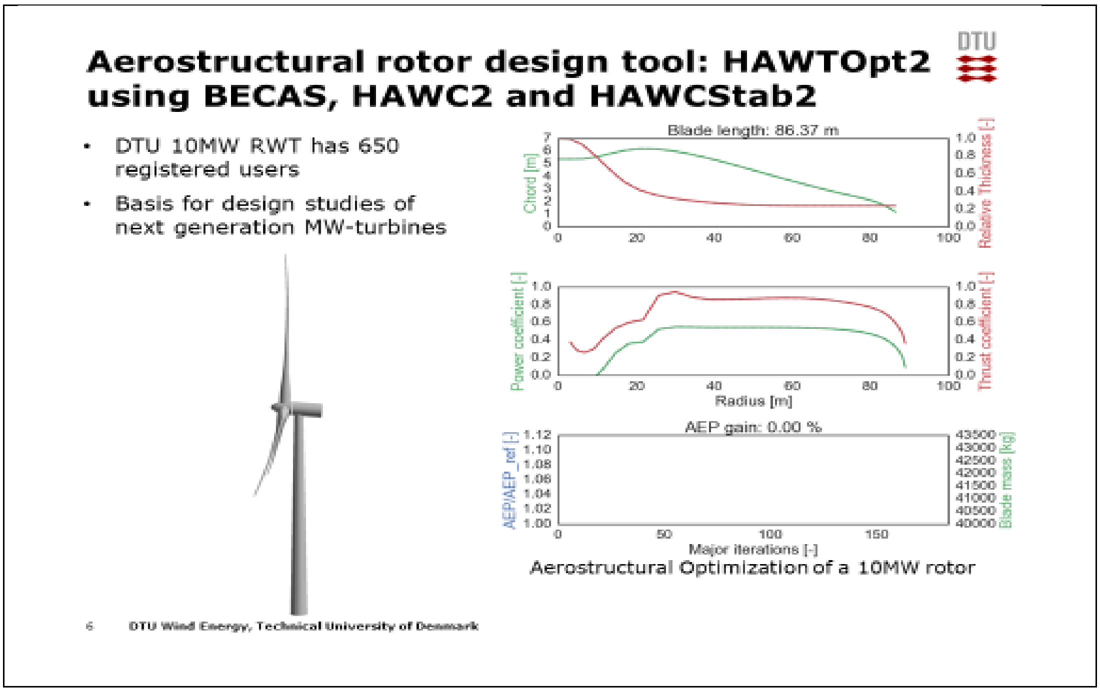
- High Reynolds no. effects validated
- Compressibility effects validated
- Aerodynamic model for active flaps validated

- Large potentials identified by introducing innovations – now for demonstration

DTU Wind Energy, Technical University of Denmark



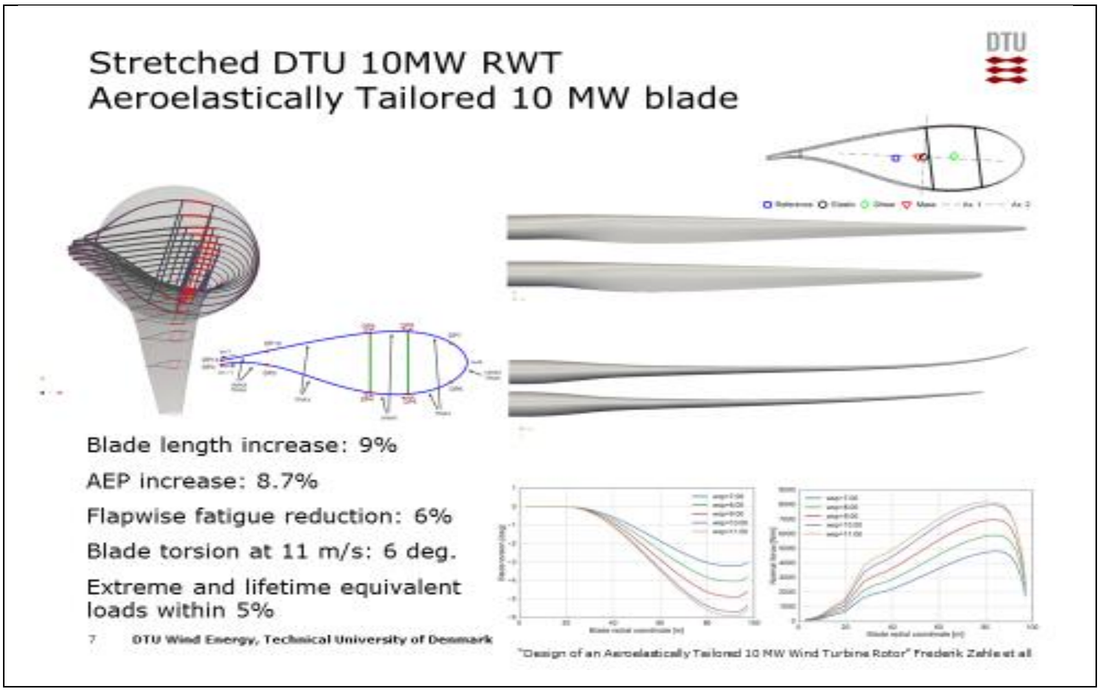
Airfoil Design using Xfoil and EllipSys2D



Aerostructural rotor design tool: HAWTOpt2 using BECAS, HAWC2 and HAWCStab2

- DTU 10MW RWT has 650 registered users
- Basis for design studies of next generation MW-turbines

Aerostructural Optimization of a 10MW rotor



Stretched DTU 10MW RWT
Aeroelastically Tailored 10 MW blade

Blade length increase: 9%

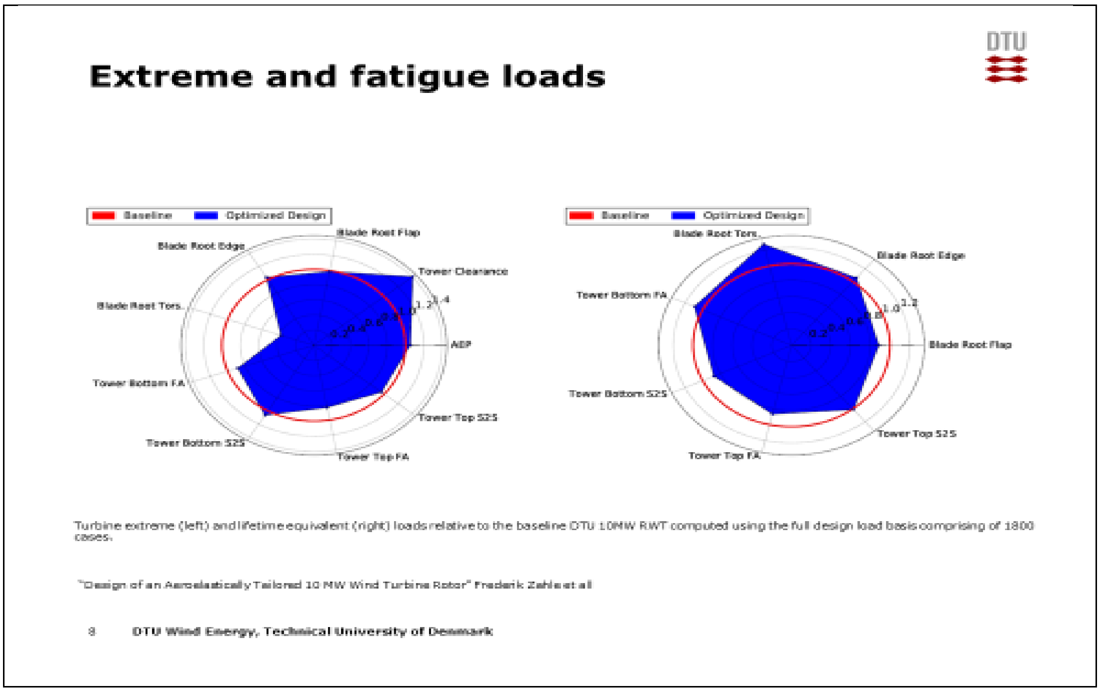
AEP increase: 8.7%

Flapwise fatigue reduction: 6%

Blade torsion at 11 m/s: 6 deg.

Extreme and lifetime equivalent loads within 5%

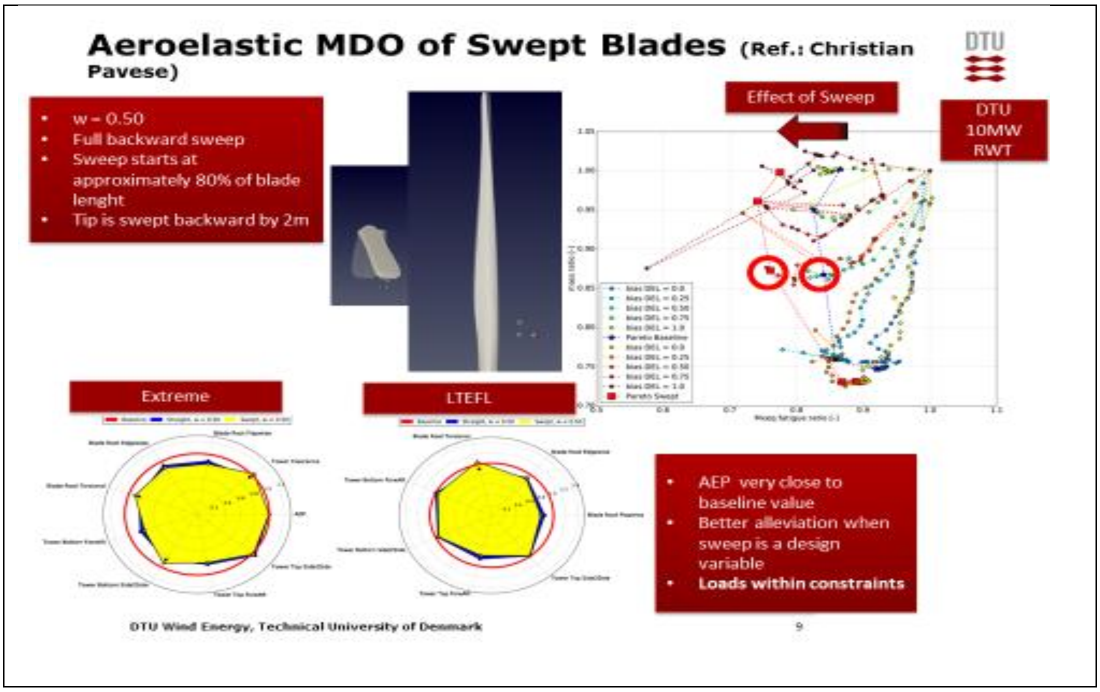
"Design of an Aeroelastically Tailored 10 MW Wind Turbine Rotor" Frederik Zahle et all



Extreme and fatigue loads

Turbine extreme (left) and lifetime equivalent (right) loads relative to the baseline DTU 10MW RWT computed using the full design load basis comprising of 1800 cases.

"Design of an Aeroelastically Tailored 10 MW Wind Turbine Rotor" Frederik Zahle et all



Aeroelastic MDO of Swept Blades (Ref.: Christian Pavese)

- w = 0.50
- Full backward sweep
- Sweep starts at approximately 80% of blade lenght
- Tip is swept backward by 2m

- AEP very close to baseline value
- Better alleviation when sweep is a design variable
- **Loads within constraints**

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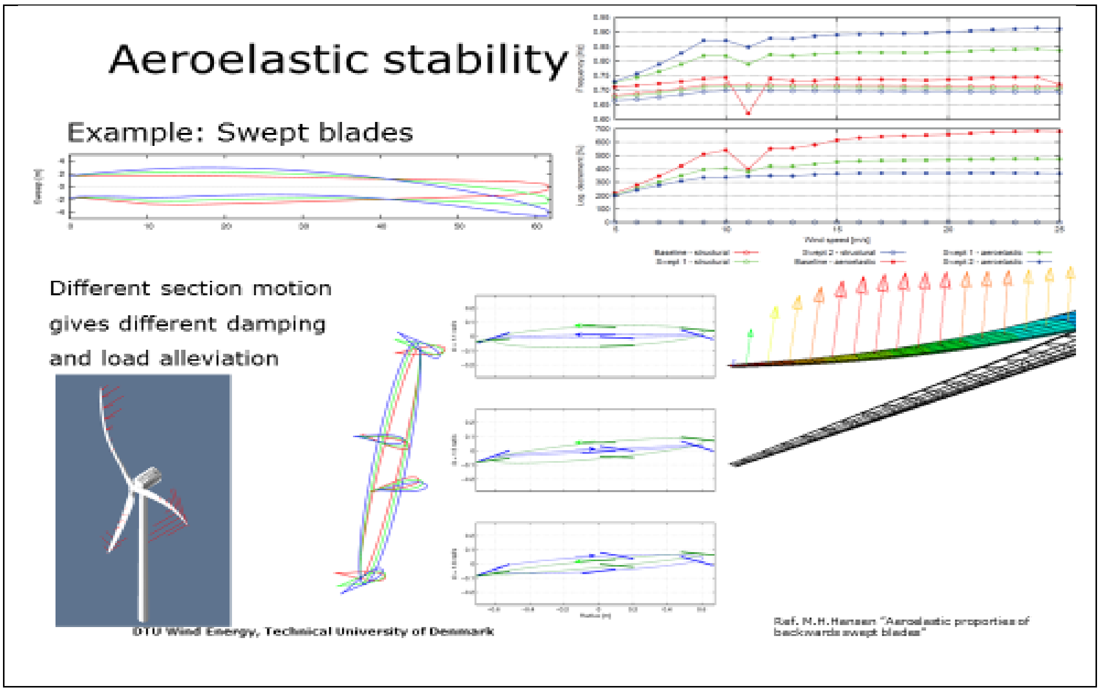


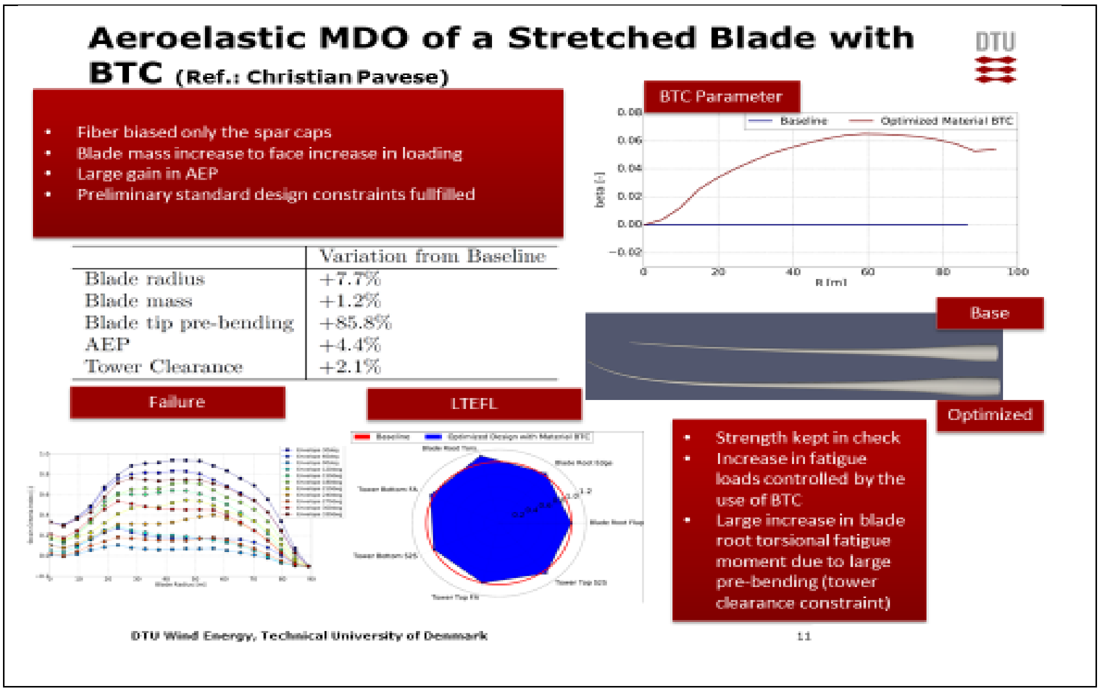
Aeroelastic stability

Example: Swept blades

Different section motion gives different damping and load alleviation

DTU Wind Energy, Technical University of Denmark

Ref. M.H.Hansen "Aeroelastic properties of backwards swept blades"



Aeroelastic MDO of a Stretched Blade with BTC (Ref.: Christian Pavese)

- Fiber biased only the spar caps
- Blade mass increase to face increase in loading
- Large gain in AEP
- Preliminary standard design constraints fullfilled

	Variation from Baseline
Blade radius	+7.7%
Blade mass	+1.2%
Blade tip pre-bending	+85.8%
AEP	+4.4%
Tower Clearance	+2.1%

BTC Parameter

Base

Optimized

Failure

LTEFL

- Strength kept in check
- Increase in fatigue loads controlled by the use of BTC
- Large increase in blade root torsional fatigue moment due to large pre-bending (tower clearance constraint)

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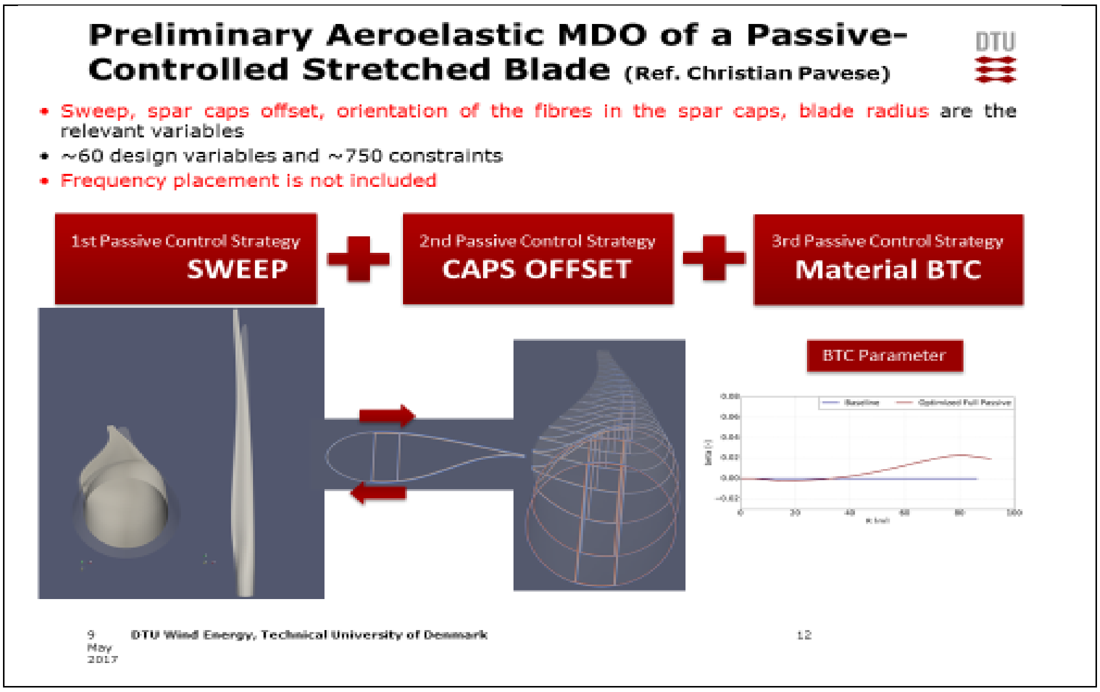


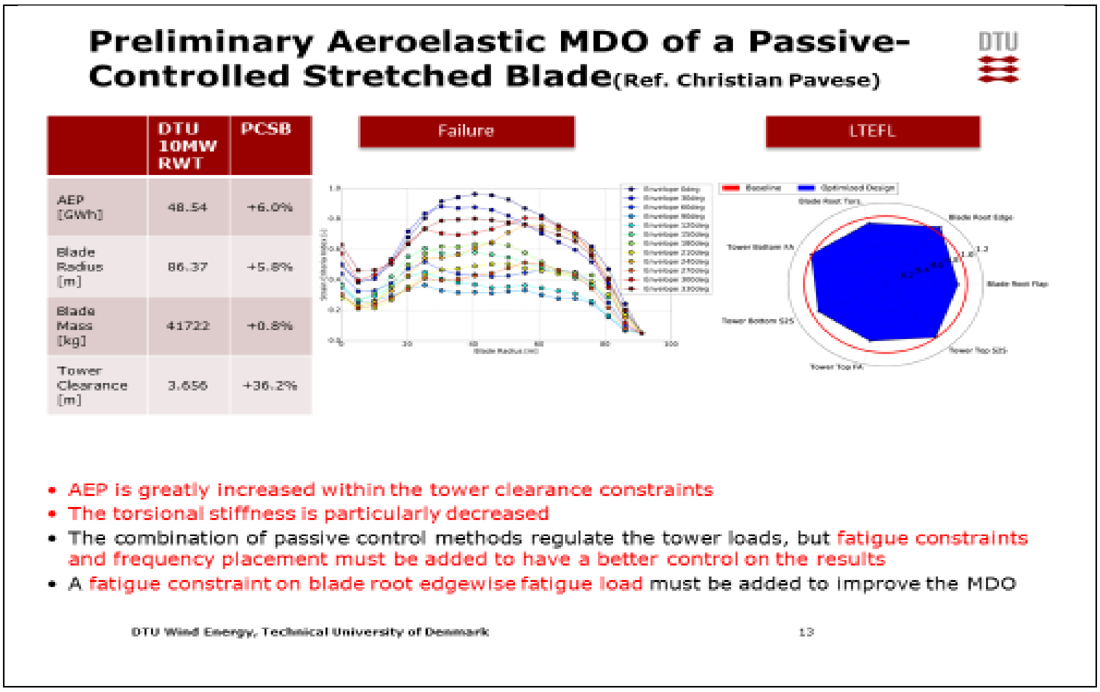
Preliminary Aeroelastic MDO of a Passive-Controlled Stretched Blade (Ref. Christian Pavese)

- Sweep, spar caps offset, orientation of the fibres in the spar caps, blade radius are the relevant variables
- ~60 design variables and ~750 constraints
- Frequency placement is not included

1st Passive Control Strategy **SWEEP** + 2nd Passive Control Strategy **CAPS OFFSET** + 3rd Passive Control Strategy **Material BTC**

BTC Parameter

9 May 2017 DTU Wind Energy, Technical University of Denmark



Preliminary Aeroelastic MDO of a Passive-Controlled Stretched Blade(Ref. Christian Pavese)

	DTU 10MW RWT	PCSB
AEP [GWh]	48.54	+6.0%
Blade Radius [m]	86.37	+5.8%
Blade Mass [kg]	41722	+0.8%
Tower Clearance [m]	3.656	+36.2%

Failure

LTEFL

- AEP is greatly increased within the tower clearance constraints
- The torsional stiffness is particularly decreased
- The combination of passive control methods regulate the tower loads, but fatigue constraints and frequency placement must be added to have a better control on the results
- A fatigue constraint on blade root edgewise fatigue load must be added to improve the MDO

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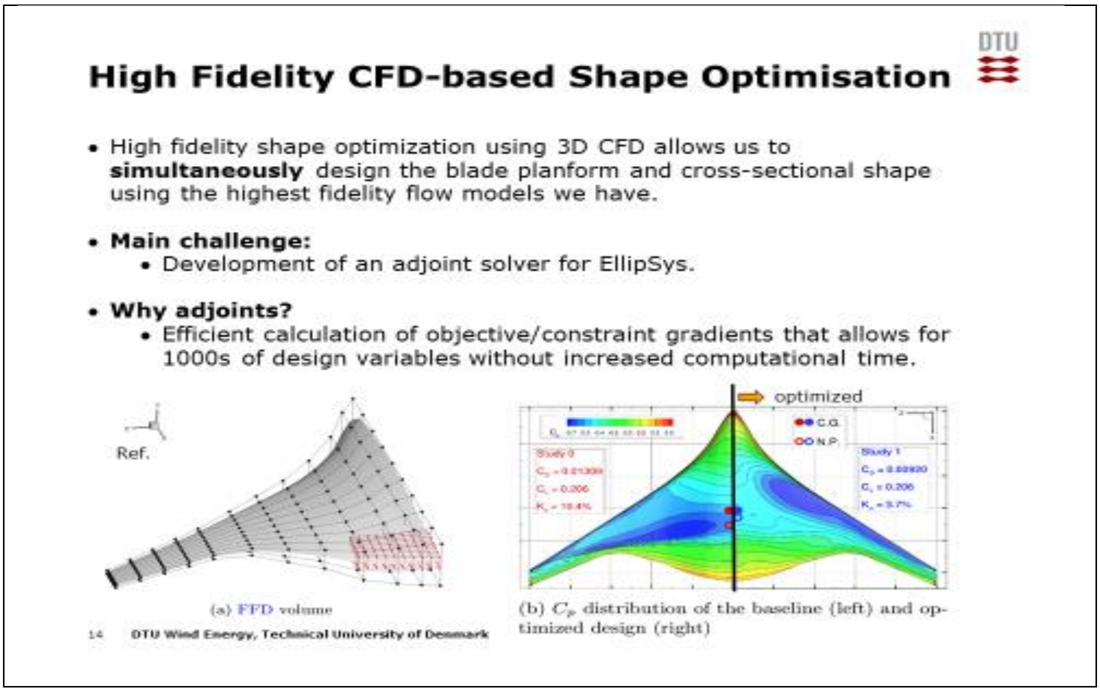

High Fidelity CFD-based Shape Optimisation

- High fidelity shape optimization using 3D CFD allows us to **simultaneously** design the blade planform and cross-sectional shape using the highest fidelity flow models we have.
- **Main challenge:**
  - Development of an adjoint solver for EllipSys.
- **Why adjoints?**
  - Efficient calculation of objective/constraint gradients that allows for 1000s of design variables without increased computational time.

(a) FFD volume

(b) C_p distribution of the baseline (left) and optimized design (right)

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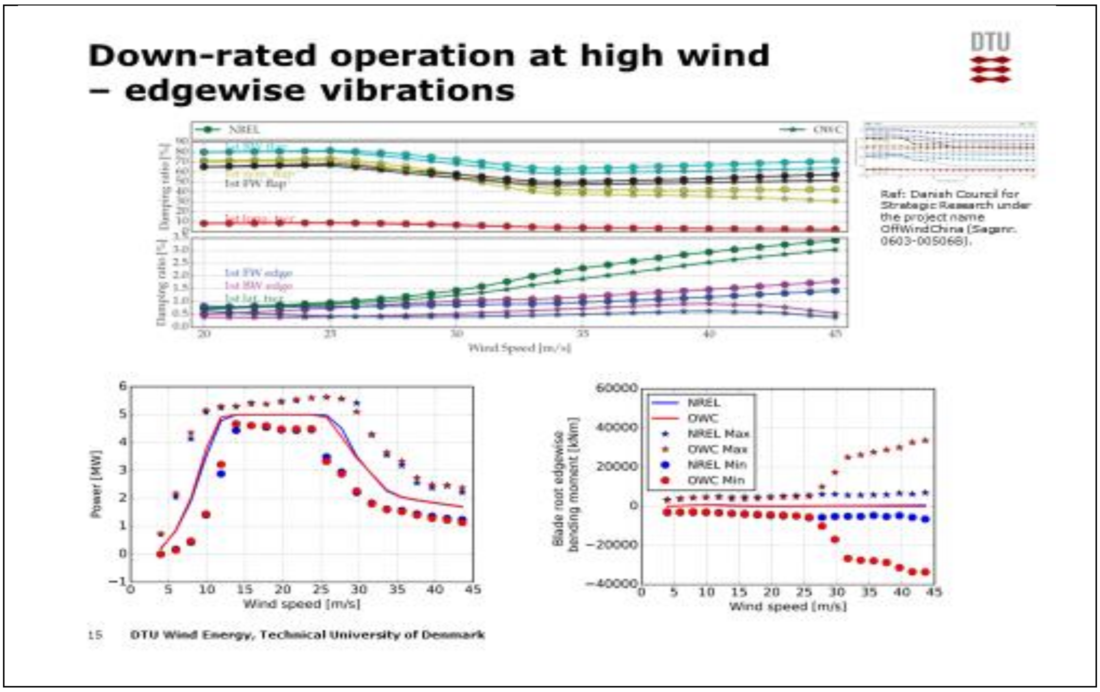

Down-rated operation at high wind – edgewise vibrations

Ref: Danish Council for Strategic Research under the project name OffWindChina (Sagsnr. 0603-00506B).

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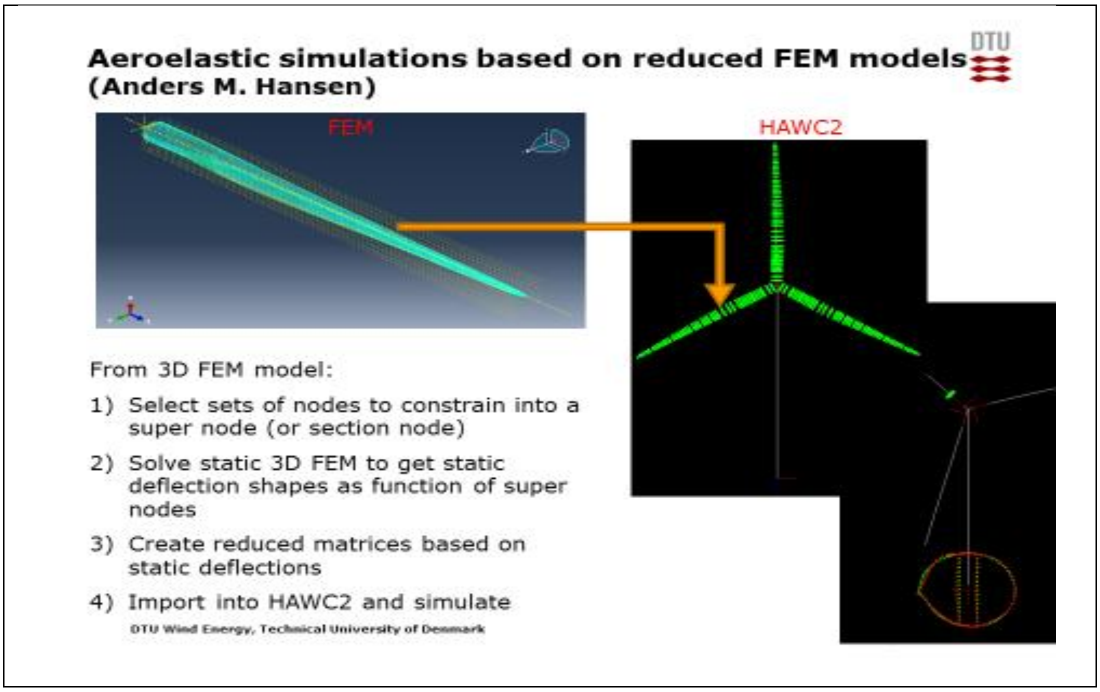

Aeroelastic simulations based on reduced FEM models (Anders M. Hansen)

From 3D FEM model:

1) Select sets of nodes to constrain into a super node (or section node)
2) Solve static 3D FEM to get static deflection shapes as function of super nodes
3) Create reduced matrices based on static deflections
4) Import into HAWC2 and simulate

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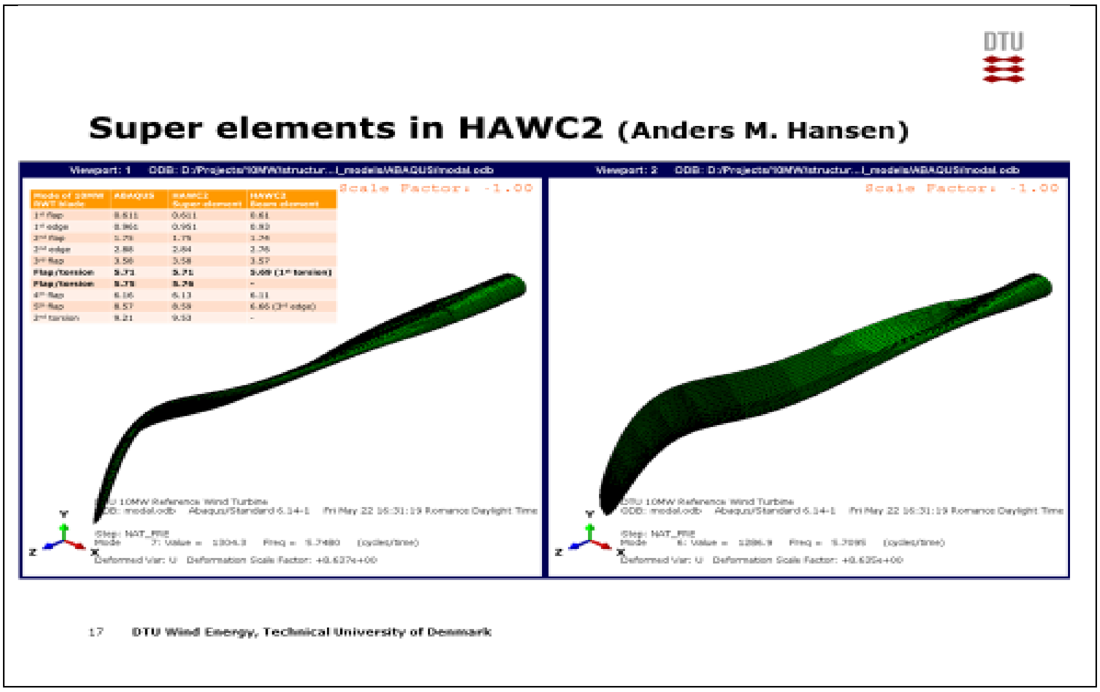


Super elements in HAWC2 (Anders M. Hansen)

Viewport: 1 ODB: D:/Projects/10MW/structur...l_models/ABAQUS/modal.odb

Scale Factor: -1.00

Mode of 10MW RWT blade	ABAQUS	HAWC2 Super element	HAWC2 Beam element
1st flap	0.611	0.611	0.61
1st edge	0.961	0.951	0.93
2nd flap	1.75	1.75	1.74
2nd edge	2.88	2.84	2.76
3rd flap	3.56	3.58	3.57
Flap/torsion	**5.71**	**5.71**	**5.69 (1st torsion)**
Flap/torsion	**5.75**	**5.79**	-
4th flap	6.16	6.13	6.11
5th flap	8.57	8.59	6.66 (3rd edge)
2nd torsion	9.21	9.53	-

DTU 10MW Reference Wind Turbine
ODB: modal.odb Abaqus/Standard 6.14-1 Fri May 22 16:31:19 Romance Daylight Time

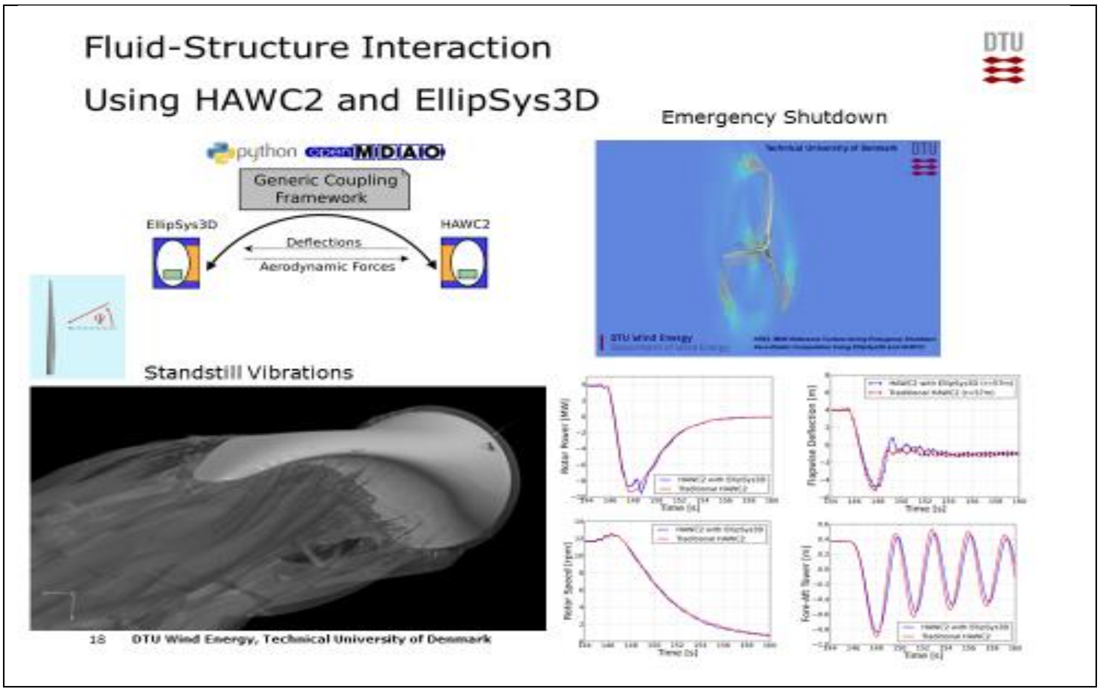
Step: NAT_FRE
Mode 7: Value = 1304.3 Freq = 5.7480 (cycles/time)
Deformed Var: U Deformation Scale Factor: +8.637e+00

Viewport: 2 ODB: D:/Projects/10MW/structur...l_models/ABAQUS/modal.odb

Scale Factor: -1.00

DTU 10MW Reference Wind Turbine
ODB: modal.odb Abaqus/Standard 6.14-1 Fri May 22 16:31:19 Romance Daylight Time

Step: NAT_FRE
Mode 6: Value = 1286.9 Freq = 5.7095 (cycles/time)
Deformed Var: U Deformation Scale Factor: +8.635e+00



Fluid-Structure Interaction
Using HAWC2 and EllipSys3D

python openMDAO

Generic Coupling Framework

EllipSys3D

HAWC2

Deflections

Aerodynamic Forces

Emergency Shutdown

Standstill Vibrations

DTU

Modelling/experiments

- Aeroacustic Poul La Cour Wind Tunnel
- Rotating Test Rig
- Research Wind Turbine
- Virtual Wind Tunnel (Digital Twin)

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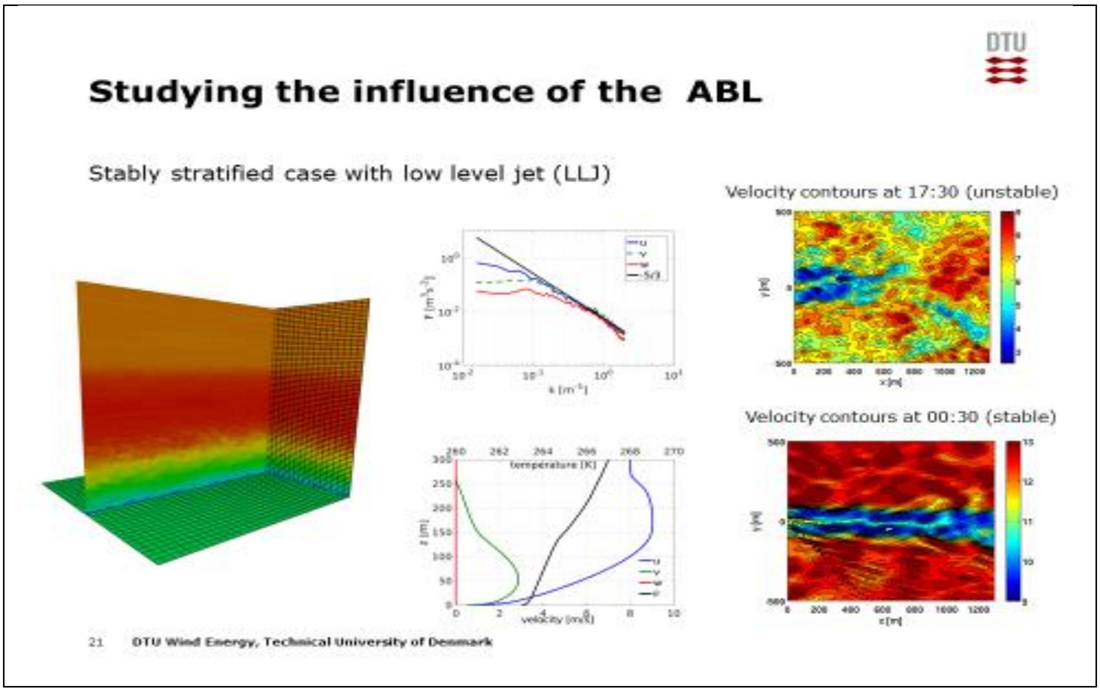
The vision

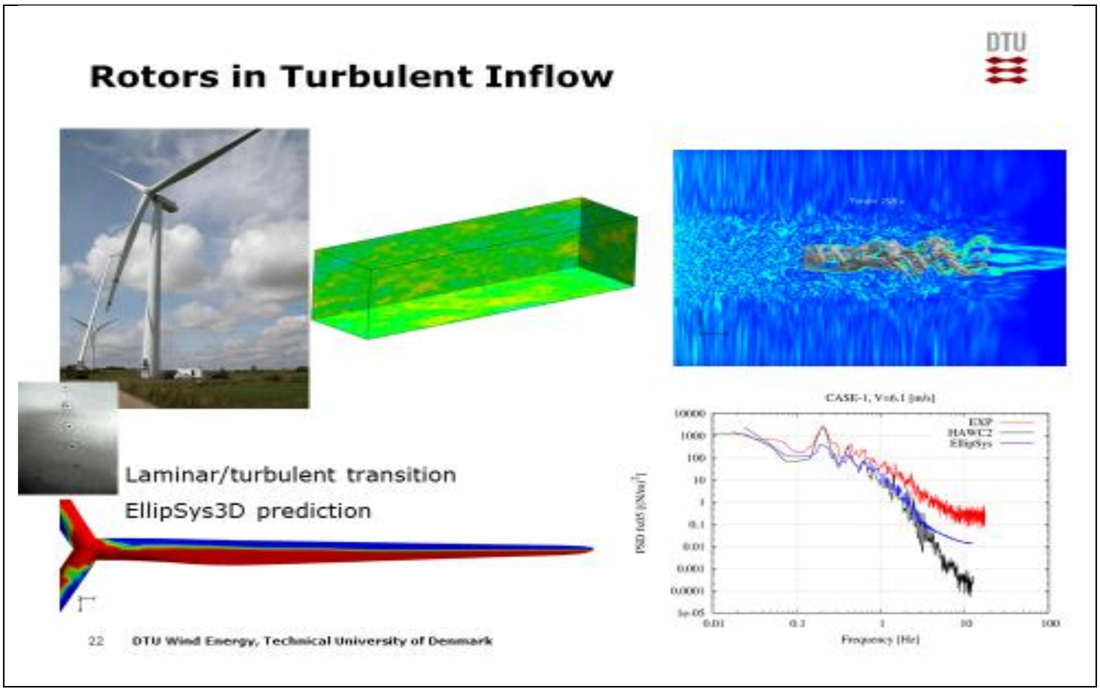


Studying the influence of the ABL

Stably stratified case with low level jet (LLJ)

Velocity contours at 17:30 (unstable)

Velocity contours at 00:30 (stable)



Rotors in Turbulent Inflow

Laminar/turbulent transition

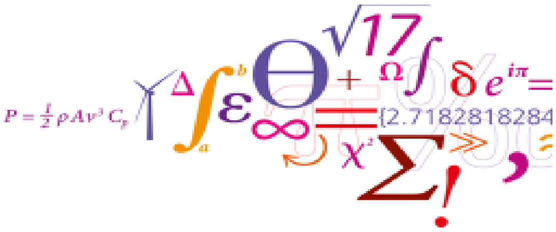
EllipSys3D prediction

Advances in smart blades

aeroservoelastic simulations & morphing flap design

IEA Wind task 11| Topical Expert Meeting on Smart Blades
27-28/04/2017, DTU, Risø, Denmark

Thanasis K. Barlas
Researcher
Aerodynamic Design



DTU Wind Energy
Department of Wind Energy

Introduction

- 11 year ago...

IEA topical expert meeting on:
The application of smart structures for large wind turbine rotor blades

Smart Rotor Blade Control for Wind Turbines

Issues on design, modeling and approach

Thanasis Barlas
PhD Researcher

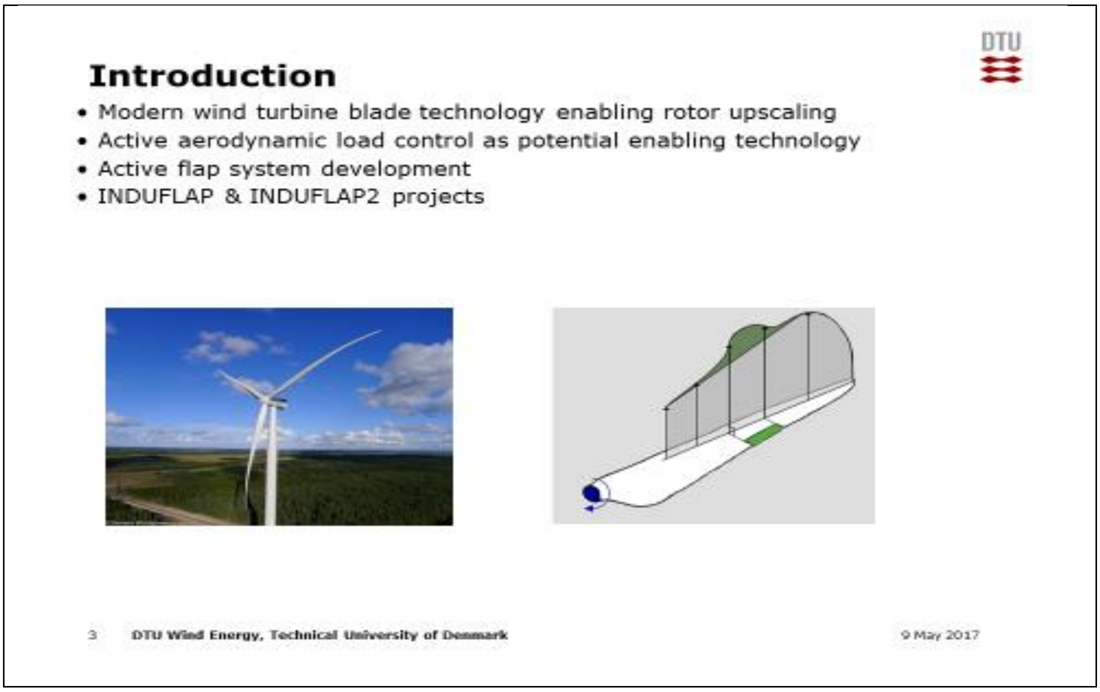
Smart Rotor Blades and Rotor Control

Challenges

- Embedded smart materials for shape control for large & controllable deflections (new blade design?)
- Aerodynamic models of smart devices (accurate analytical - unsteady CFD?)
- Efficient & reliable control algorithms (time lags?)

Questions?

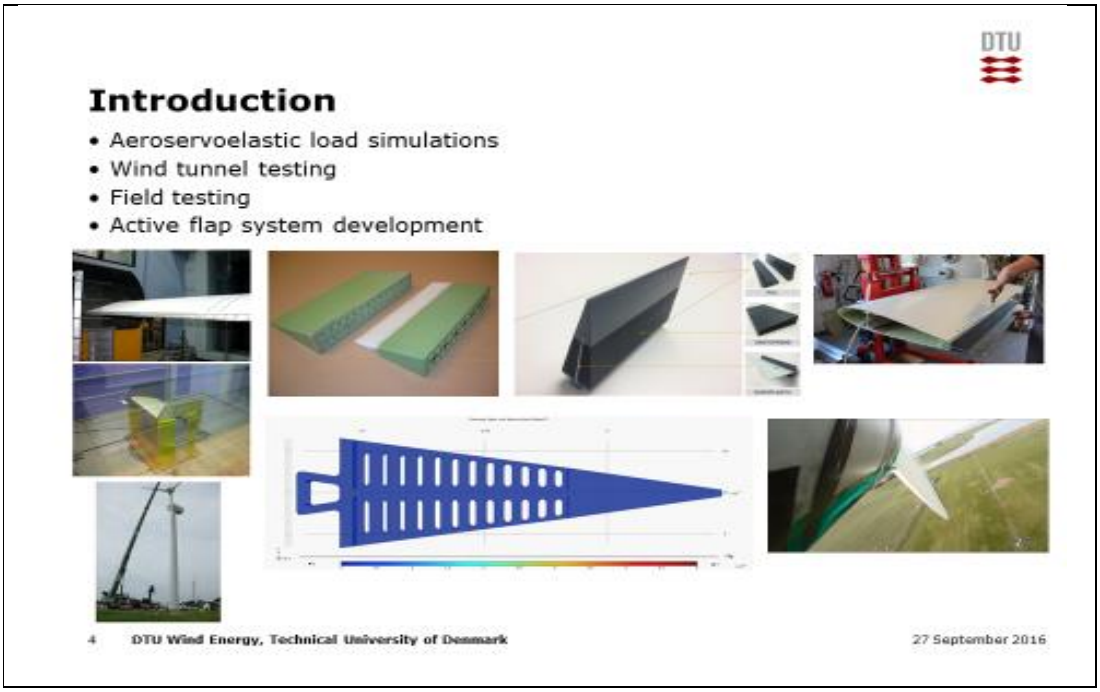
Smart Rotor Blades and Rotor Control



Introduction

- Modern wind turbine blade technology enabling rotor upscaling
- Active aerodynamic load control as potential enabling technology
- Active flap system development
- INDUFLAP & INDUFLAP2 projects

3 DTU Wind Energy, Technical University of Denmark 9 May 2017



Introduction

- Aeroservoelastic load simulations
- Wind tunnel testing
- Field testing
- Active flap system development

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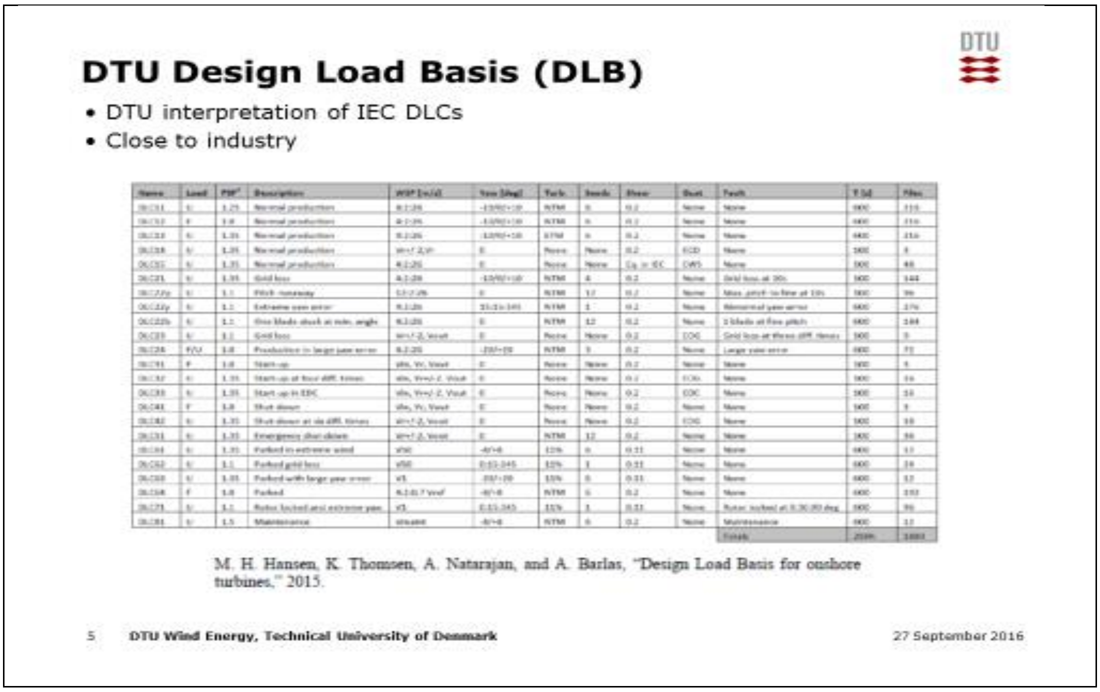
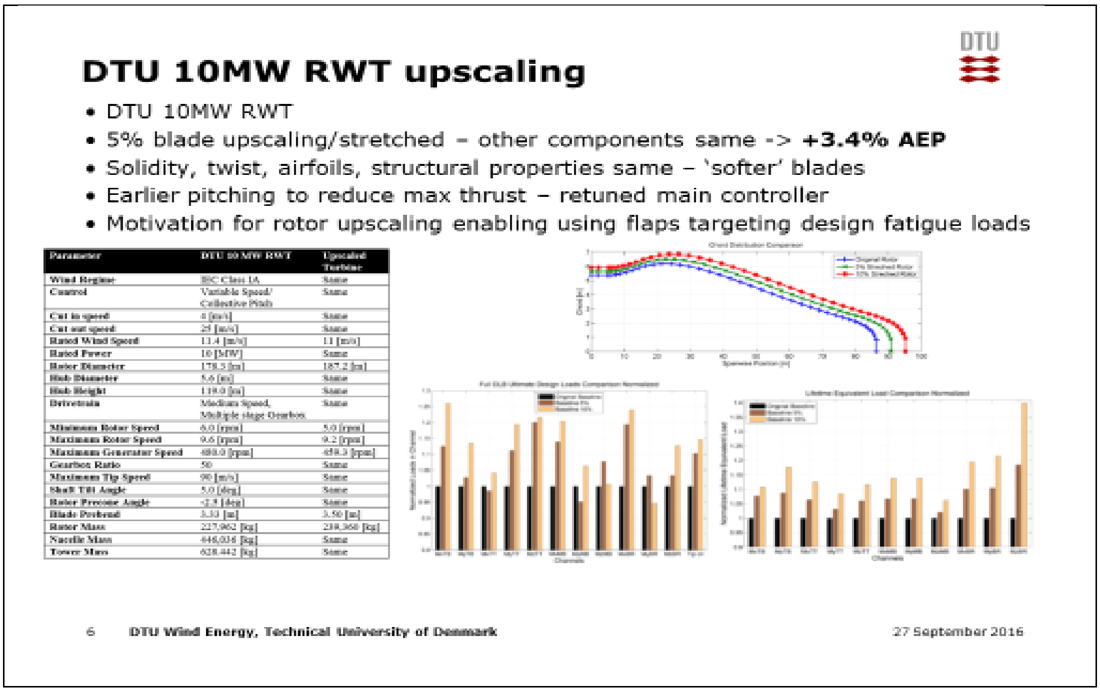


DTU Design Load Basis (DLB)

- DTU interpretation of IEC DLCs
- Close to industry

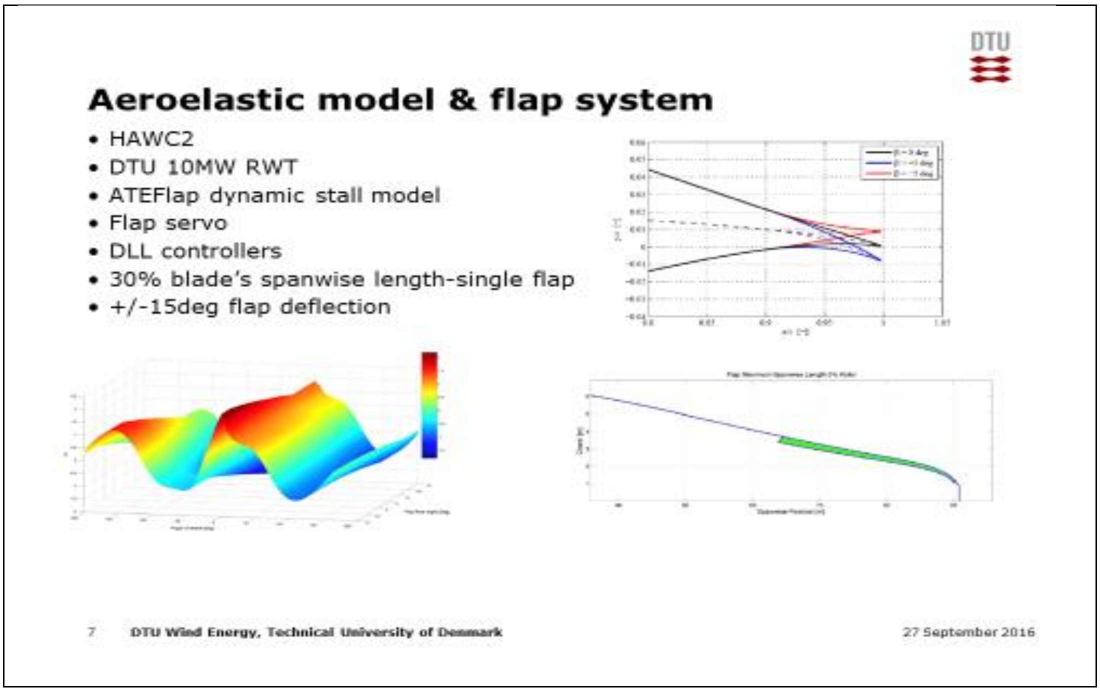
M. H. Hansen, K. Thomsen, A. Natarajan, and A. Barlas, "Design Load Basis for onshore turbines," 2015.



DTU 10MW RWT upscaling

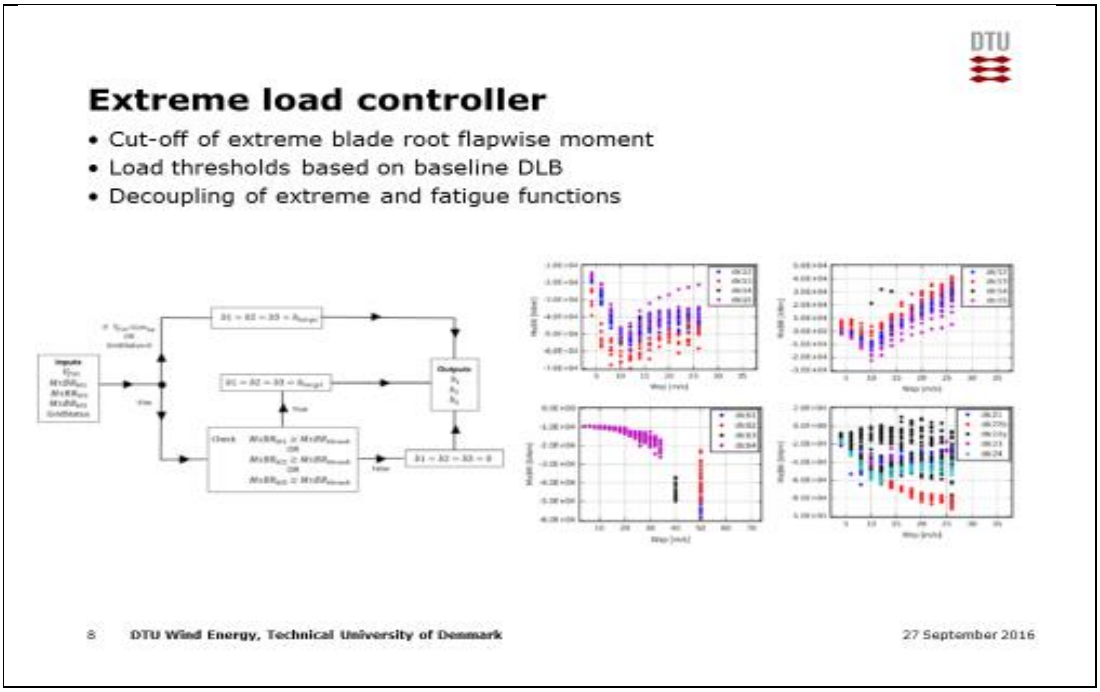
- DTU 10MW RWT
- 5% blade upscaling/stretched – other components same -> **+3.4% AEP**
- Solidity, twist, airfoils, structural properties same – 'softer' blades
- Earlier pitching to reduce max thrust – retuned main controller
- Motivation for rotor upscaling enabling using flaps targeting design fatigue loads

Parameter	DTU 10 MW RWT	Upscaled Turbine
Wind Regime	IEC Class 1A	Same
Control	Variable Speed/ Collective Pitch	Same
Cut in speed	4 [m/s]	Same
Cut out speed	25 [m/s]	Same
Rated Wind Speed	11.4 [m/s]	11 [m/s]
Rated Power	10 [MW]	Same
Rotor Diameter	178.3 [m]	187.2 [m]
Hub Diameter	5.6 [m]	Same
Hub Height	119.0 [m]	Same
Drivetrain	Medium Speed, Multiple stage Gearbox	Same
Minimum Rotor Speed	6.0 [rpm]	5.0 [rpm]
Maximum Rotor Speed	9.6 [rpm]	9.2 [rpm]
Maximum Generator Speed	480.0 [rpm]	459.3 [rpm]
Gearbox Ratio	50	Same
Maximum Tip Speed	90 [m/s]	Same
Shaft Tilt Angle	5.0 [deg]	Same
Rotor Precone Angle	-2.5 [deg]	Same
Blade Prebend	3.33 [m]	3.50 [m]
Rotor Mass	227,962 [kg]	238,368 [kg]
Nacelle Mass	446,036 [kg]	Same
Tower Mass	628,442 [kg]	Same



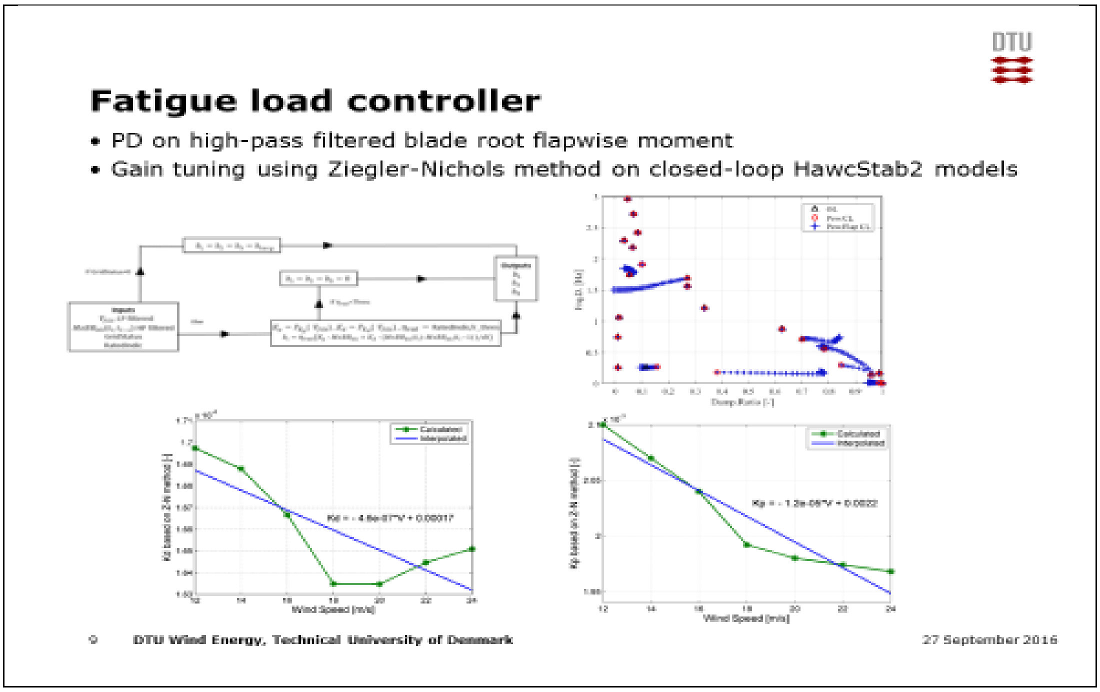
Aeroelastic model & flap system

- HAWC2
- DTU 10MW RWT
- ATEFlap dynamic stall model
- Flap servo
- DLL controllers
- 30% blade's spanwise length-single flap
- +/-15deg flap deflection



Extreme load controller

- Cut-off of extreme blade root flapwise moment
- Load thresholds based on baseline DLB
- Decoupling of extreme and fatigue functions



DTU

Fatigue load controller

- PD on high-pass filtered blade root flapwise moment
- Gain tuning using Ziegler-Nichols method on closed-loop HawcStab2 models

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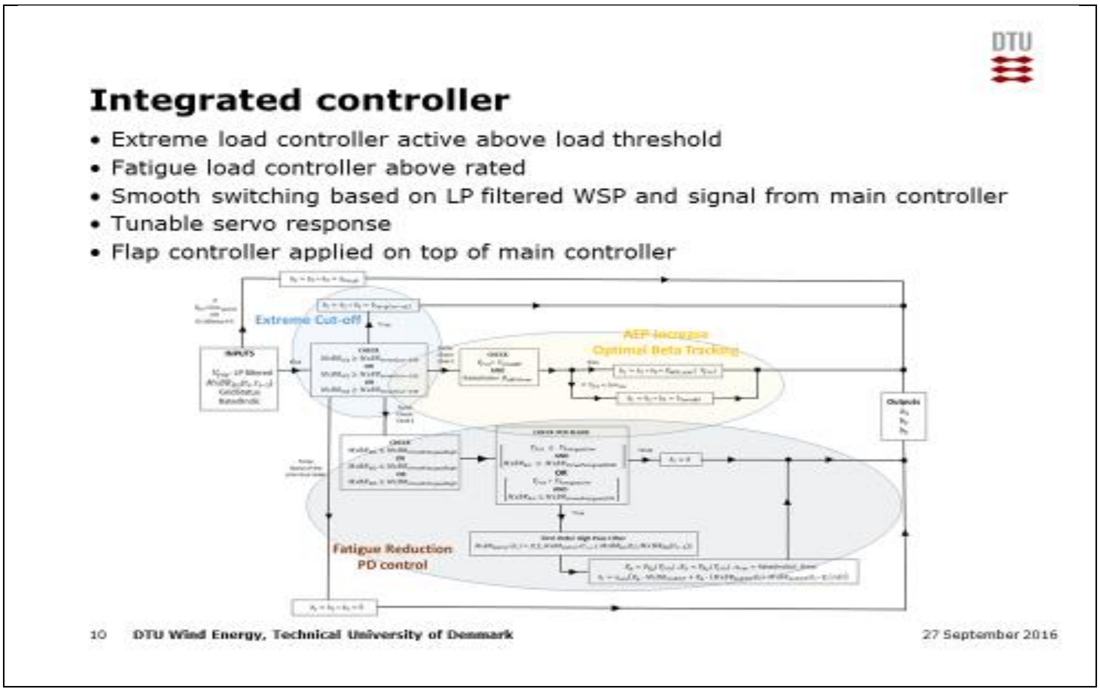

DTU

Integrated controller

- Extreme load controller active above load threshold
- Fatigue load controller above rated
- Smooth switching based on LP filtered WSP and signal from main controller
- Tunable servo response
- Flap controller applied on top of main controller

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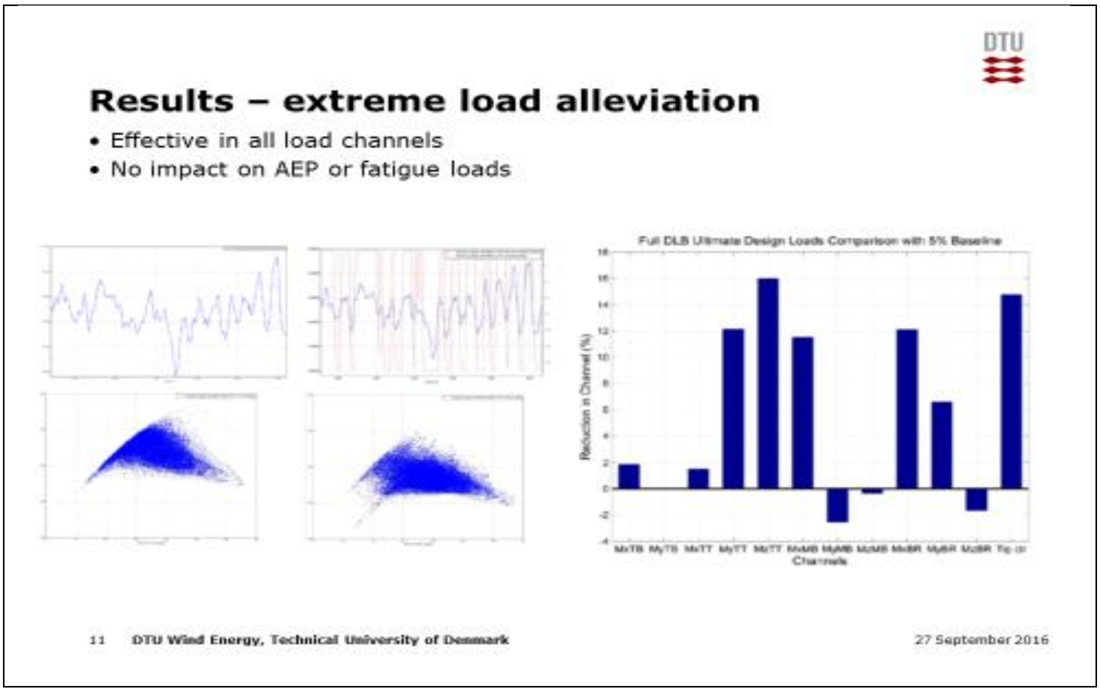
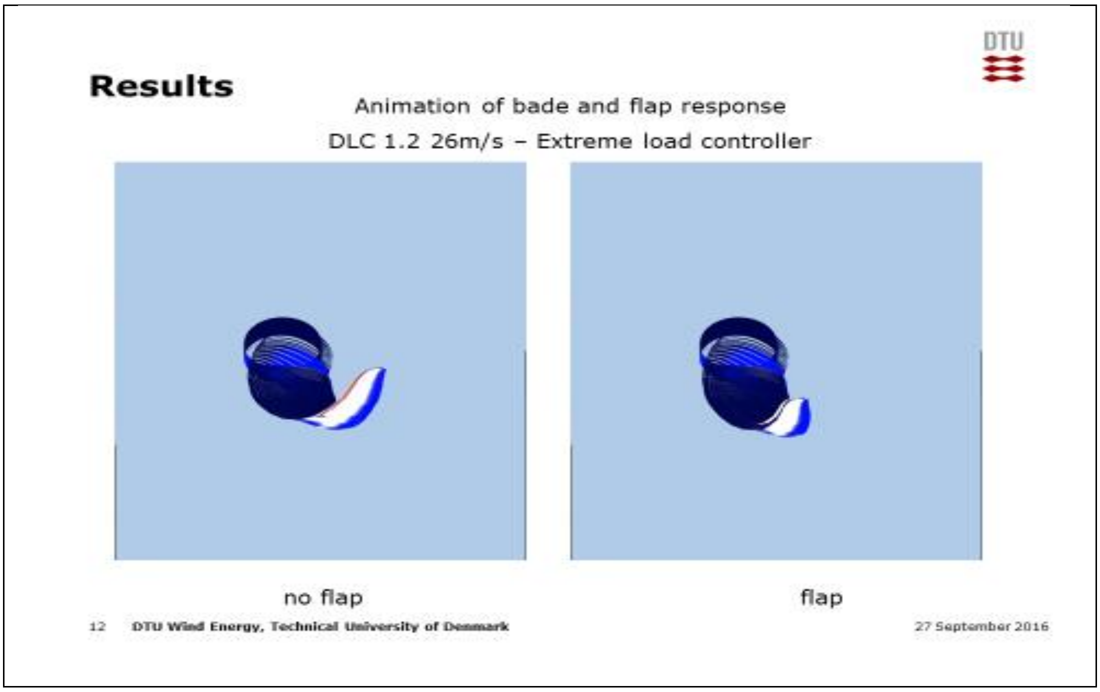


Results – extreme load alleviation

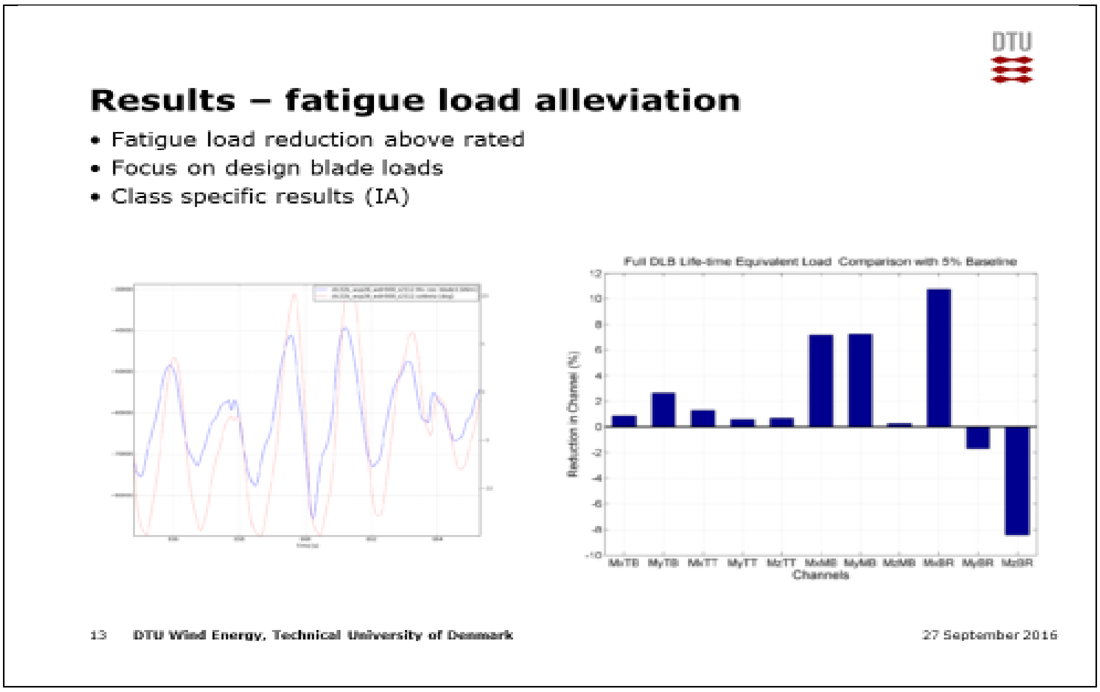
- Effective in all load channels
- No impact on AEP or fatigue loads



Results

Animation of bade and flap response

DLC 1.2 26m/s – Extreme load controller



Results – fatigue load alleviation

- Fatigue load reduction above rated
- Focus on design blade loads
- Class specific results (IA)

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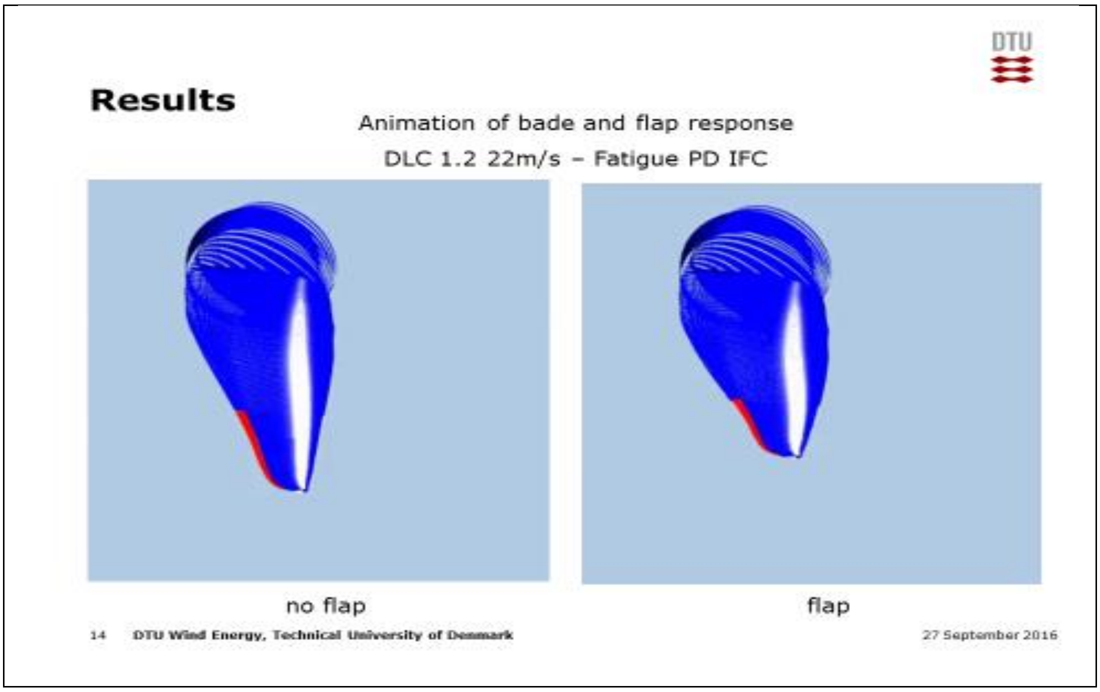

Results

Animation of bade and flap response

DLC 1.2 22m/s – Fatigue PD IFC

no flap

flap

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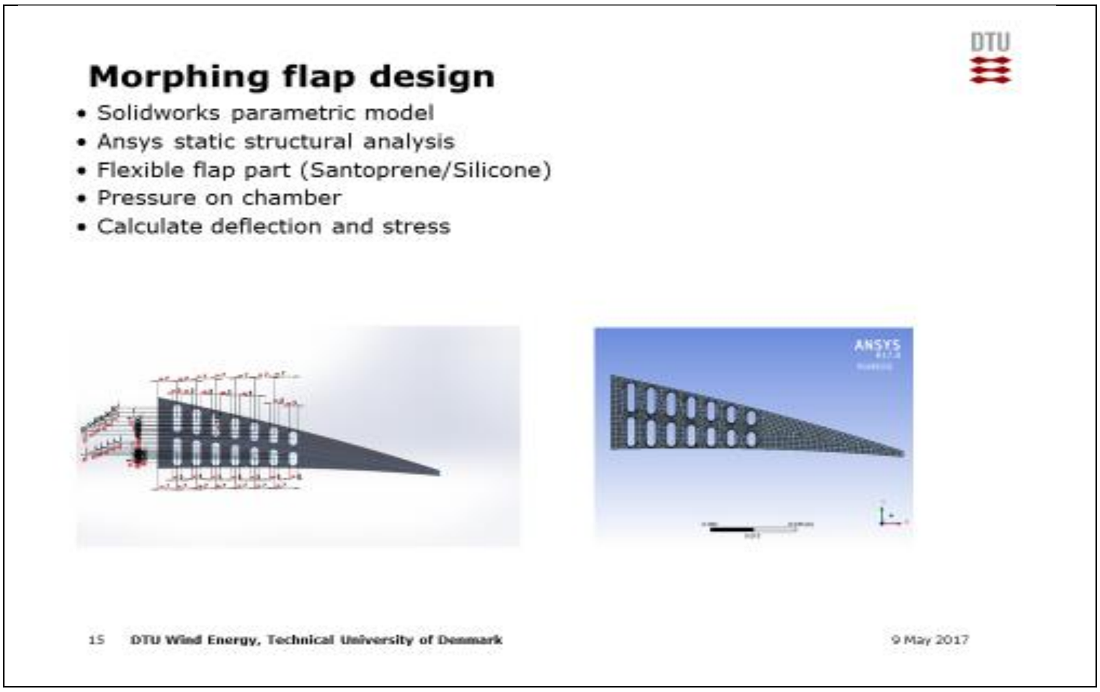
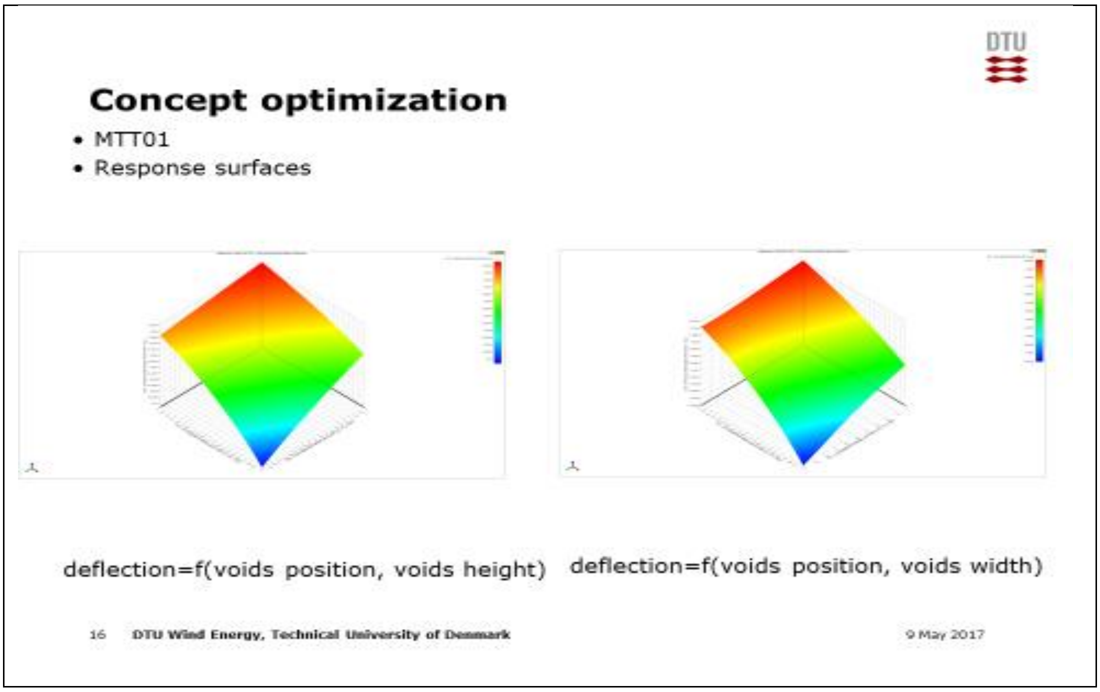


Morphing flap design

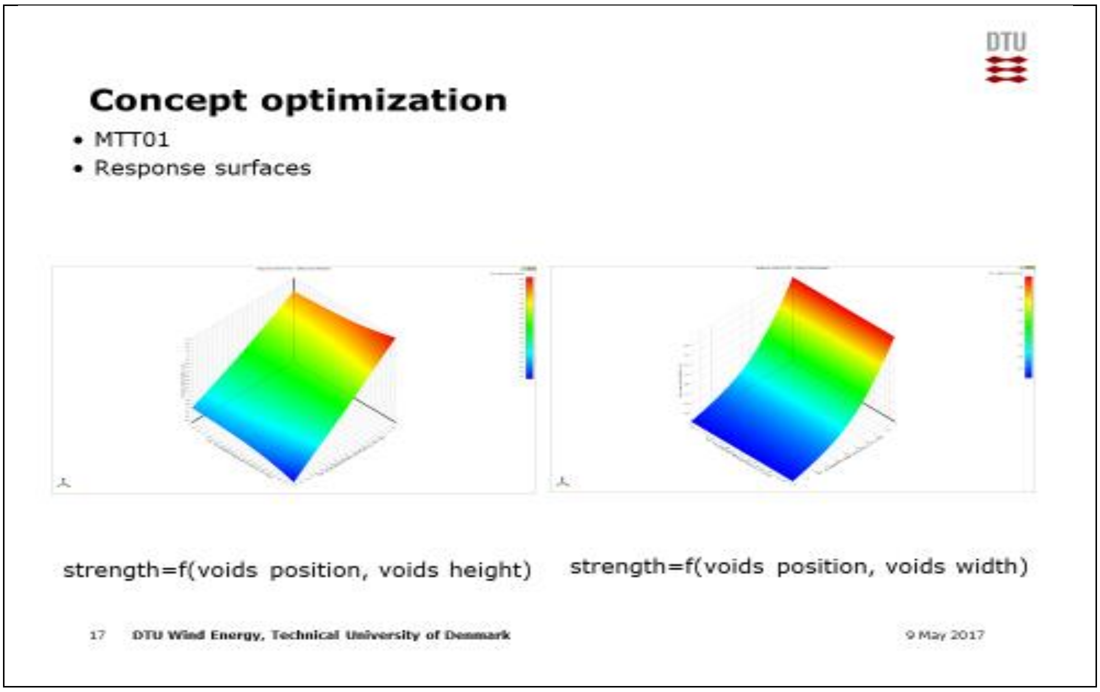
- Solidworks parametric model
- Ansys static structural analysis
- Flexible flap part (Santoprene/Silicone)
- Pressure on chamber
- Calculate deflection and stress



Concept optimization

- MTT01
- Response surfaces

deflection=f(voids position, voids height) deflection=f(voids position, voids width)

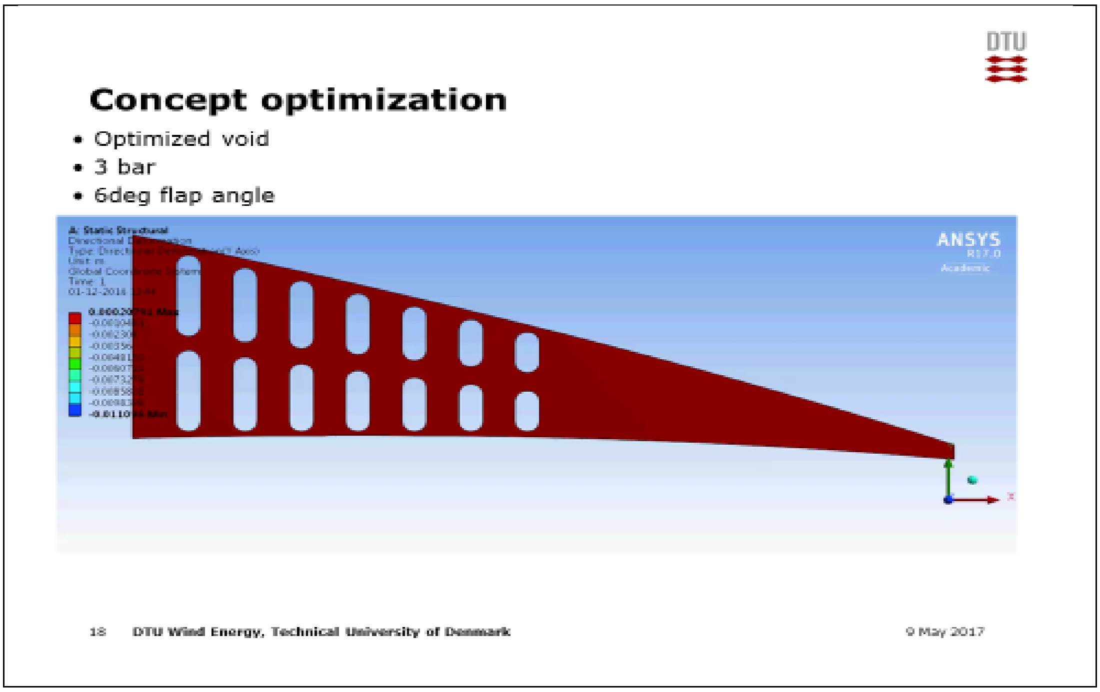


Concept optimization

- MTT01
- Response surfaces

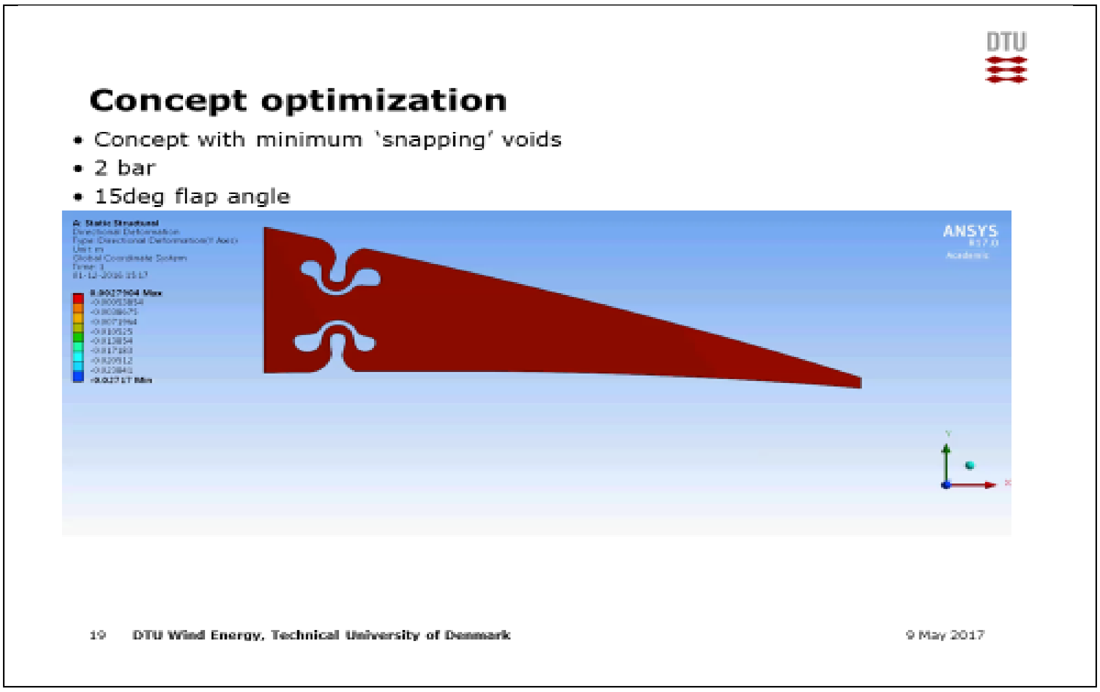
strength=f(voids position, voids height)

strength=f(voids position, voids width)



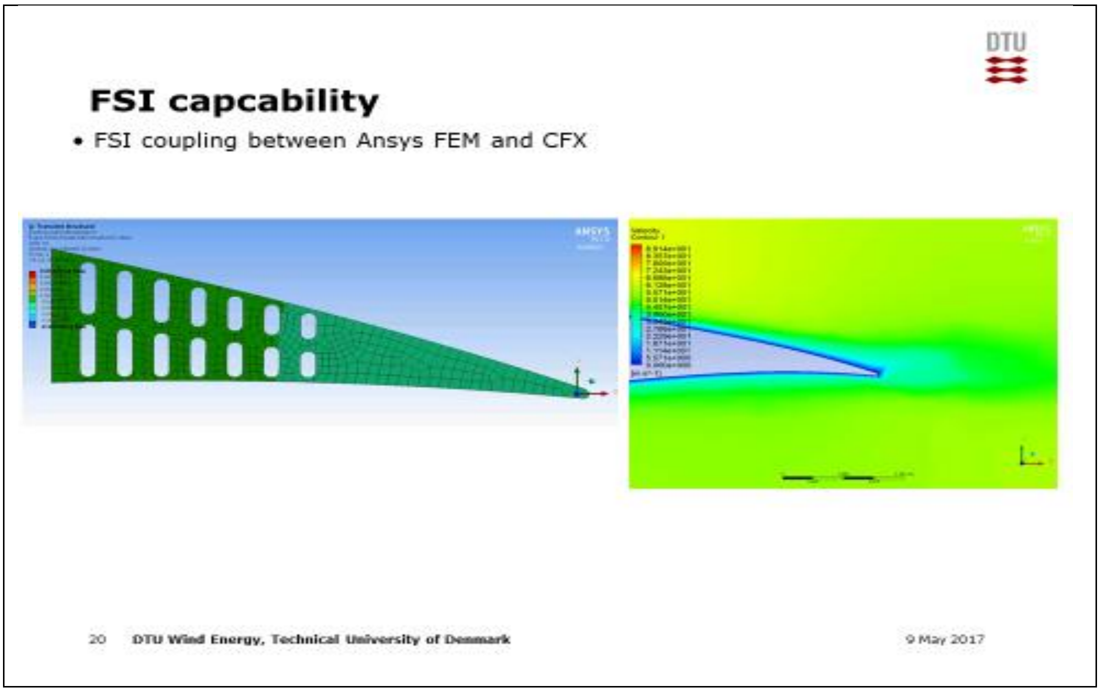
Concept optimization

- Optimized void
- 3 bar
- 6deg flap angle



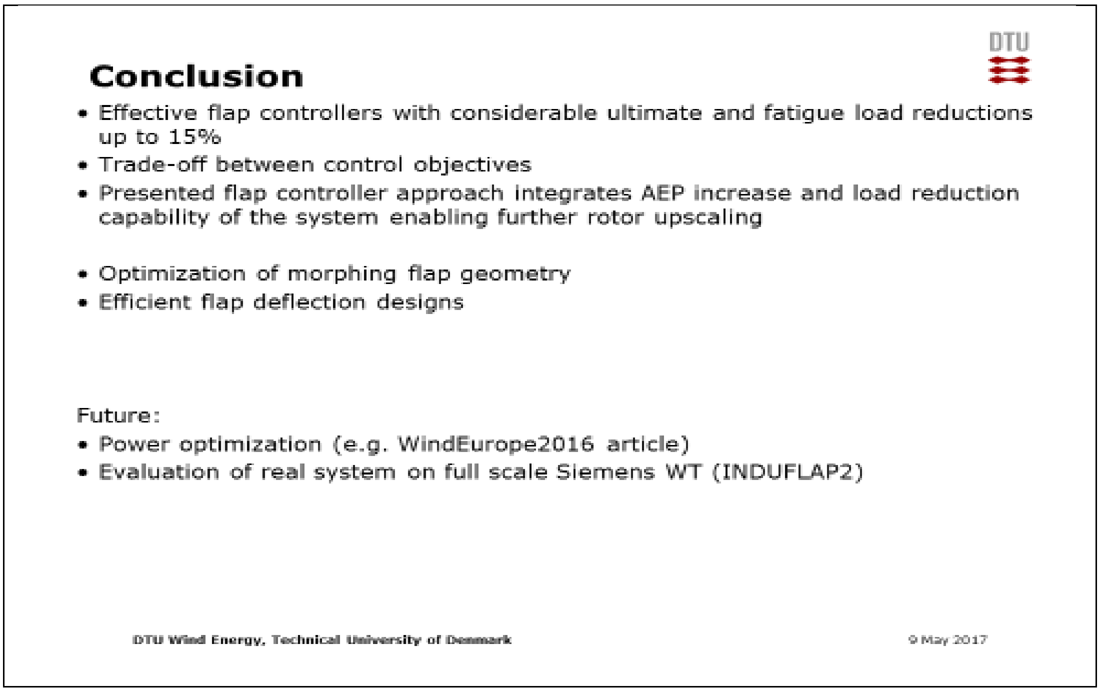
Concept optimization

- Concept with minimum 'snapping' voids
- 2 bar
- 15deg flap angle



FSI capcability

- FSI coupling between Ansys FEM and CFX

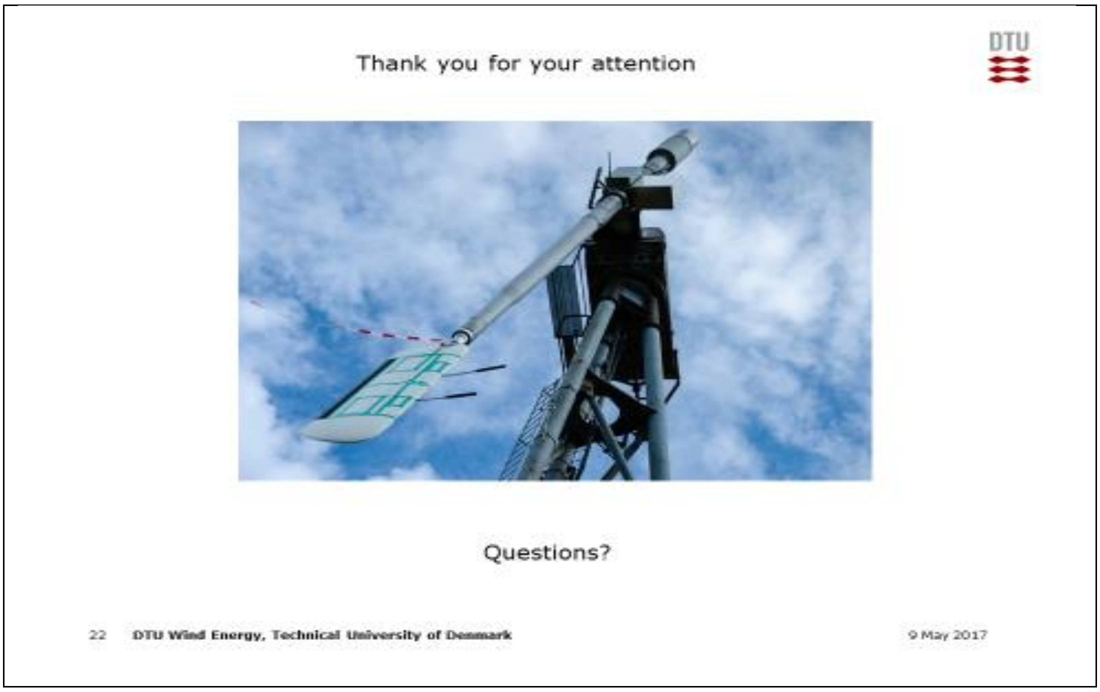


Conclusion

- Effective flap controllers with considerable ultimate and fatigue load reductions up to 15%
- Trade-off between control objectives
- Presented flap controller approach integrates AEP increase and load reduction capability of the system enabling further rotor upscaling

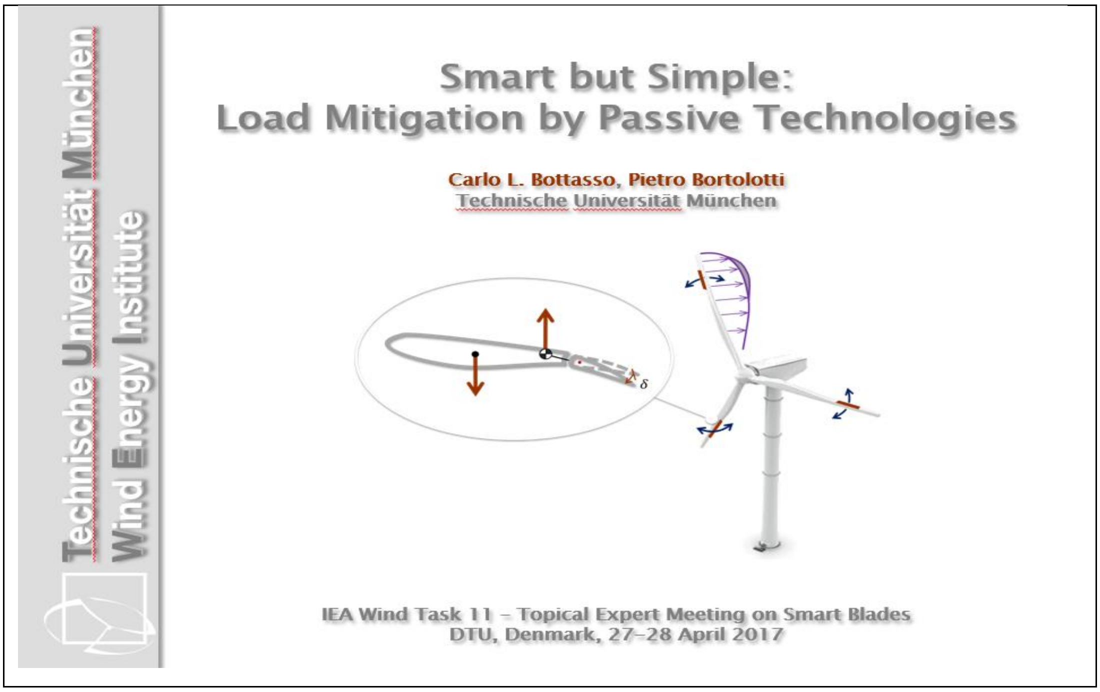
- Optimization of morphing flap geometry
- Efficient flap deflection designs

Future:
- Power optimization (e.g. WindEurope2016 article)
- Evaluation of real system on full scale Siemens WT (INDUFLAP2)



Thank you for your attention

Questions?

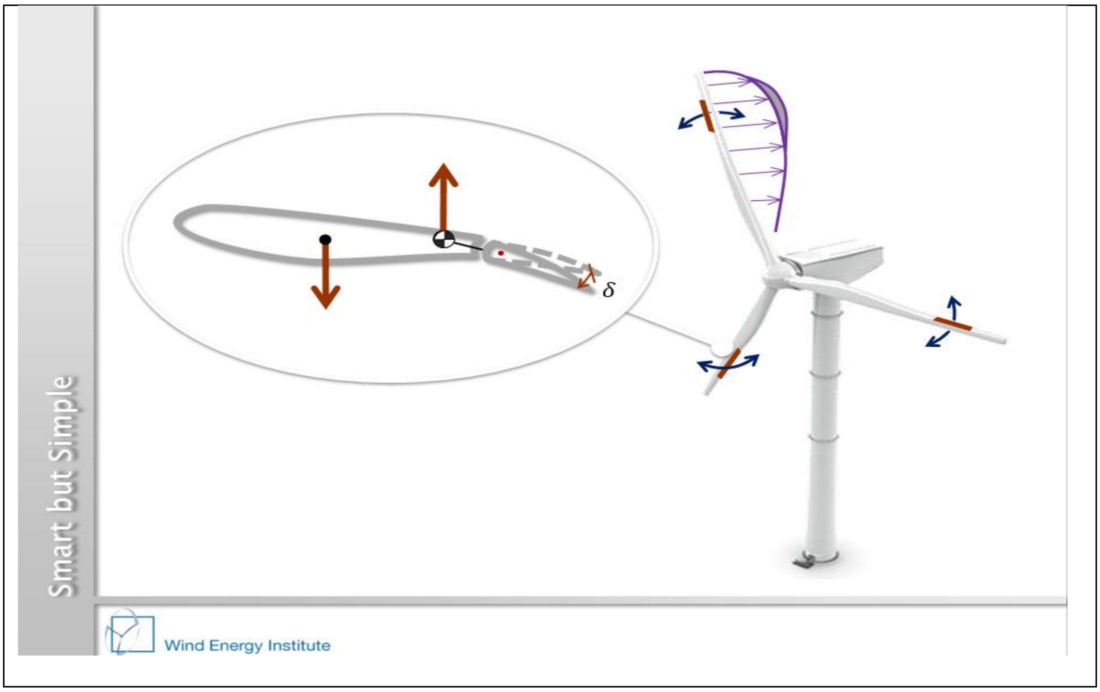


Technische Universität München
Wind Energy Institute

Smart but Simple:
Load Mitigation by Passive Technologies

Carlo L. Bottasso, Pietro Bortolotti
Technische Universität München

IEA Wind Task 11 – Topical Expert Meeting on Smart Blades
DTU, Denmark, 27-28 April 2017



Smart but Simple

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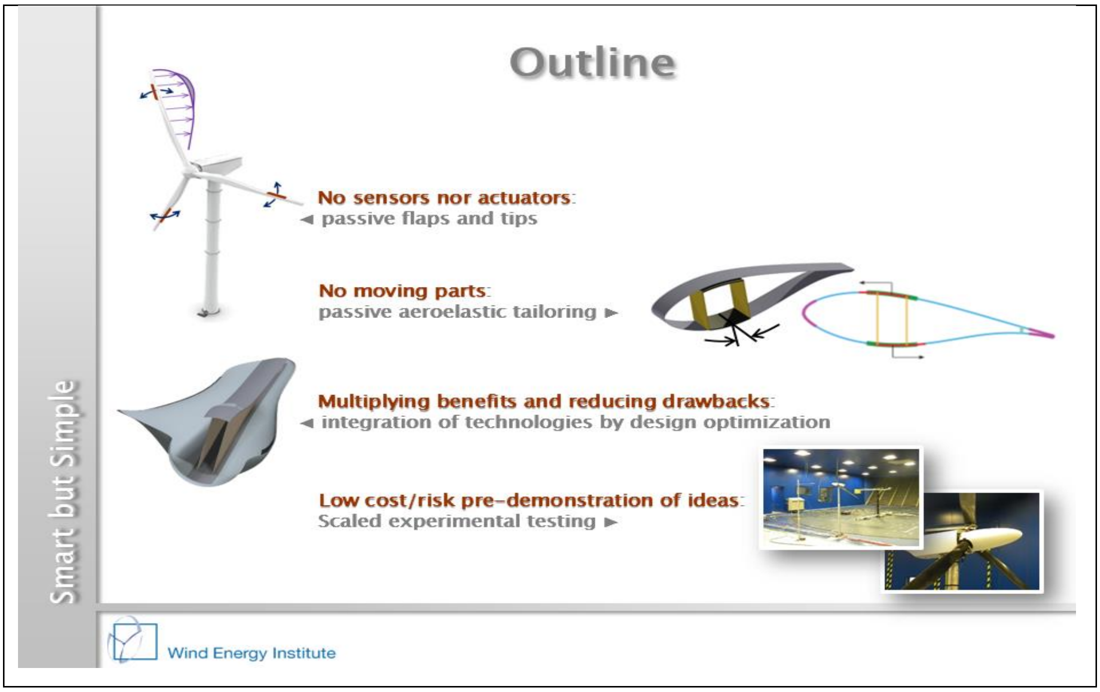

Outline

No sensors nor actuators:
◄ passive flaps and tips

No moving parts:
passive aeroelastic tailoring ►

Multiplying benefits and reducing drawbacks:
◄ integration of technologies by design optimization

Low cost/risk pre-demonstration of ideas:
Scaled experimental testing ►

Smart but Simple

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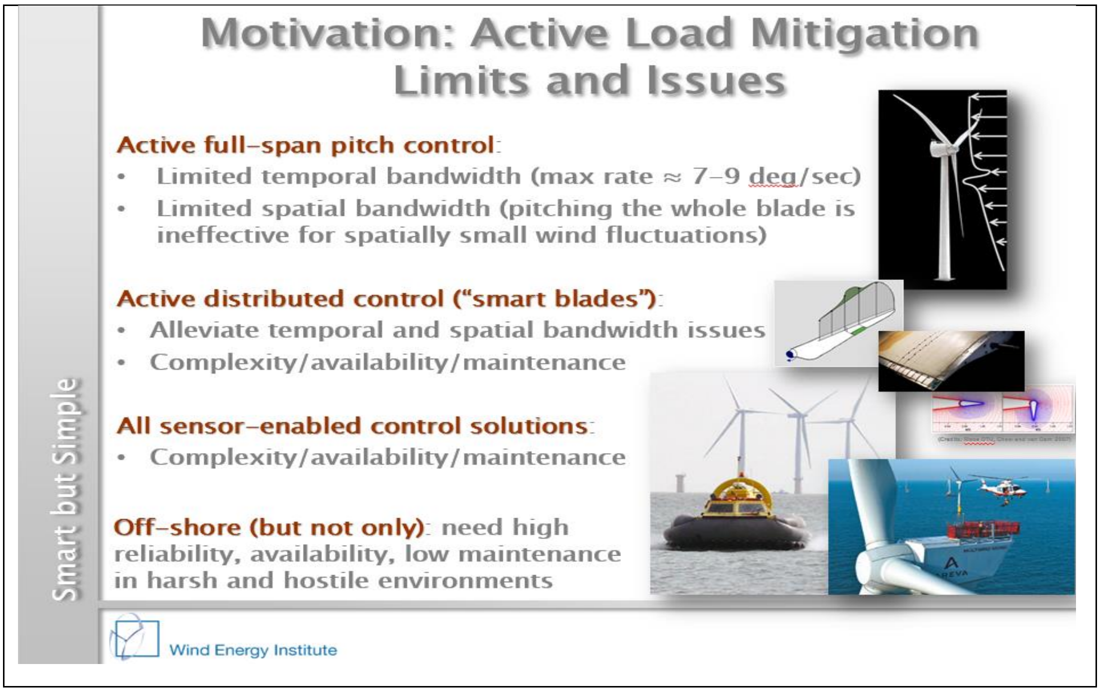

Motivation: Active Load Mitigation Limits and Issues

Active full-span pitch control:
- Limited temporal bandwidth (max rate ≈ 7-9 deg/sec)
- Limited spatial bandwidth (pitching the whole blade is ineffective for spatially small wind fluctuations)

Active distributed control ("smart blades"):
- Alleviate temporal and spatial bandwidth issues
- Complexity/availability/maintenance

All sensor-enabled control solutions:
- Complexity/availability/maintenance

Off-shore (but not only): need high reliability, availability, low maintenance in harsh and hostile environments

Smart but Simple

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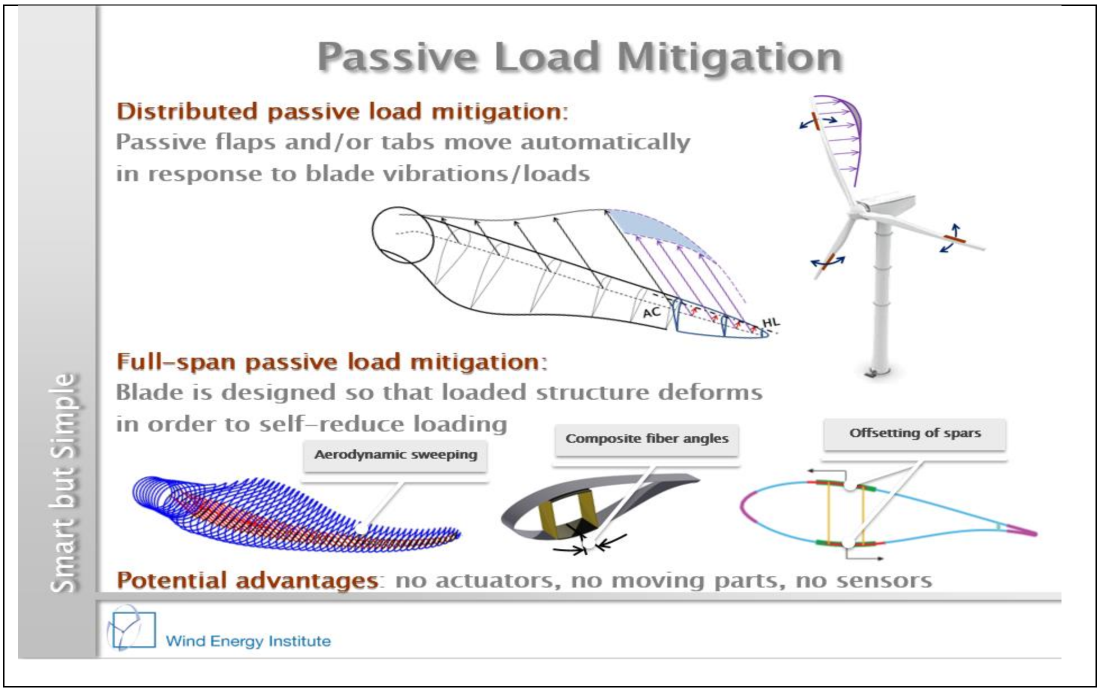


Passive Load Mitigation

Distributed passive load mitigation:
Passive flaps and/or tabs move automatically in response to blade vibrations/loads

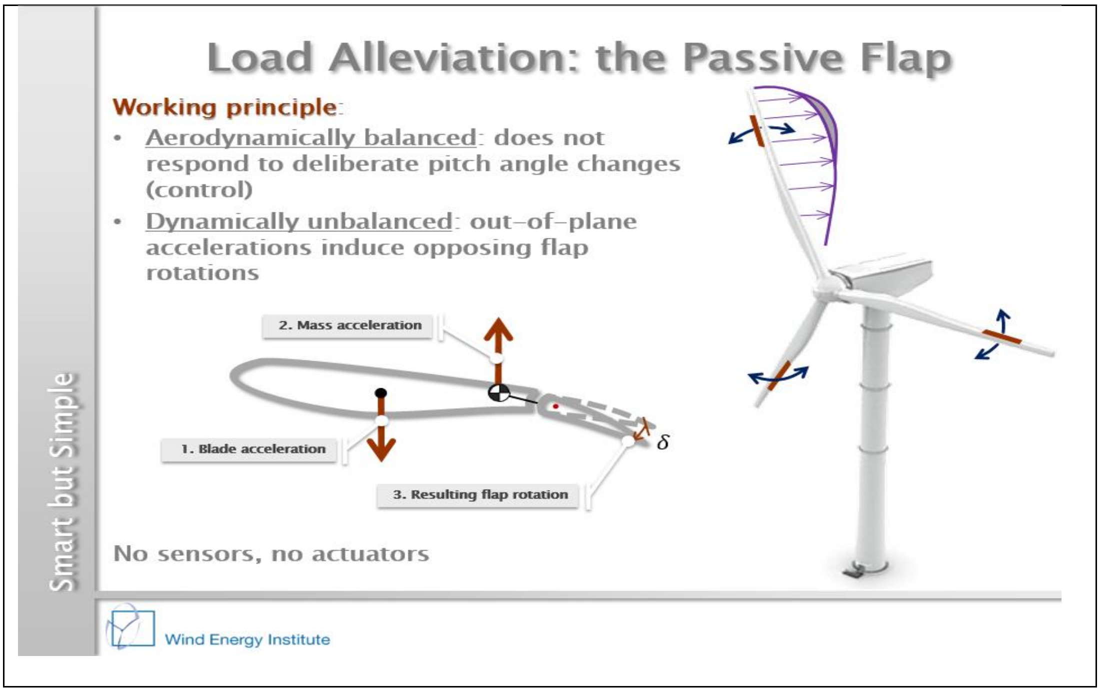
Full-span passive load mitigation:
Blade is designed so that loaded structure deforms in order to self-reduce loading

Aerodynamic sweeping

Composite fiber angles

Offsetting of spars

Potential advantages: no actuators, no moving parts, no sensors



Load Alleviation: the Passive Flap

Working principle:

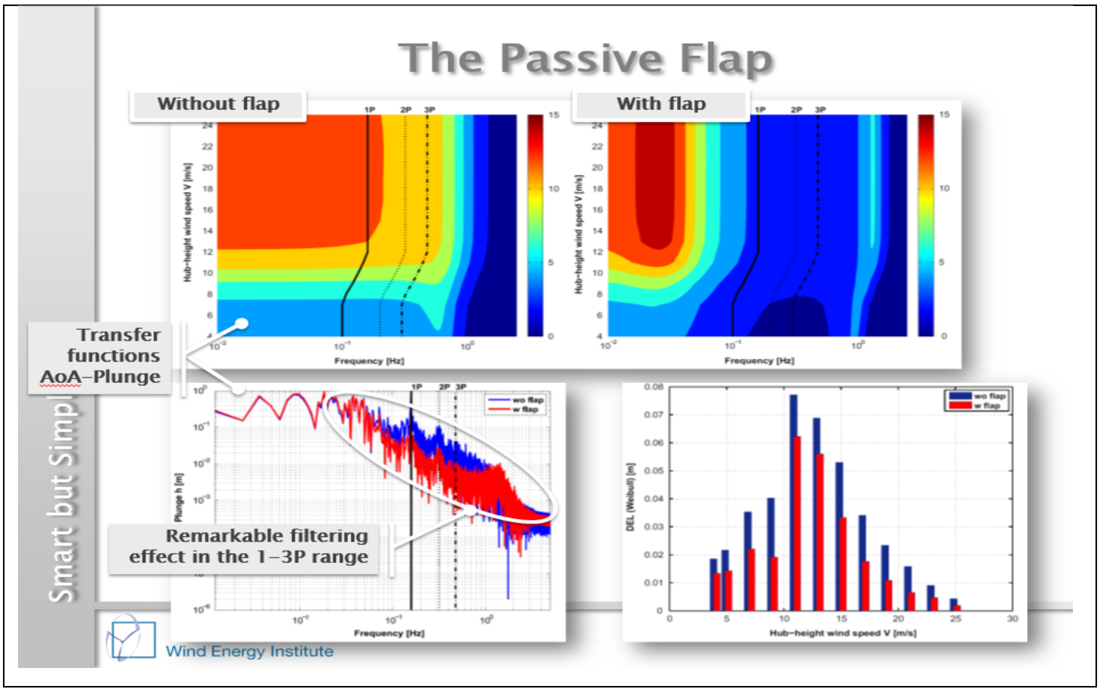
- Aerodynamically balanced: does not respond to deliberate pitch angle changes (control)
- Dynamically unbalanced: out-of-plane accelerations induce opposing flap rotations

2. Mass acceleration

1. Blade acceleration

3. Resulting flap rotation

No sensors, no actuators



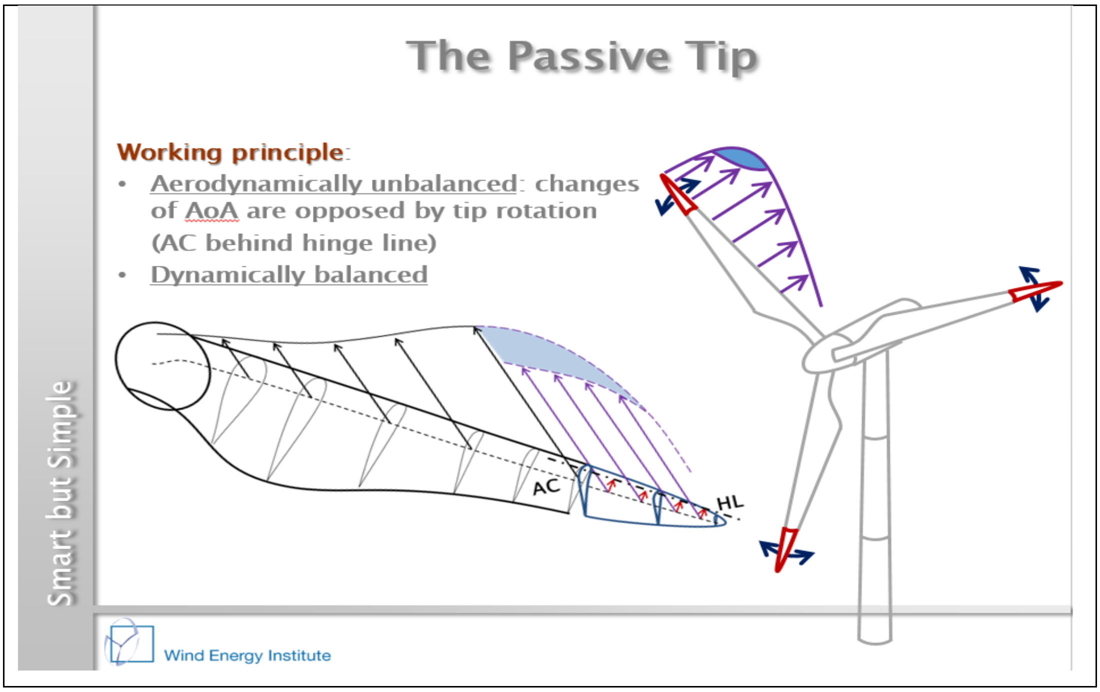
The Passive Flap

Without flap

With flap

Transfer functions AoA–Plunge

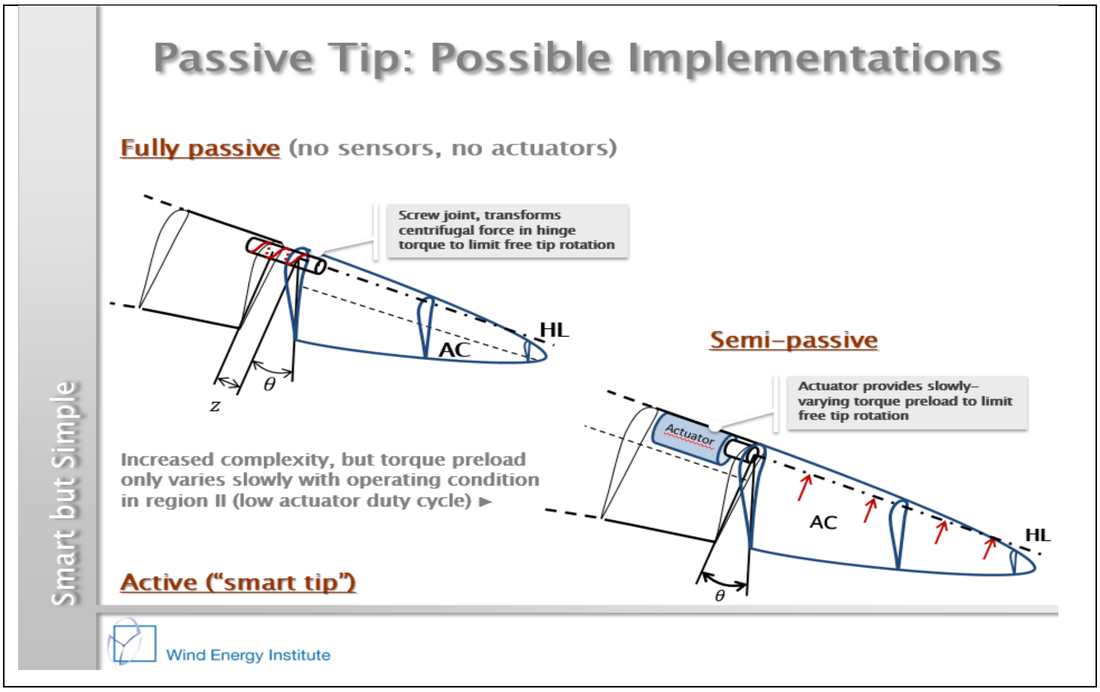
Remarkable filtering effect in the 1–3P range



The Passive Tip

Working principle:

- Aerodynamically unbalanced: changes of AoA are opposed by tip rotation (AC behind hinge line)
- Dynamically balanced



Passive Tip: Possible Implementations

Fully passive (no sensors, no actuators)

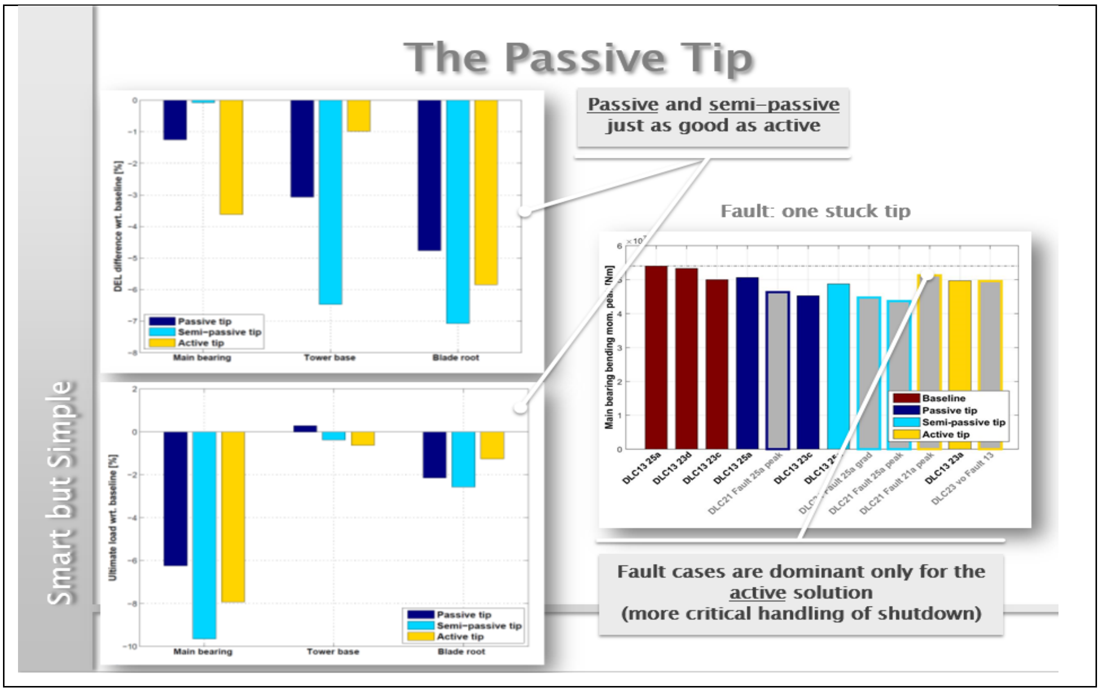
Screw joint, transforms centrifugal force in hinge torque to limit free tip rotation

Semi-passive

Actuator provides slowly-varying torque preload to limit free tip rotation

Increased complexity, but torque preload only varies slowly with operating condition in region II (low actuator duty cycle) ►

Active ("smart tip")

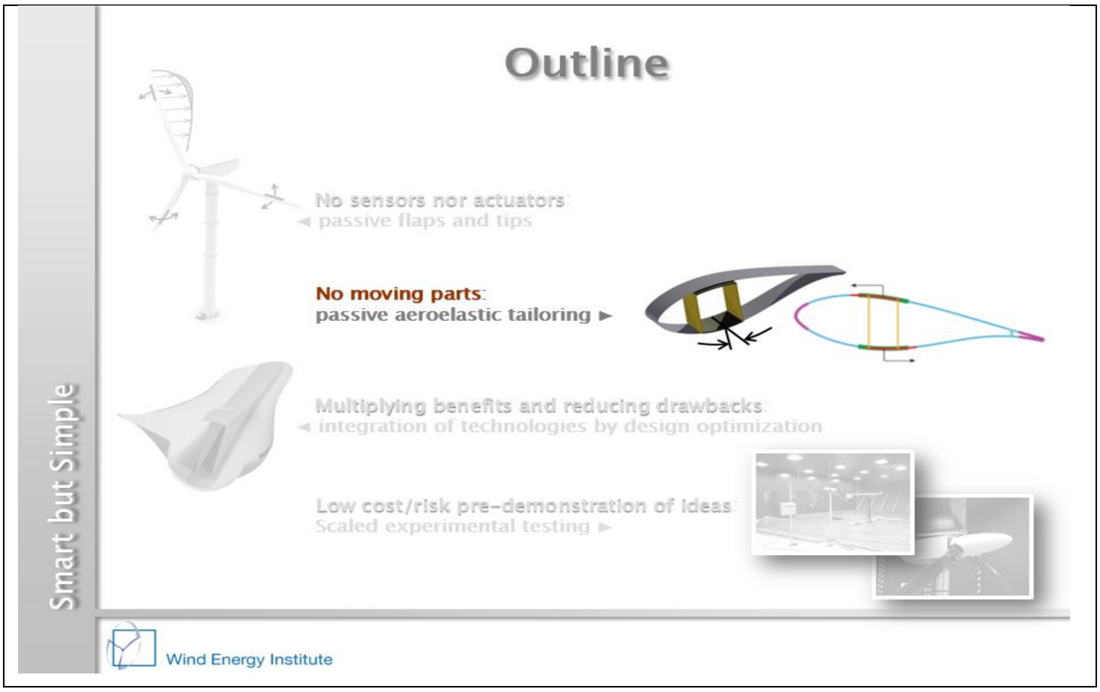


The Passive Tip

Passive and semi-passive just as good as active

Fault: one stuck tip

Fault cases are dominant only for the active solution
(more critical handling of shutdown)



Smart but Simple

Outline

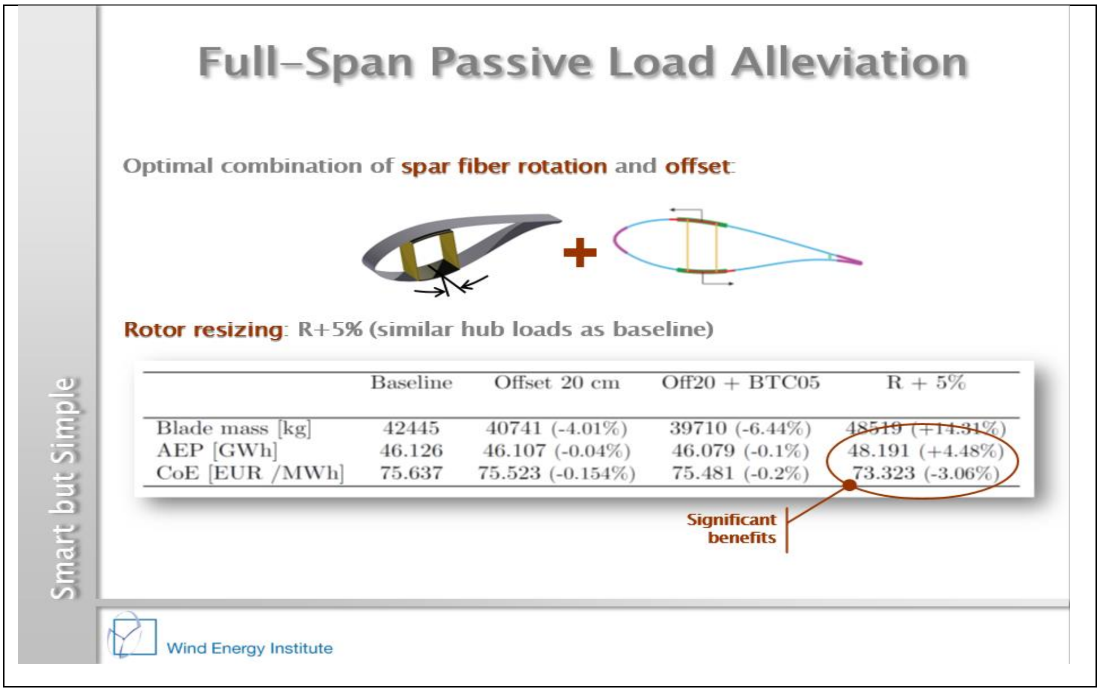
No sensors nor actuators:
◄ passive flaps and tips

No moving parts:
passive aeroelastic tailoring ►

Multiplying benefits and reducing drawbacks:
◄ integration of technologies by design optimization

Low cost/risk pre-demonstration of ideas:
Scaled experimental testing ►

Wind Energy Institute



Smart but Simple

Full–Span Passive Load Alleviation

Optimal combination of **spar fiber rotation** and **offset**:

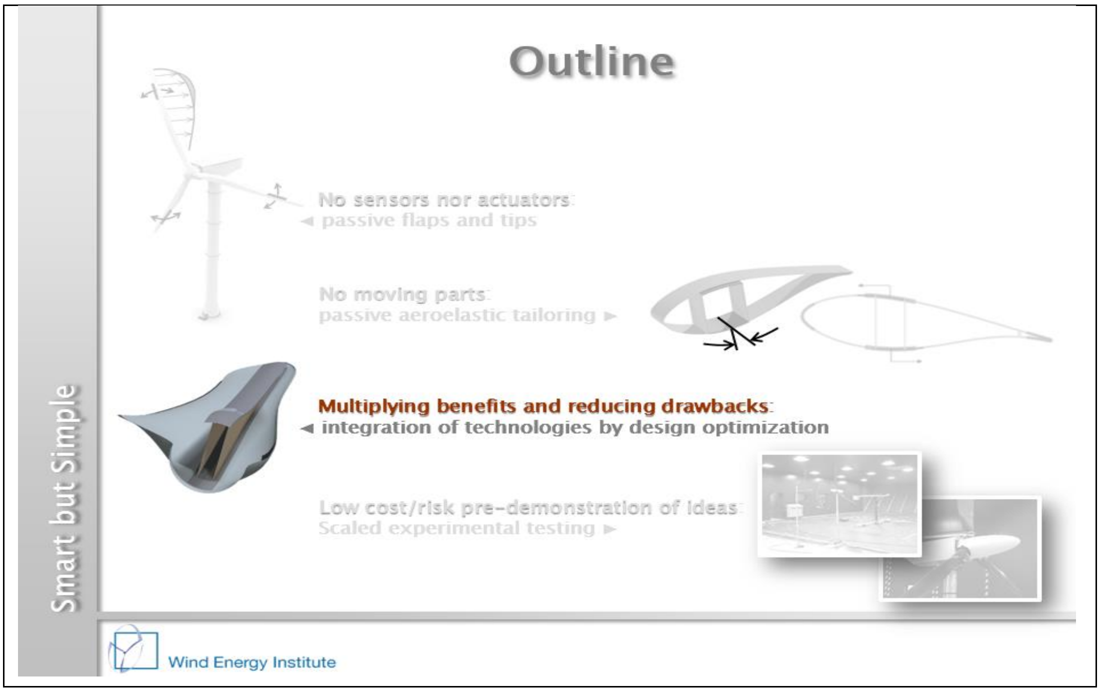
+

Rotor resizing: R+5% (similar hub loads as baseline)

	Baseline	Offset 20 cm	Off20 + BTC05	R + 5%
Blade mass [kg]	42445	40741 (-4.01%)	39710 (-6.44%)	48519 (+14.31%)
AEP [GWh]	46.126	46.107 (-0.04%)	46.079 (-0.1%)	48.191 (+4.48%)
CoE [EUR /MWh]	75.637	75.523 (-0.154%)	75.481 (-0.2%)	73.323 (-3.06%)

Significant benefits

Wind Energy Institute



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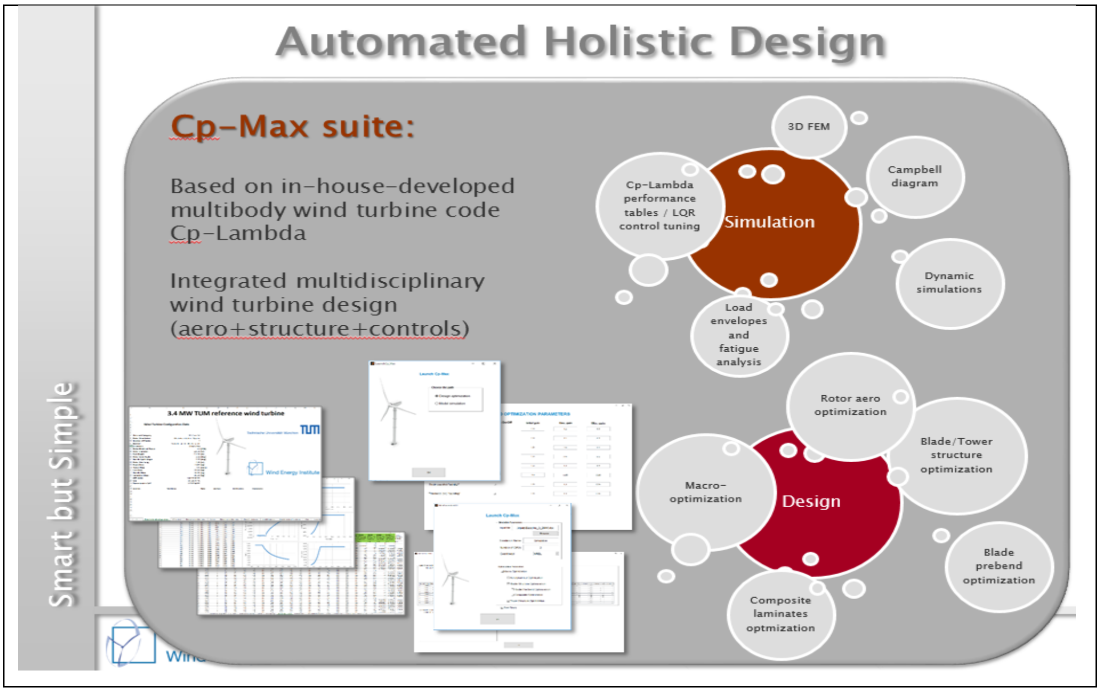
Smart but Simple

Wind Energy Institute



Automated Holistic Design

Cp-Max suite:

Based on in-house-developed multibody wind turbine code Cp-Lambda

Integrated multidisciplinary wind turbine design (aero+structure+controls)

3.4 MW TUM reference wind turbine

Simulation

3D FEM

Cp-Lambda performance tables / LQR control tuning

Campbell diagram

Dynamic simulations

Load envelopes and fatigue analysis

Design

Rotor aero optimization

Blade/Tower structure optimization

Macro-optimization

Blade prebend optimization

Composite laminates optmization

Smart but Simple

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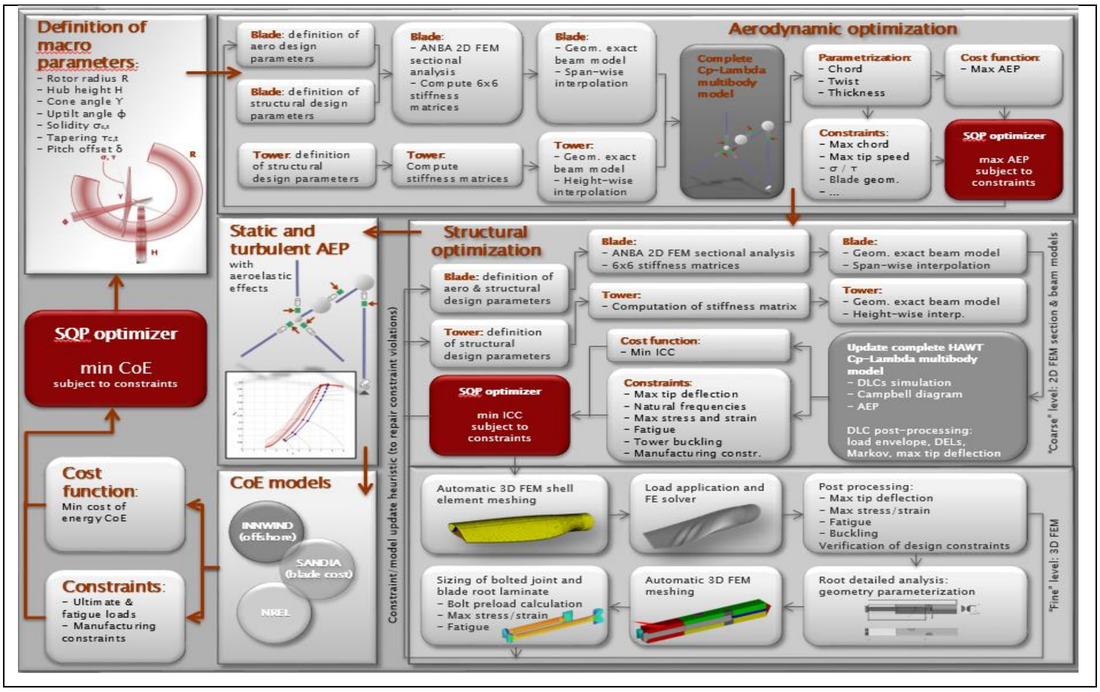


Definition of macro parameters:
- Rotor radius R
- Hub height H
- Cone angle Υ
- Uptilt angle ϕ
- Solidity $\sigma_{c,t}$
- Tapering $\tau_{c,t}$
- Pitch offset δ

SQP optimizer
min CoE
subject to constraints

Cost function:
Min cost of energy CoE

Constraints:
- Ultimate & fatigue loads
- Manufacturing constraints

Aerodynamic optimization

Blade: definition of aero design parameters

Blade: definition of structural design parameters

Blade:
- ANBA 2D FEM sectional analysis
- Compute 6x6 stiffness matrices

Blade:
- Geom. exact beam model
- Span-wise interpolation

Tower: definition of structural design parameters

Tower: Compute stiffness matrices

Tower:
- Geom. exact beam model
- Height-wise interpolation

Complete Cp-Lambda multibody model

Parametrization:
- Chord
- Twist
- Thickness

Cost function:
- Max AEP

Constraints:
- Max chord
- Max tip speed
- σ / τ
- Blade geom.
- ...

SQP optimizer
max AEP
subject to constraints

Static and turbulent AEP
with aeroelastic effects

CoE models

Constraint/model update heuristic (to repair constraint violations)

Structural optimization

Blade: definition of aero & structural design parameters

Tower: definition of structural design parameters

Blade:
- ANBA 2D FEM sectional analysis
- 6x6 stiffness matrices

Blade:
- Geom. exact beam model
- Span-wise interpolation

Tower:
- Computation of stiffness matrix

Tower:
- Geom. exact beam model
- Height-wise interp.

Cost function:
- Min ICC

Constraints:
- Max tip deflection
- Natural frequencies
- Max stress and strain
- Fatigue
- Tower buckling
- Manufacturing constr.

SQP optimizer
min ICC
subject to constraints

Update complete HAWT Cp-Lambda multibody model
- DLCs simulation
- Campbell diagram
- AEP

DLC post-processing:
load envelope, DELs, Markov, max tip deflection

"Coarse" level: 2D FEM section & beam models

Automatic 3D FEM shell element meshing

Load application and FE solver

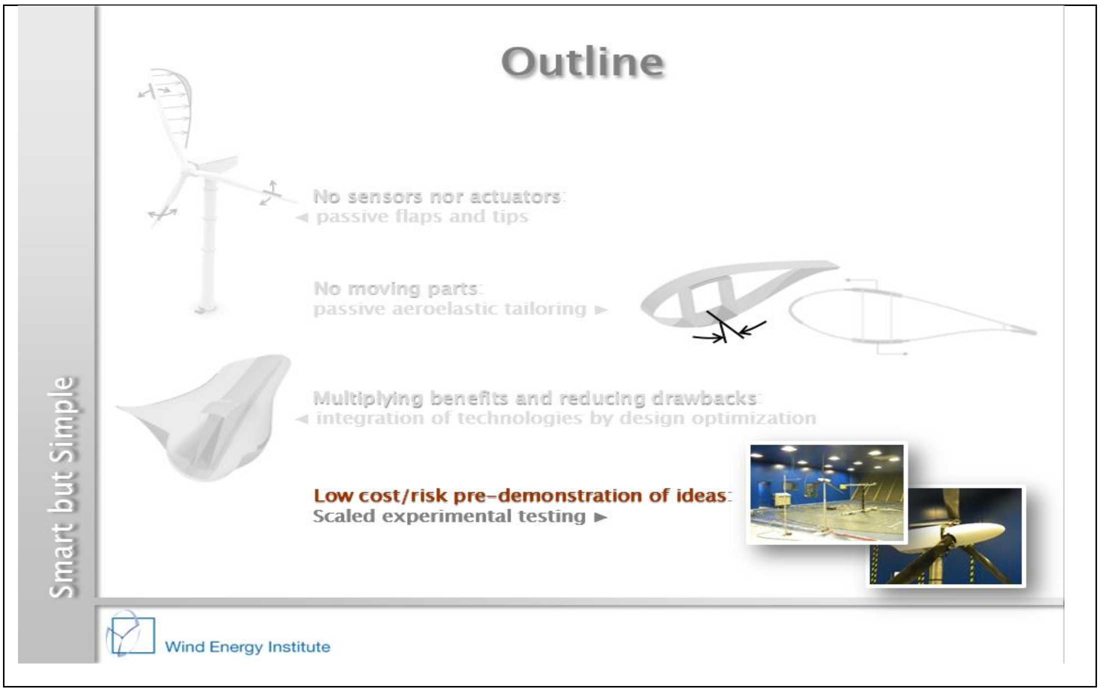
Post processing:
- Max tip deflection
- Max stress/strain
- Fatigue
- Buckling
Verification of design constraints

Sizing of bolted joint and blade root laminate
- Bolt preload calculation
- Max stress/strain
- Fatigue

Automatic 3D FEM meshing

Root detailed analysis:
geometry parameterization

"Fine" level: 3D FEM



Outline

No sensors nor actuators:
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passive aeroelastic tailoring ►

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Low cost/risk pre-demonstration of ideas:
Scaled experimental testing ►

Smart but Simple

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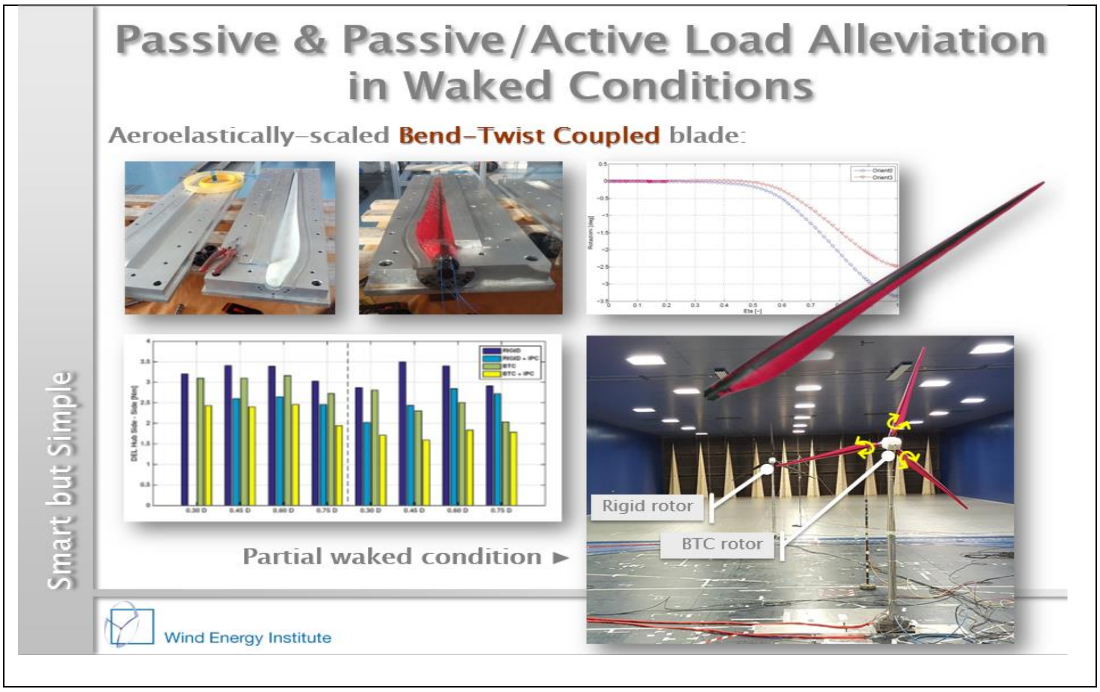
G1 & G2 Scaled Wind Turbines

Smart but Simple

Win



Passive & Passive/Active Load Alleviation in Waked Conditions

Aeroelastically-scaled **Bend-Twist Coupled** blade:

Partial waked condition ►

Smart but Simple

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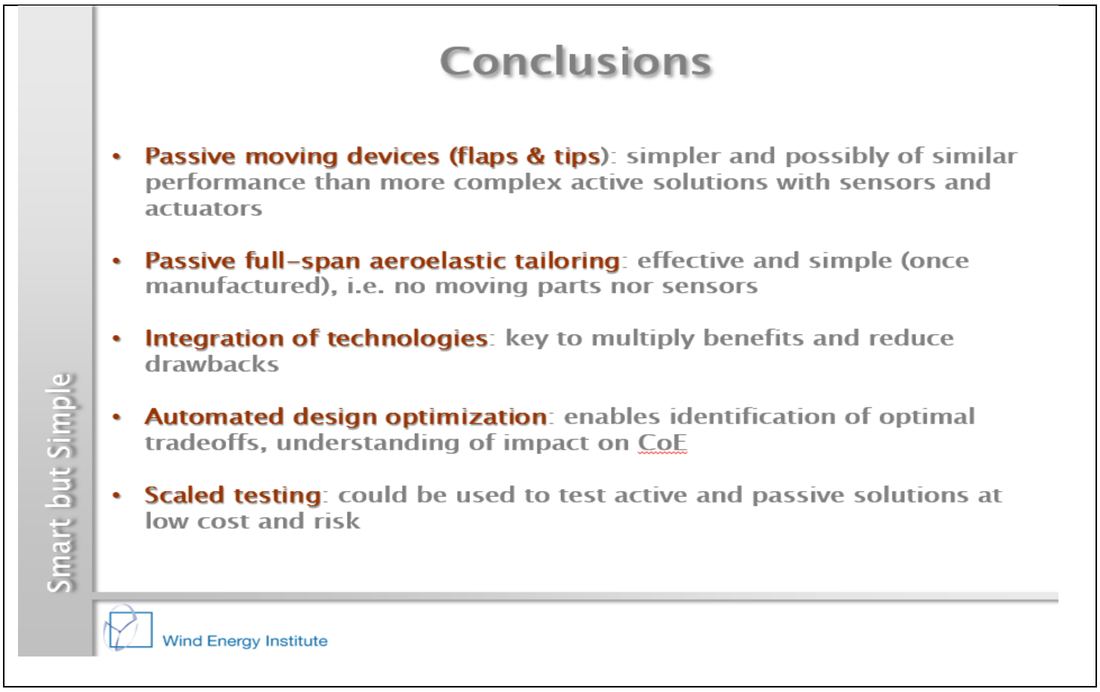

Smart but Simple

Conclusions

- **Passive moving devices (flaps & tips)**: simpler and possibly of similar performance than more complex active solutions with sensors and actuators
- **Passive full-span aeroelastic tailoring**: effective and simple (once manufactured), i.e. no moving parts nor sensors
- **Integration of technologies**: key to multiply benefits and reduce drawbacks
- **Automated design optimization**: enables identification of optimal tradeoffs, understanding of impact on CoE
- **Scaled testing**: could be used to test active and passive solutions at low cost and risk

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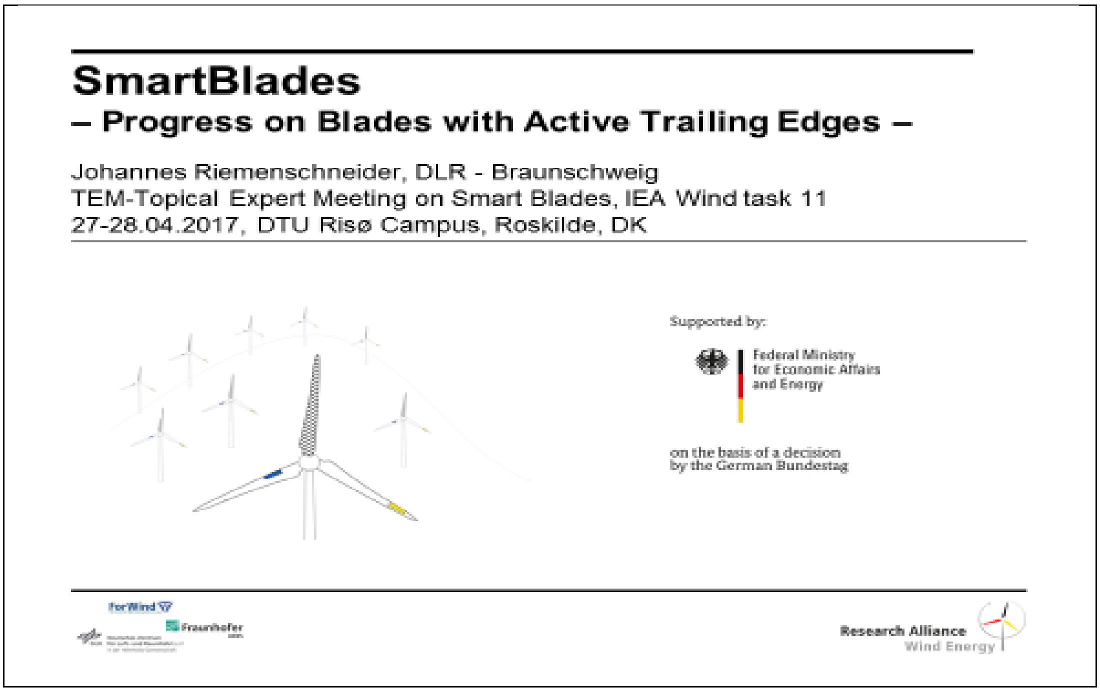

SmartBlades

– Progress on Blades with Active Trailing Edges –

Johannes Riemenschneider, DLR - Braunschweig
TEM-Topical Expert Meeting on Smart Blades, IEA Wind task 11
27-28.04.2017, DTU Risø Campus, Roskilde, DK

Supported by:

Federal Ministry
for Economic Affairs
and Energy

on the basis of a decision
by the German Bundestag

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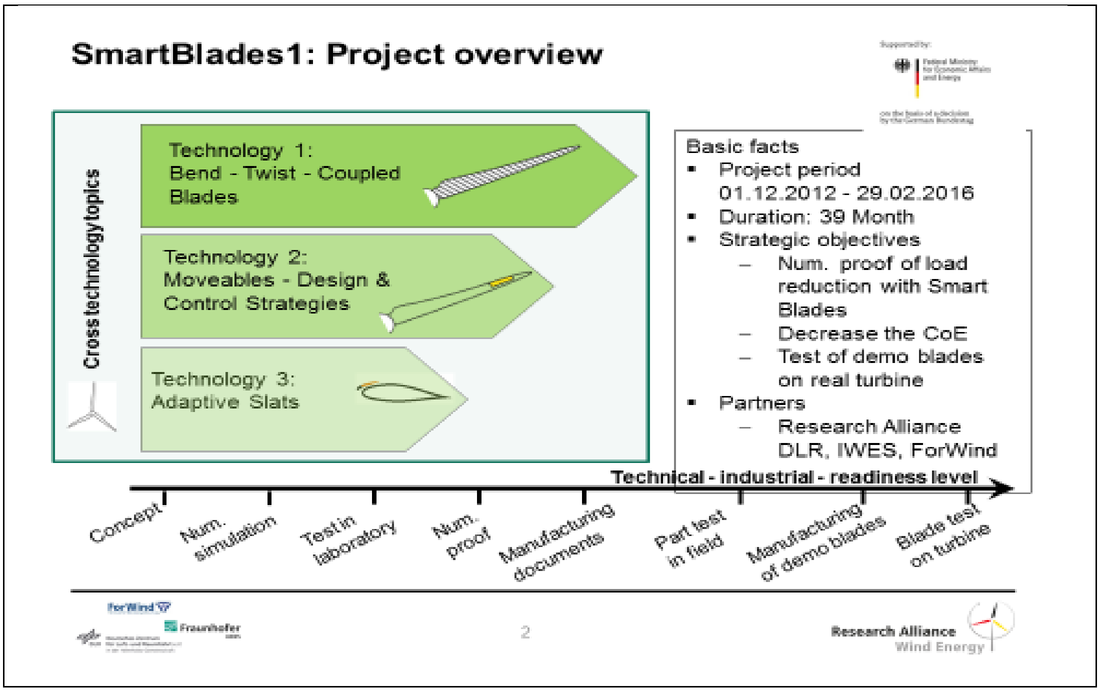
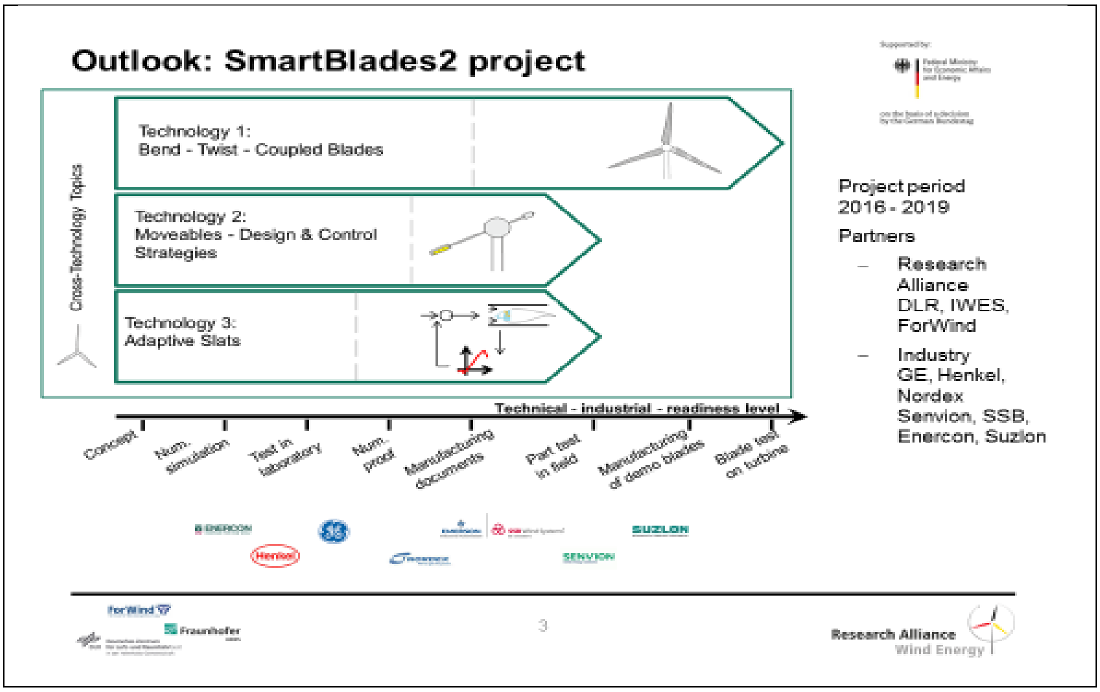
Research Alliance
Wind Energy



SmartBlades1: Project overview

Basic facts

- Project period
  01.12.2012 - 29.02.2016
- Duration: 39 Month
- Strategic objectives
  - Num. proof of load reduction with Smart Blades
  - Decrease the CoE
  - Test of demo blades on real turbine
- Partners
  - Research Alliance DLR, IWES, ForWind



Outlook: SmartBlades2 project

Project period
2016 - 2019

Partners

- Research Alliance DLR, IWES, ForWind
- Industry GE, Henkel, Nordex Senvion, SSB, Enercon, Suzlon

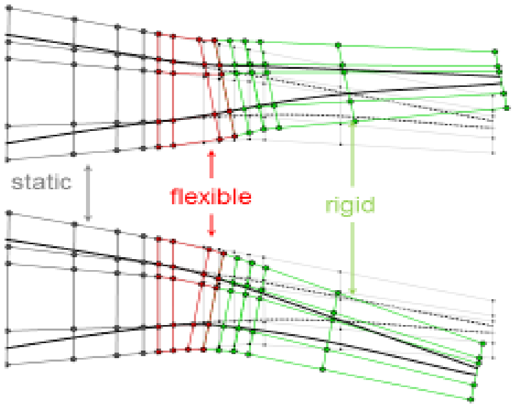
Outline

- **Aerodynamics – Trailing edge shape**
- Control – IBC vs. IFC
- Acoustics – Noise sources of discrete flaps
- Structure – Concept to validation experiment

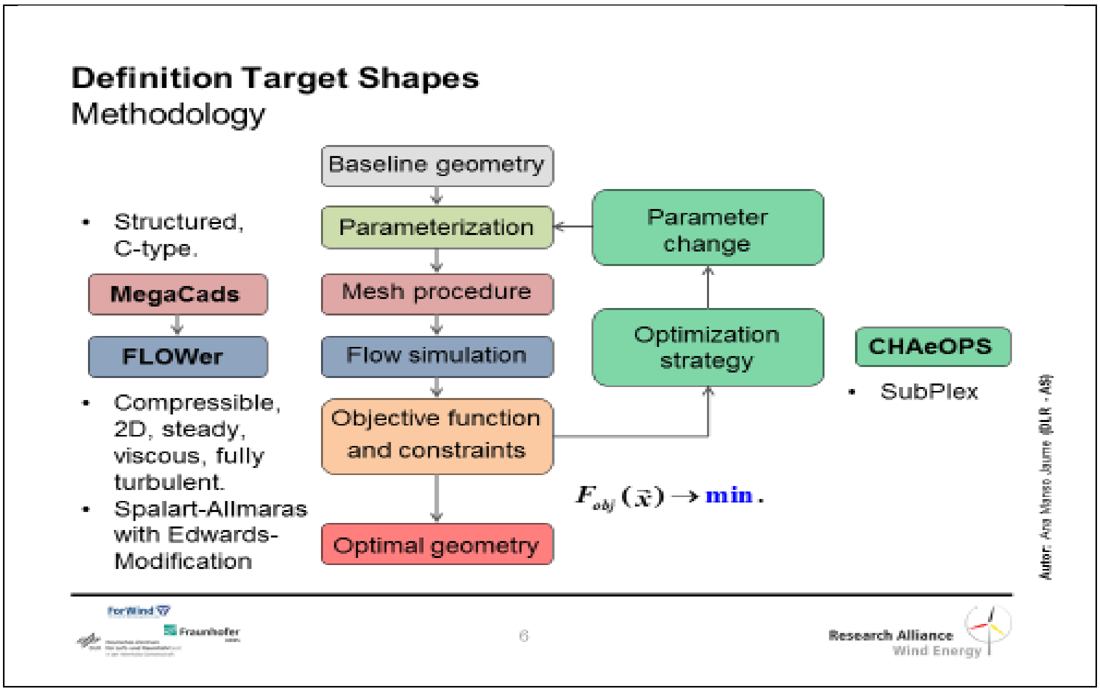
Definition Target Shapes
Methodology

Free-form deformation method:

- Definition of enclosing NURB-Spline-volume
- Capture of the geometry (determination of the NURBS-parameters)
- Definition of the deformed NURBS-volume
- Evaluation of the NURBS-parameters in the deformed volume
- The rigid section is not deformed



Autor: Ana Manso Jaume (DLR - AS)



Definition Target Shapes
Methodology

- Structured, C-type.

MegaCads

FLOWer

- Compressible, 2D, steady, viscous, fully turbulent.
- Spalart-Allmaras with Edwards-Modification

Baseline geometry

Parameterization

Mesh procedure

Flow simulation

Objective function and constraints

Optimal geometry

Parameter change

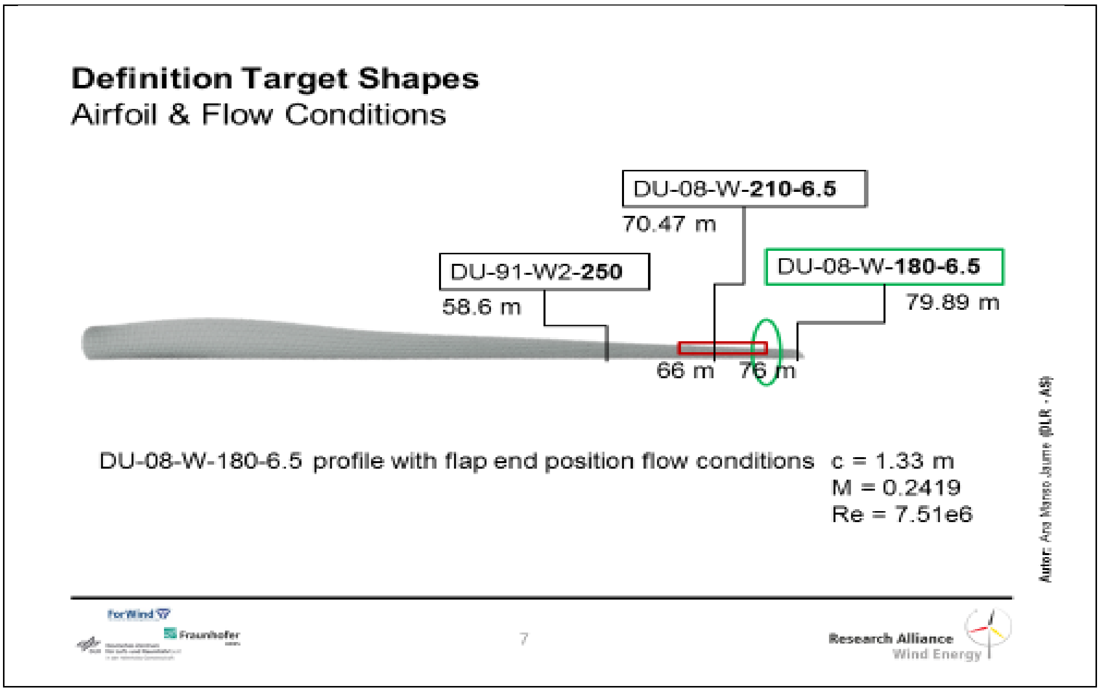
Optimization strategy

$F_{obj}(\vec{x}) \rightarrow \min .$

CHAeOPS

- SubPlex

Autor: Ana Manso Jaume (DLR - AS)

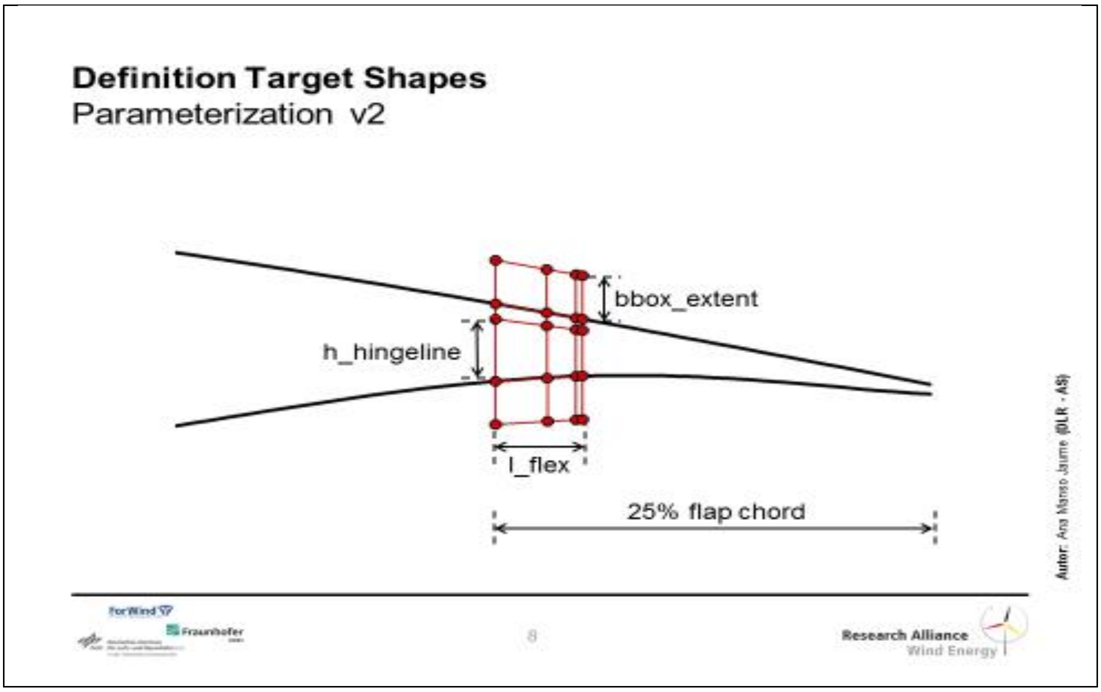


Definition Target Shapes
Airfoil & Flow Conditions

DU-08-W-180-6.5 profile with flap end position flow conditions

c = 1.33 m
M = 0.2419
Re = 7.51e6

Autor: Ana Manso Jaume (DLR - AS)



Definition Target Shapes
Parameterization v2

Autor: Ana Manso Jaume (DLR - AS)

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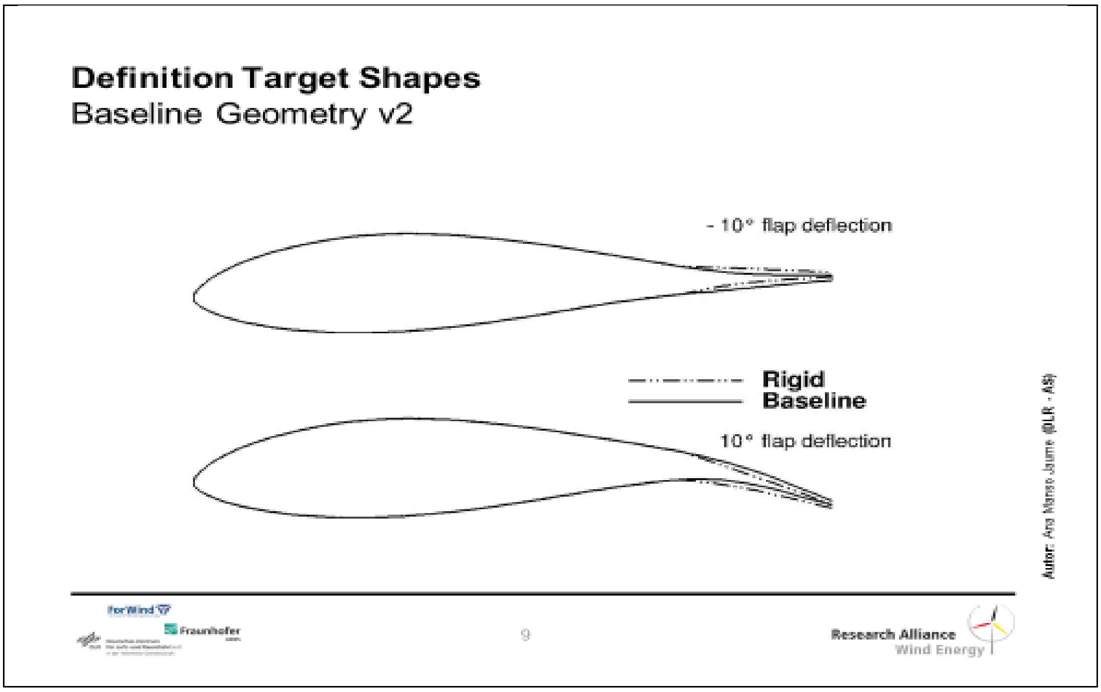
Research Alliance Wind Energy



Definition Target Shapes
Baseline Geometry v2

Autor: Ana Manso Jaume (DLR - AS)

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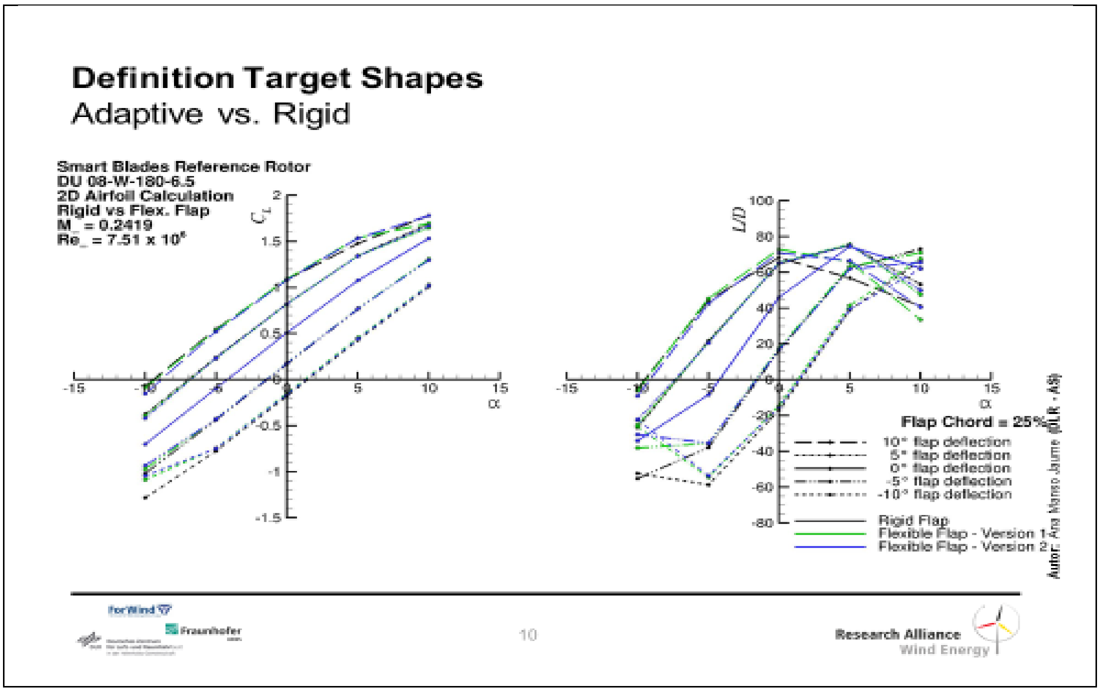
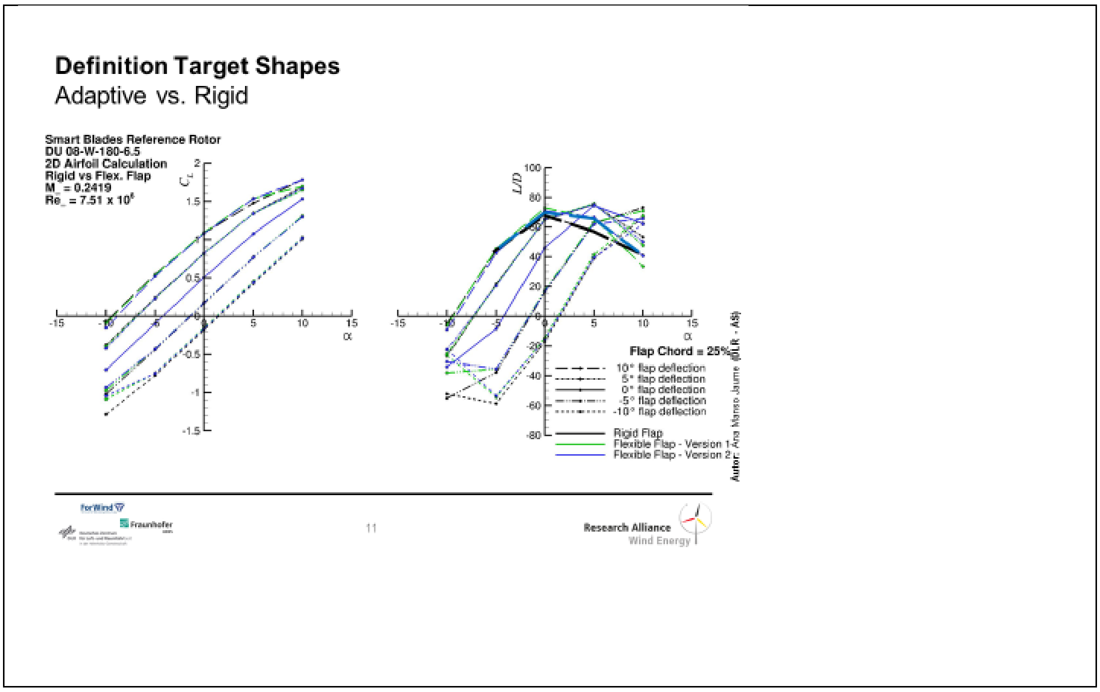
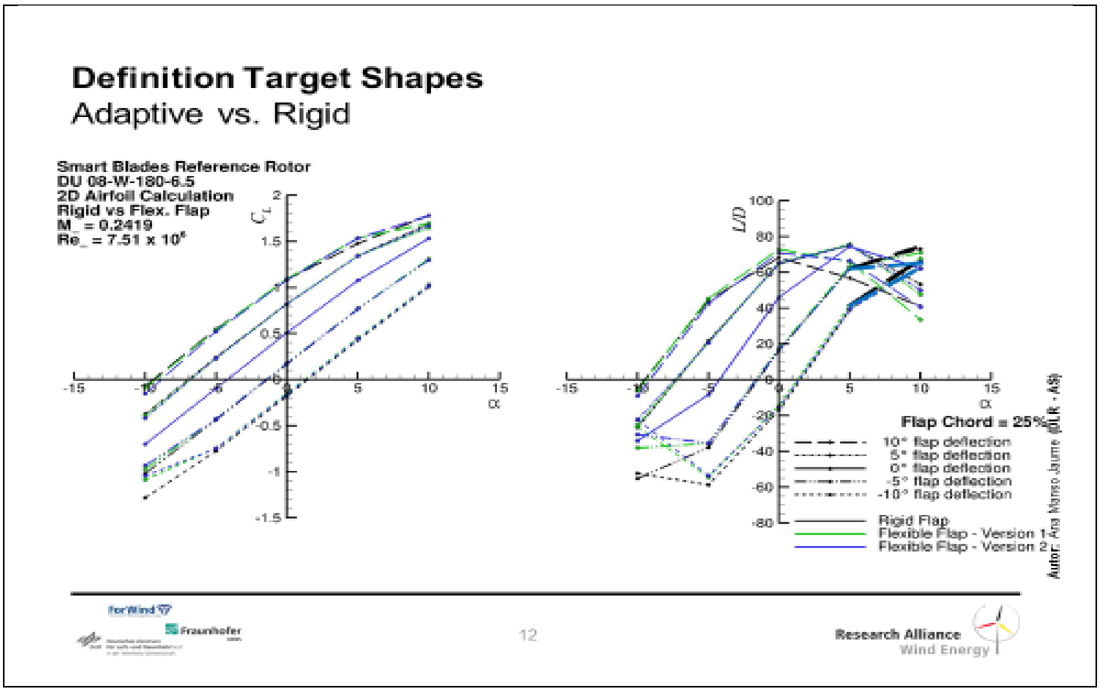


Definition Target Shapes
Adaptive vs. Rigid

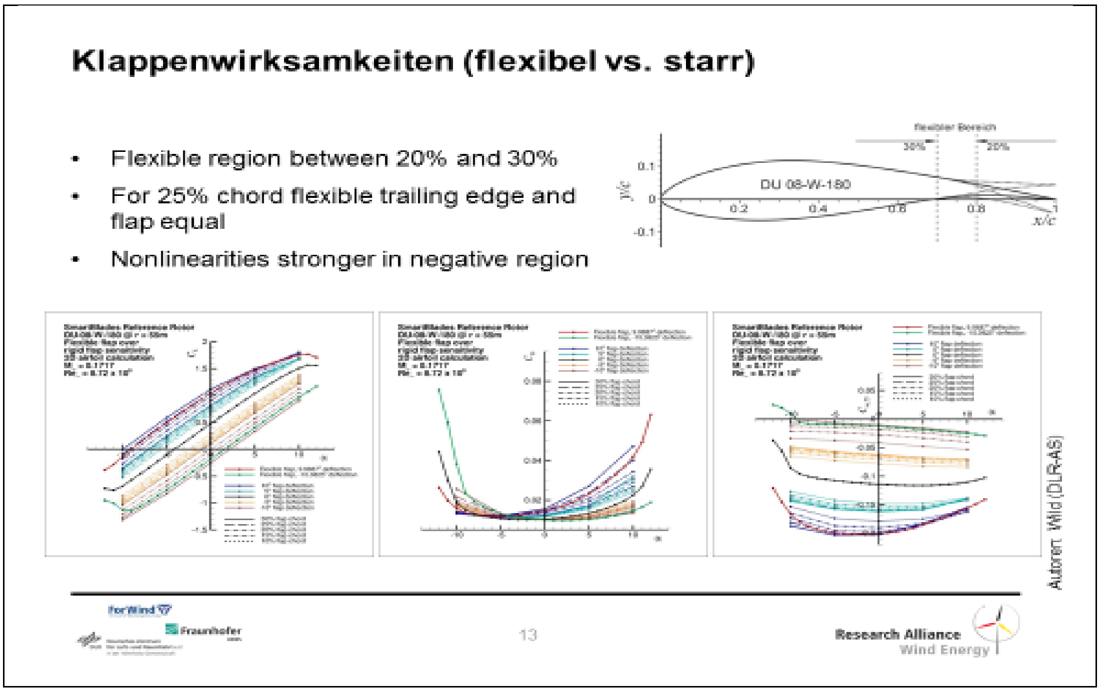


Definition Target Shapes
Adaptive vs. Rigid



Definition Target Shapes
Adaptive vs. Rigid

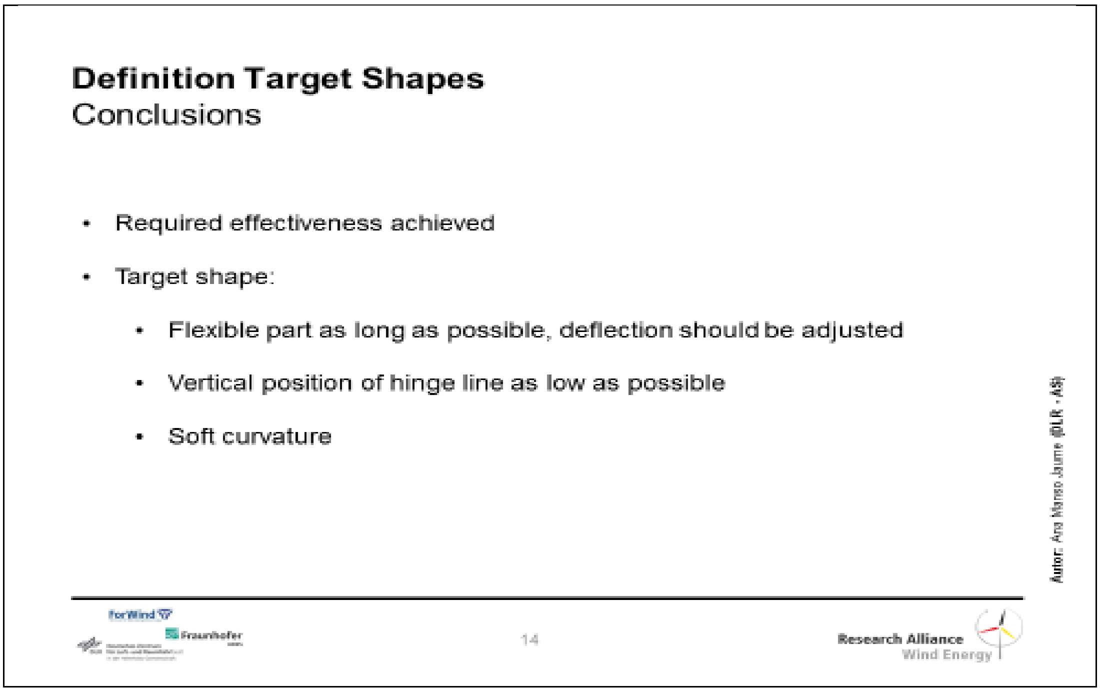
Autor: Ana Manso Jaume (DLR - AS)



Klappenwirksamkeiten (flexibel vs. starr)

- Flexible region between 20% and 30%
- For 25% chord flexible trailing edge and flap equal
- Nonlinearities stronger in negative region

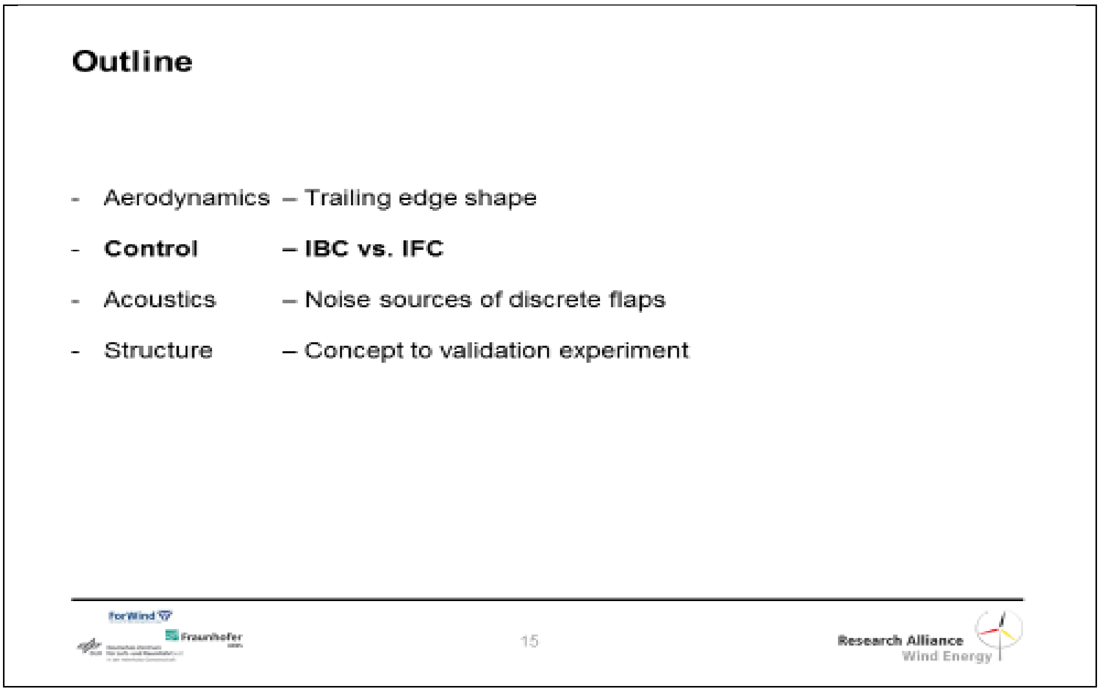
Autoren: Wild (DLR-AS)



Definition Target Shapes
Conclusions

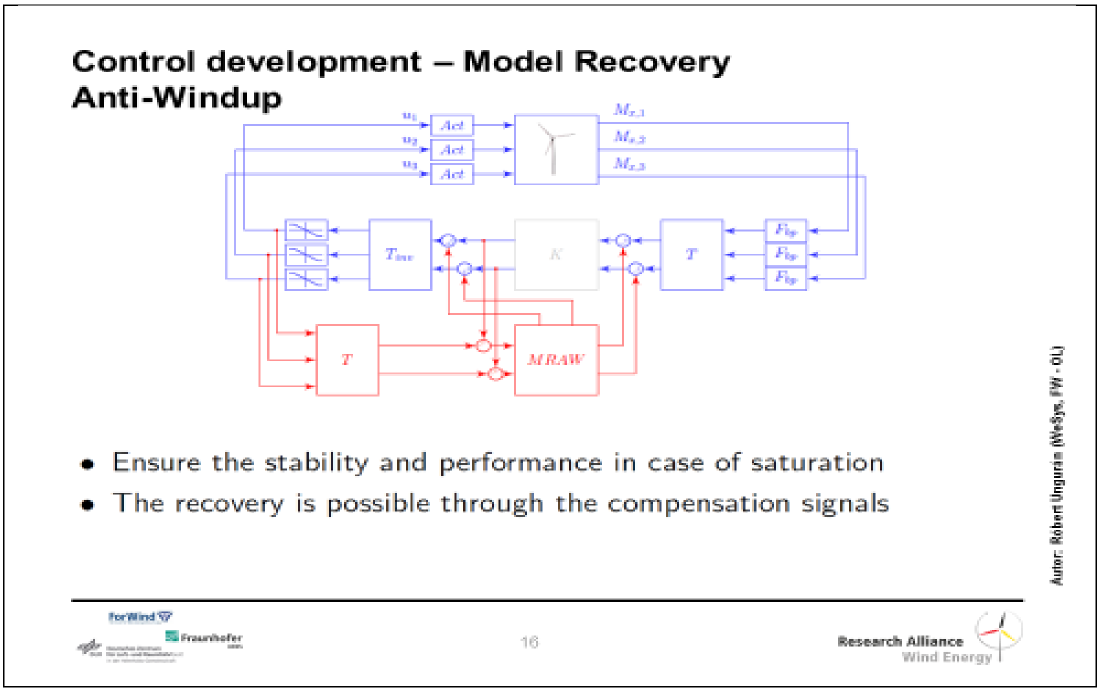
- Required effectiveness achieved
- Target shape:
  - Flexible part as long as possible, deflection should be adjusted
  - Vertical position of hinge line as low as possible
  - Soft curvature

Autor: Ana Manso Jaume (DLR - AS)



Outline

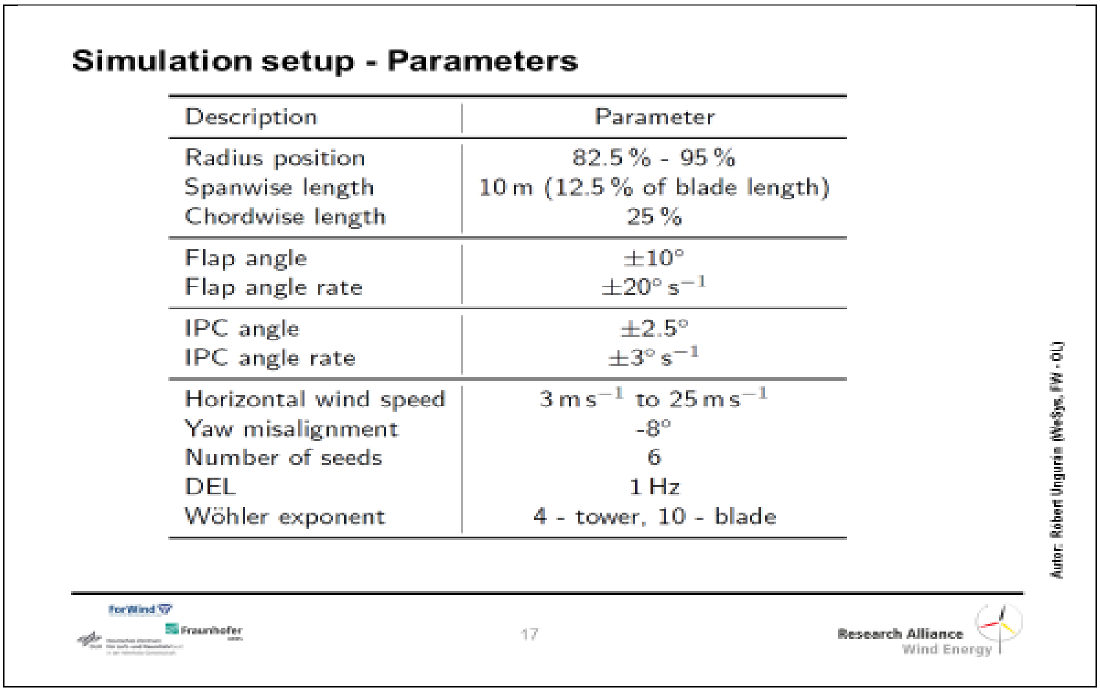
- Aerodynamics – Trailing edge shape
- **Control – IBC vs. IFC**
- Acoustics – Noise sources of discrete flaps
- Structure – Concept to validation experiment



Control development – Model Recovery Anti-Windup

- Ensure the stability and performance in case of saturation
- The recovery is possible through the compensation signals

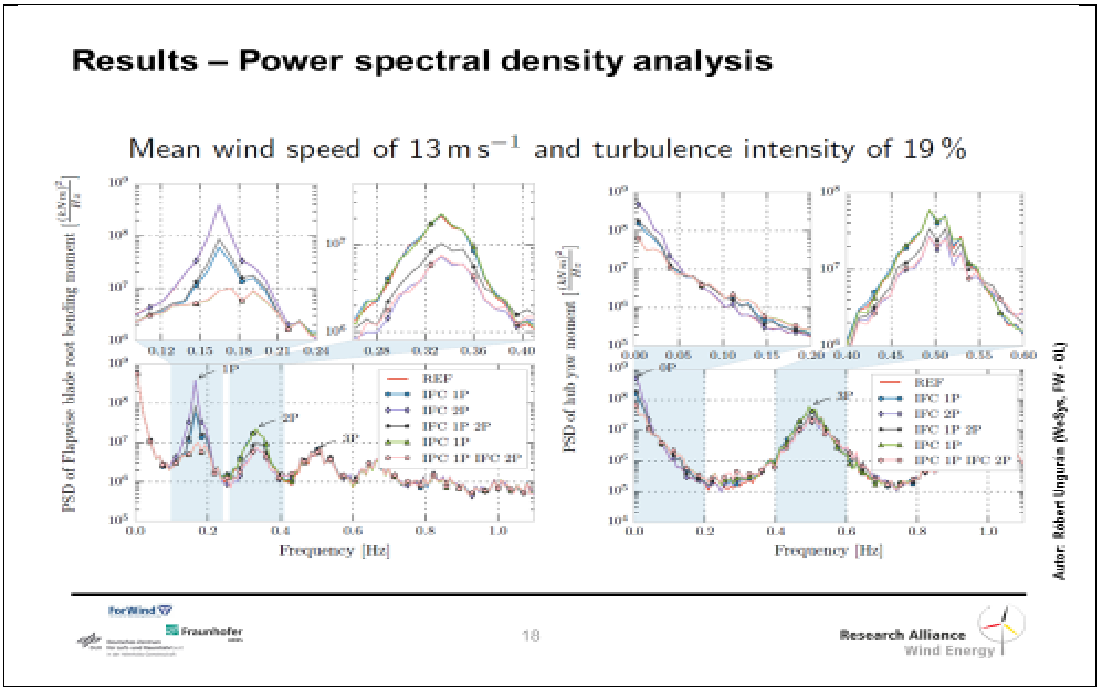
Autor: Robert Ungurán (WeSys, FW - OL)



Simulation setup - Parameters

Description	Parameter
Radius position	82.5 % - 95 %
Spanwise length	10 m (12.5 % of blade length)
Chordwise length	25 %
Flap angle	±10°
Flap angle rate	$\pm 20^\circ\,\mathrm{s}^{-1}$
IPC angle	±2.5°
IPC angle rate	$\pm 3^\circ\,\mathrm{s}^{-1}$
Horizontal wind speed	$3\,\mathrm{m\,s^{-1}}$ to $25\,\mathrm{m\,s^{-1}}$
Yaw misalignment	-8°
Number of seeds	6
DEL	1 Hz
Wöhler exponent	4 - tower, 10 - blade

Autor: Robert Ungurán (WeSys, FW - OL)



Results – Power spectral density analysis

Mean wind speed of $13\,\mathrm{m\,s^{-1}}$ and turbulence intensity of 19 %

Autor: Robert Ungurán (WeSys, FW - OL)

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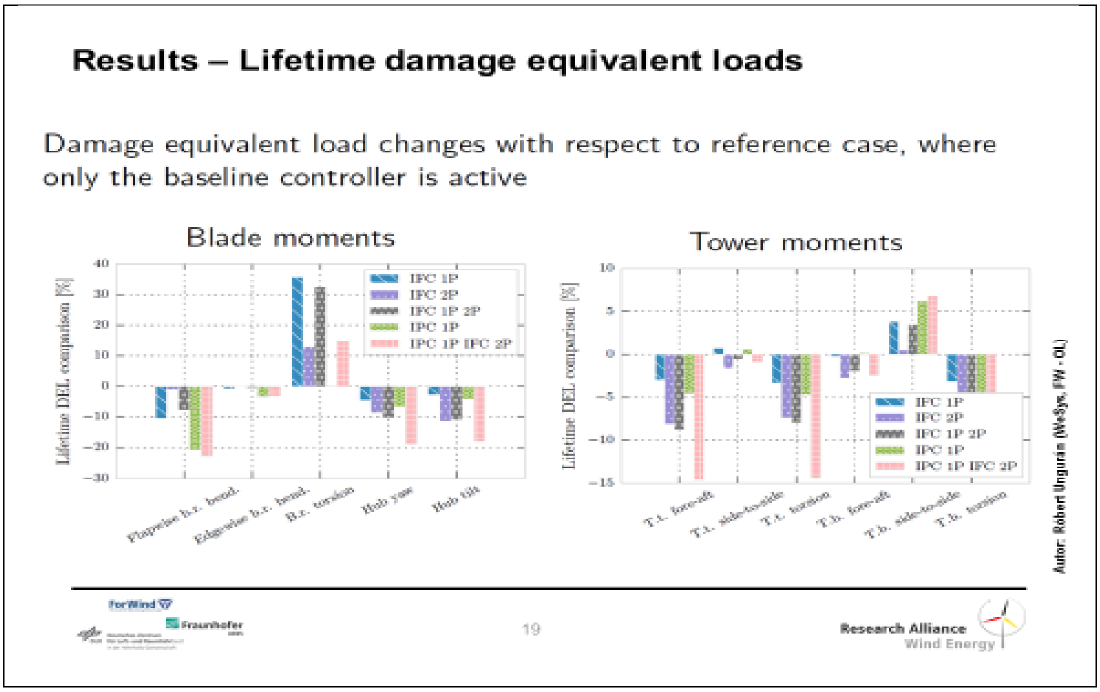
Wind Energy



Results – Lifetime damage equivalent loads

Damage equivalent load changes with respect to reference case, where only the baseline controller is active

Autor: Robert Ungurán (WeSys, FW - OL)

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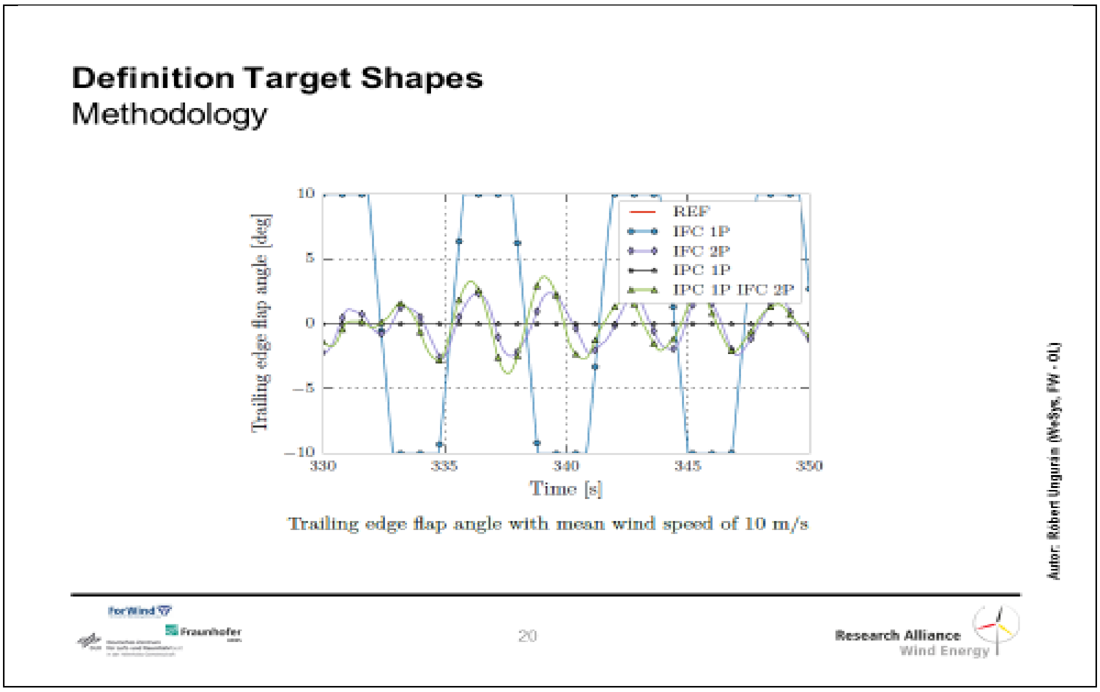
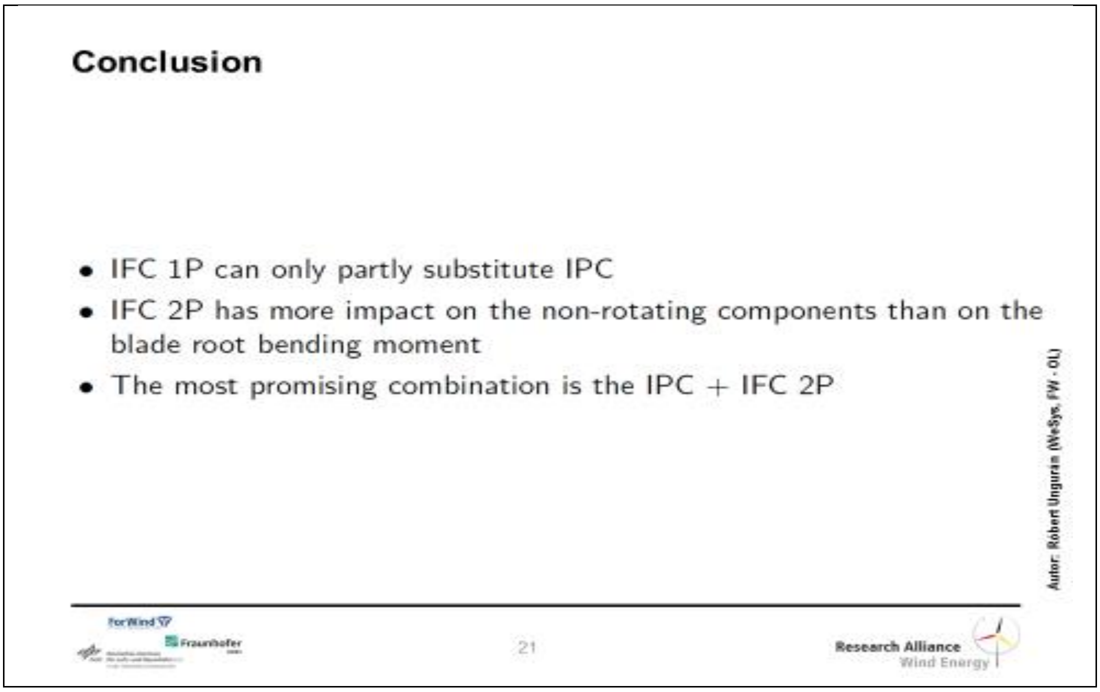


Definition Target Shapes
Methodology

Trailing edge flap angle with mean wind speed of 10 m/s

Autor: Robert Unguran (WeSys, FW - OL)



Conclusion

- IFC 1P can only partly substitute IPC
- IFC 2P has more impact on the non-rotating components than on the blade root bending moment
- The most promising combination is the IPC + IFC 2P

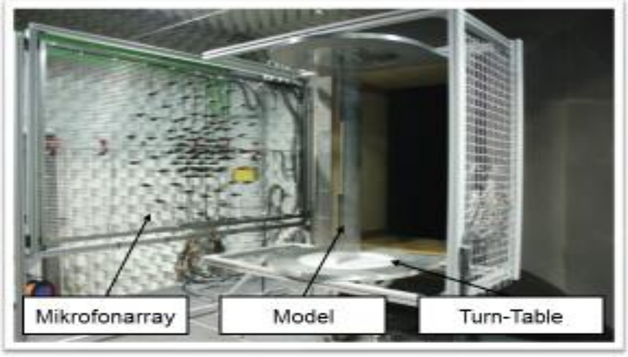
Autor: Robert Unguran (WeSys, FW - OL)

Outline

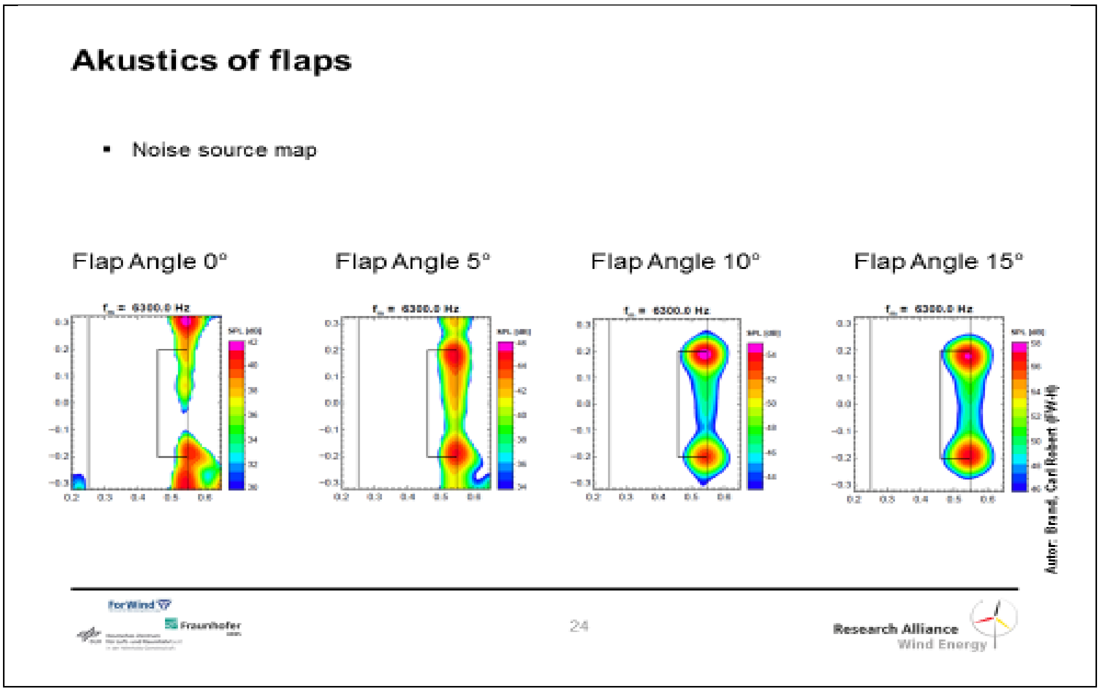
- Aerodynamics – Trailing edge shape
- Control – IBC vs. IFC
- **Acoustics – Noise sources of discrete flaps**
- Structure – Concept to validation experiment

Akustics of flaps

- Aeroacoustic experimental investigation



Autor: Brand, Carl Robert (FW-H)

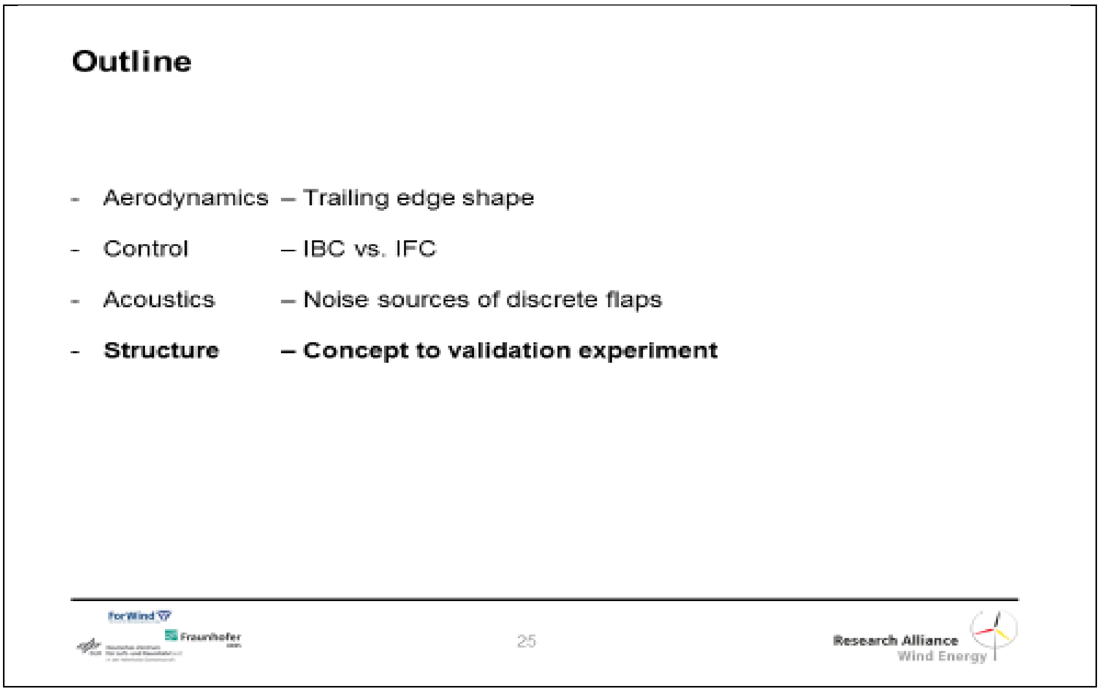


Akustics of flaps

- Noise source map

Flap Angle 0°   Flap Angle 5°   Flap Angle 10°   Flap Angle 15°

Autor: Brand, Carl Robert (IFW-H)



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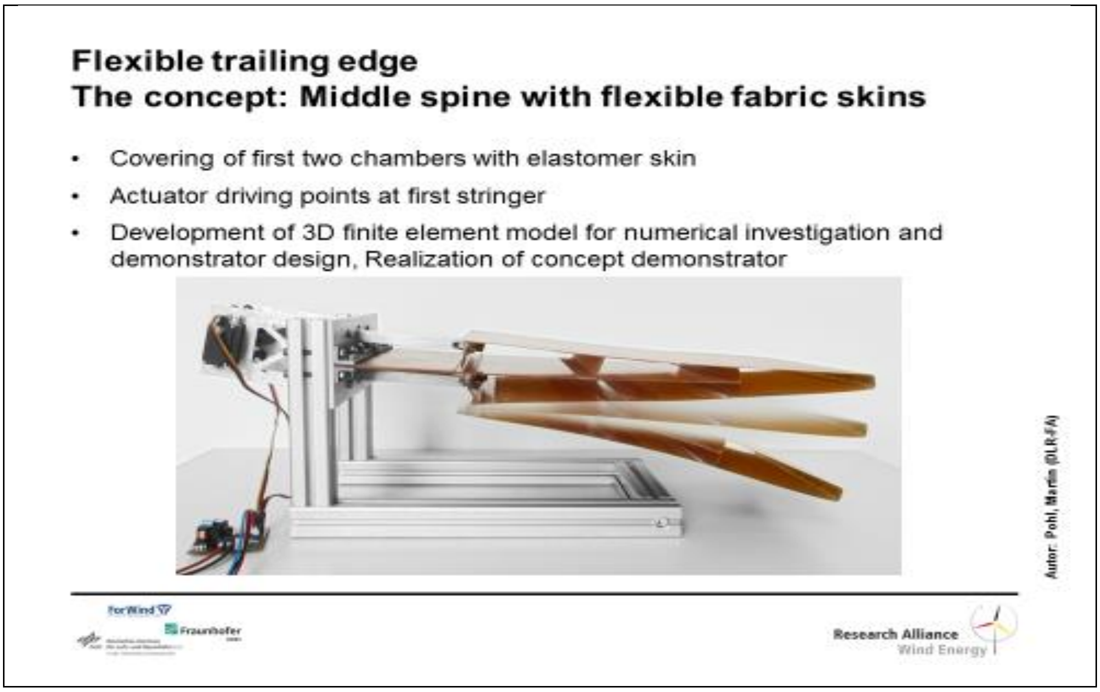
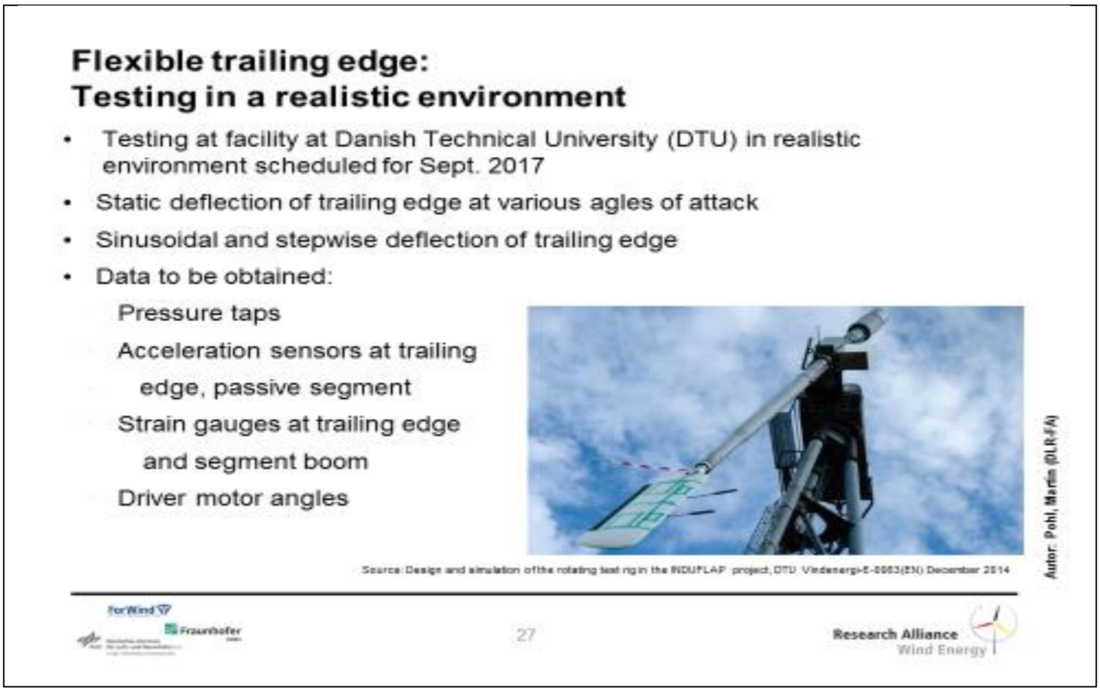
- Acoustics – Noise sources of discrete flaps
- **Structure – Concept to validation experiment**



Flexible trailing edge
The concept: Middle spine with flexible fabric skins

- Covering of first two chambers with elastomer skin
- Actuator driving points at first stringer
- Development of 3D finite element model for numerical investigation and demonstrator design, Realization of concept demonstrator

Autor: Pohl, Martin (DLR-FA)

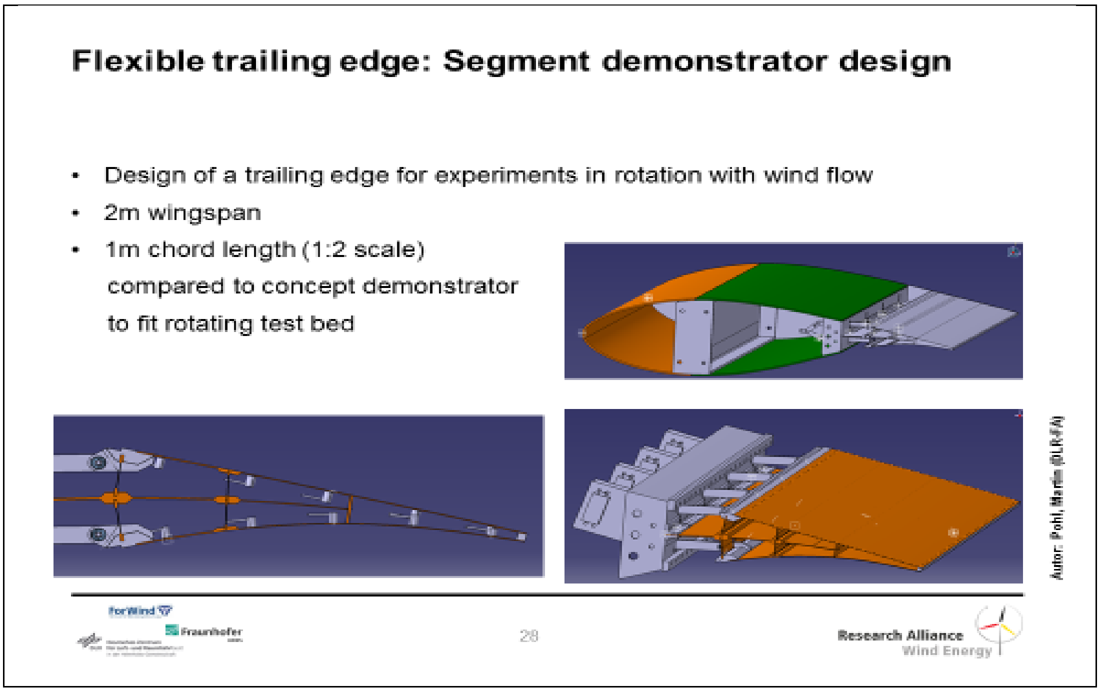


Flexible trailing edge:
Testing in a realistic environment

- Testing at facility at Danish Technical University (DTU) in realistic environment scheduled for Sept. 2017
- Static deflection of trailing edge at various agles of attack
- Sinusoidal and stepwise deflection of trailing edge
- Data to be obtained:
  - Pressure taps
  - Acceleration sensors at trailing edge, passive segment
  - Strain gauges at trailing edge and segment boom
  - Driver motor angles

Source: Design and simulation of the rotating test rig in the INDUFLAP project, DTU Vindenergi-E-0063(EN) December 2014

Autor: Pohl, Martin (DLR-FA)



Flexible trailing edge: Segment demonstrator design

- Design of a trailing edge for experiments in rotation with wind flow
- 2m wingspan
- 1m chord length (1:2 scale) compared to concept demonstrator to fit rotating test bed

Autor: Pohl, Martin (DLR-FA)

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Research Alliance Wind Energy

Flexible trailing edge: Segment demonstrator design

- Finished flexible trailing edge demonstrator
- Passive Segment

Autor: Pohl, Martin (DLR-FA)

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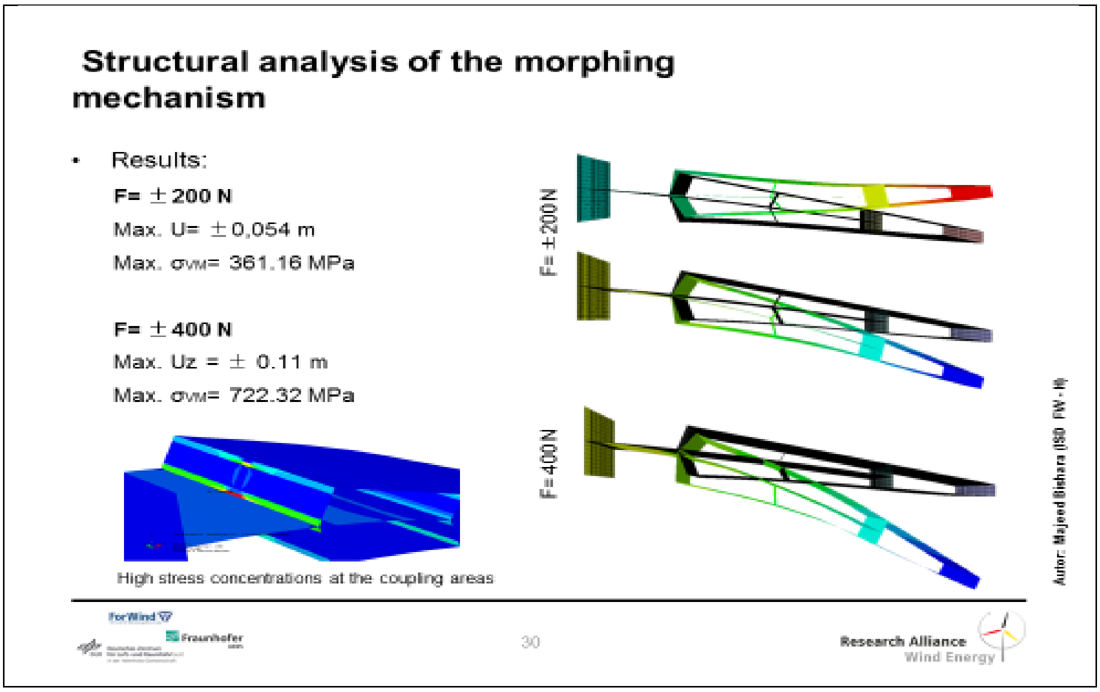


Structural analysis of the morphing mechanism

- Results:

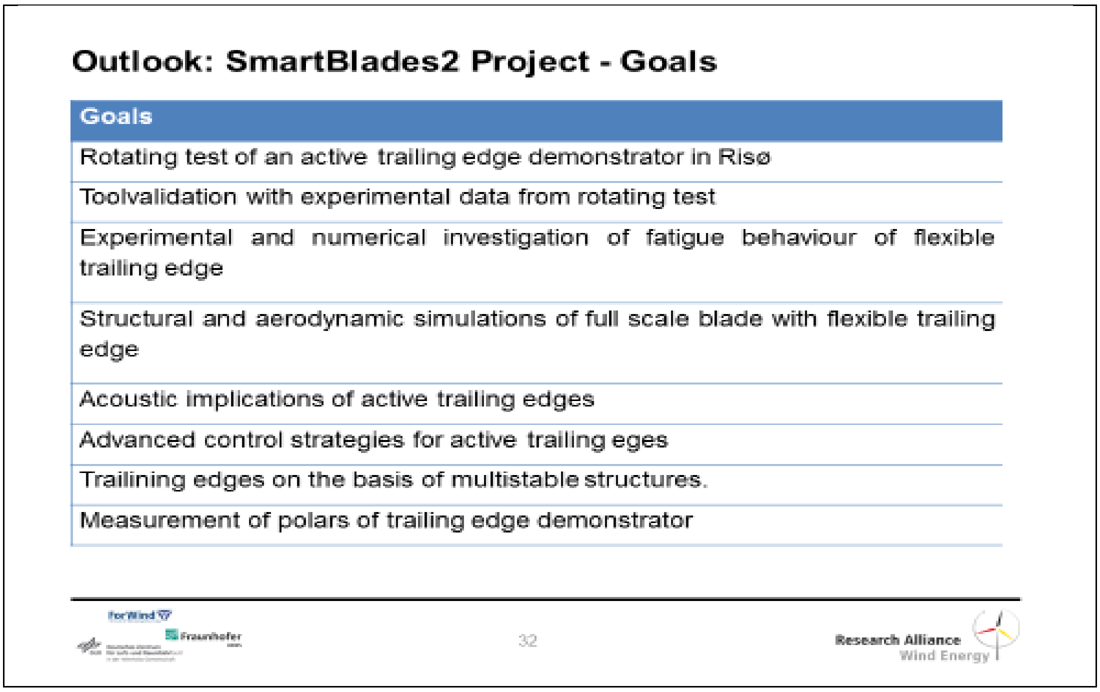
F= ±200 N
Max. U= ±0,054 m
Max. σ_{VM}= 361.16 MPa

F= ±400 N
Max. Uz = ± 0.11 m
Max. σ_{VM}= 722.32 MPa

High stress concentrations at the coupling areas

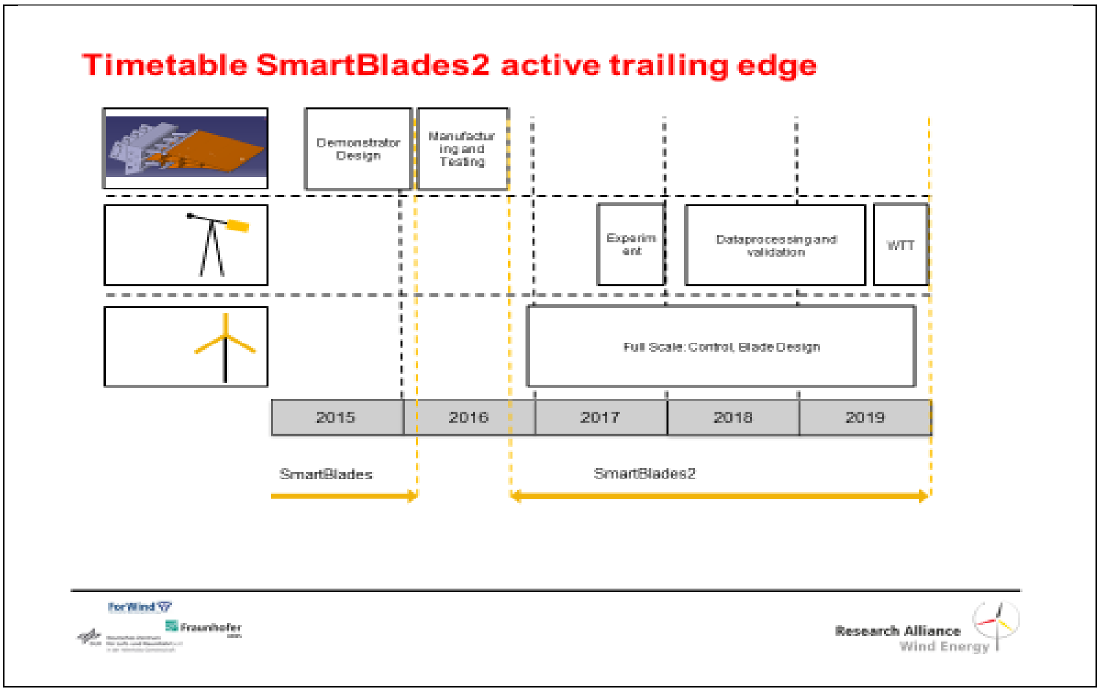
SmartBlades with Active Trailing Edges Publications:

Aerodynamics	J. Wild, A. Manso Jaume (2016): „*Design of Aerodynamic Target Shapes for an Adaptive Trailing Edge Flap*", SmartBlades Conference, Stade
Control	[1] R. Unguran; M.Kühn (2014); *Feedback Control of Blades Trailing Edge Flaps for Blade Root Mitigation*, Deutschen Strömungsmechanischen Arbeitsgemeinschaft Symposium (STAB)
Acoustics	[1] Wolff, T.; Ernst, B.; Seume, J.R. (2014): *Aerodynamic Behavior of an Airfoil with Morphing Trailing Edge for Wind Turbine Applications*, The Science of Making Torque from Wind 2014, 18-20 June 2014, Copenhagen, Denmark [2] Brand, C.R.; Seume, J.R. (2014): *Flaps for Wind Turbine Applications: First Results of the Experimental Investigations*, Wind Turbine Sound 2014 - EWEA Technology Workshop, Malmö, Schweden
Structure	M. Pohl, J. Riemenschneider (2017): *Konzipierung, Auslegung und Vermessung einer formveränderlichen Hinterkante für ein Windenergierotorblatt*, 4SmartS 2017, Braunschweig, Germany H.P. Monner; O. Huxdorf; M. Pohl; J. Riemenschneider; T. Homeyer; M. Hölling (2017) *Smart structures for wind energy turbines*. AIAA SciTech 2017, 9.-13. Jan. 2017, Grapevine, Texas, USA

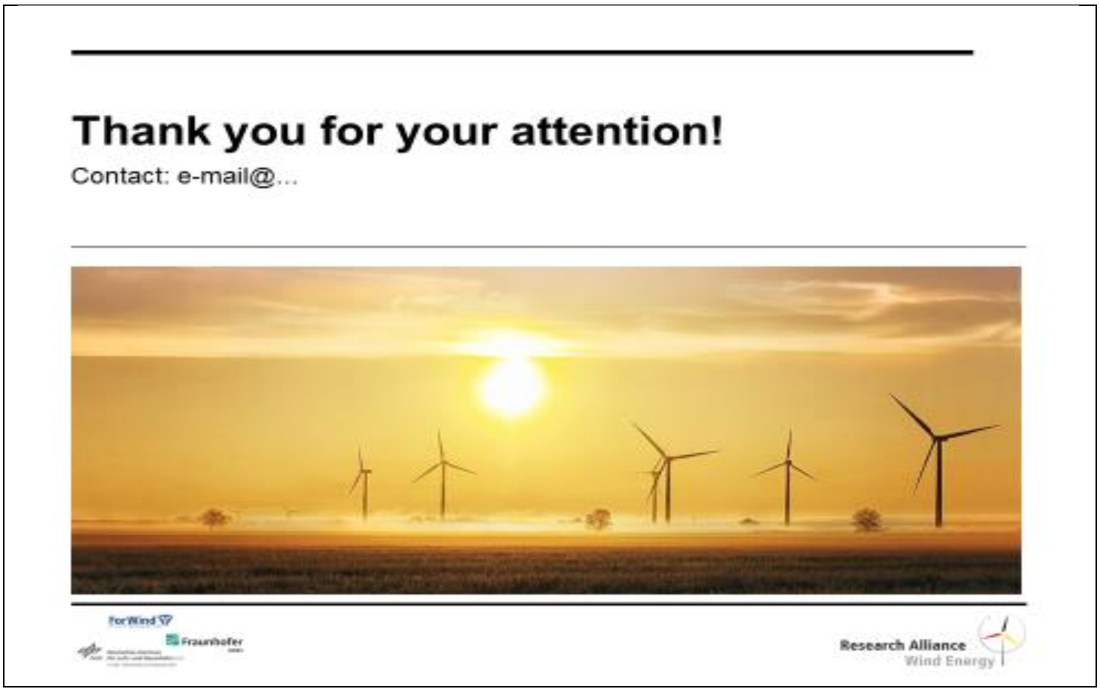


Outlook: SmartBlades2 Project - Goals

Goals
Rotating test of an active trailing edge demonstrator in Risø
Toolvalidation with experimental data from rotating test
Experimental and numerical investigation of fatigue behaviour of flexible trailing edge
Structural and aerodynamic simulations of full scale blade with flexible trailing edge
Acoustic implications of active trailing edges
Advanced control strategies for active trailing eges
Trailining edges on the basis of multistable structures.
Measurement of polars of trailing edge demonstrator



Timetable SmartBlades2 active trailing edge



Thank you for your attention!

Contact: e-mail@...

Experiences with passive and active controls in Aerospace, Automotive and wind field

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

SEAPOWER scrl
Consorzio con l'Università di Napoli Federico II

Università degli Studi di Napoli Federico II

DIPARTIMENTO DI INGEGNERIA INDUSTRIALE

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Consortium with University of Naples Federico II

We are an applied research group made by 12 researchers and we mainly work in two different fields:

1. Small/Medium vertical and horizontal axis wind turbines
2. Marine currents (vertical and horizontal axis hydro turbine) and wave energy converters

From the Academia to the real world: technology transfer through Spin-off companies born out of the ADAG applied research group

SEAPOWER scrl
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Public/private non profit consortium for renewable energy
www.seapowerscrl.com

In the field from more than 25 years!!

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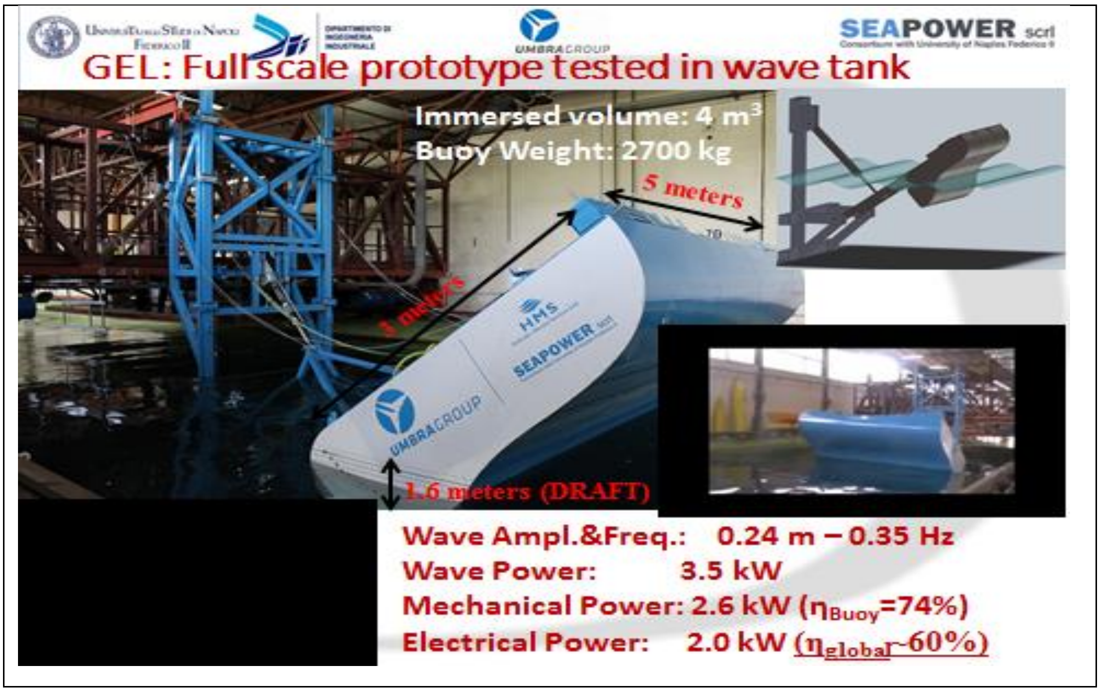
OCEAN ENERGY: Projects and Real Prototypes

RIVER POWER(2010)

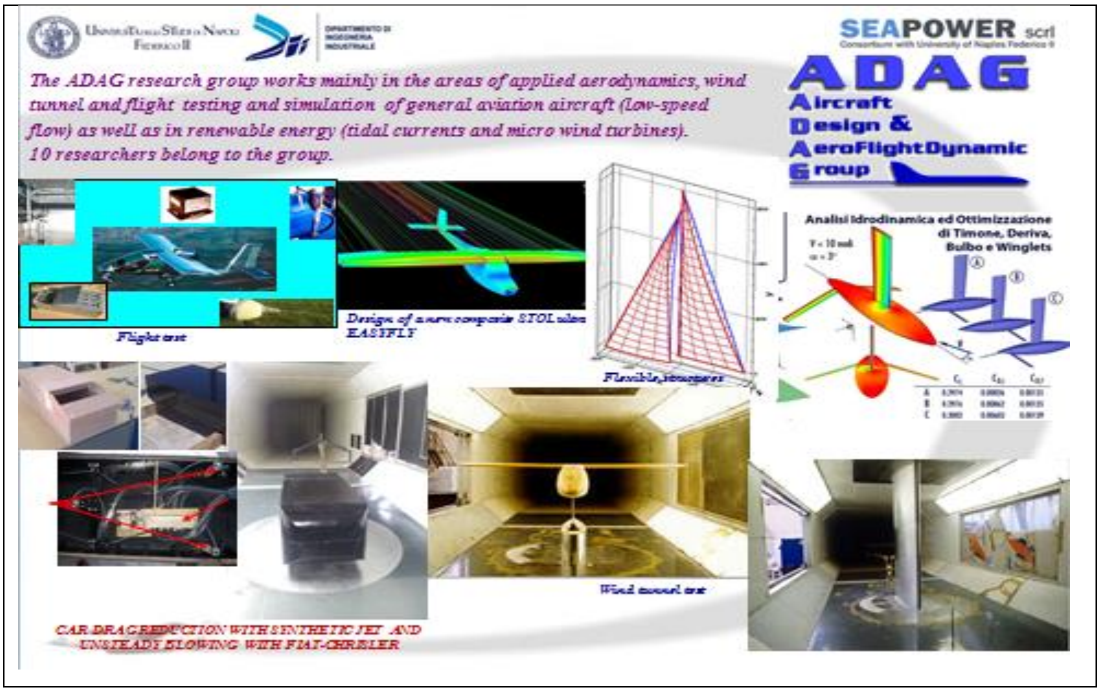
Kobold (1998)

GEM(2005-)



GEL: Full scale prototype tested in wave tank

Wave Ampl.&Freq.: 0.24 m – 0.35 Hz
Wave Power: 3.5 kW
Mechanical Power: 2.6 kW (η_{Buoy}=74%)
Electrical Power: 2.0 kW (η_{global}~60%)



The ADAG research group works mainly in the areas of applied aerodynamics, wind tunnel and flight testing and simulation of general aviation aircraft (low-speed flow) as well as in renewable energy (tidal currents and micro wind turbines). 10 researchers belong to the group.

ADAG
Aircraft
Design &
AeroFlightDynamic
Group

CAR DRAG REDUCTION WITH SYNTHETIC JET AND UNSTEADY BLOWING WITH FIAT-CHRISLER

SEAPOWER scrl

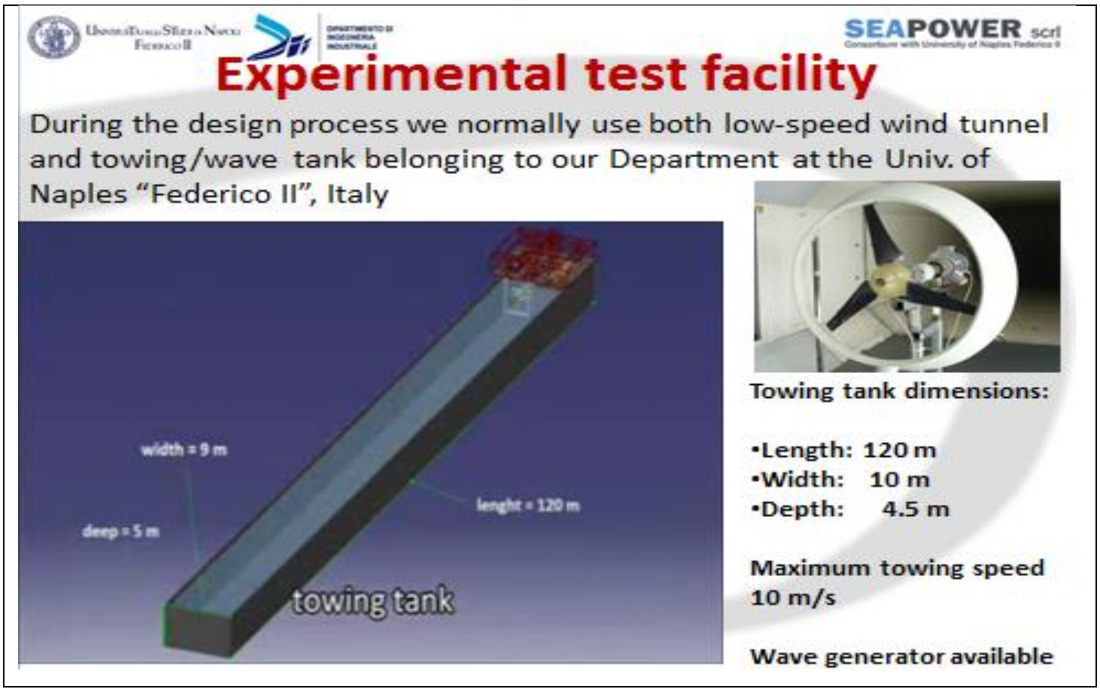
We mange the main low speed wind tunnel

Wind tunnel test

Main characteristics :

Test section dimensions: 2.0 m x 1.4 m
Maximum speed: 150 Km/h (42 m/s)
Turbulence level: 0.1%

ACTIVE FLOW CONTROL



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Experimental test facility

During the design process we normally use both low-speed wind tunnel and towing/wave tank belonging to our Department at the Univ. of Naples "Federico II", Italy

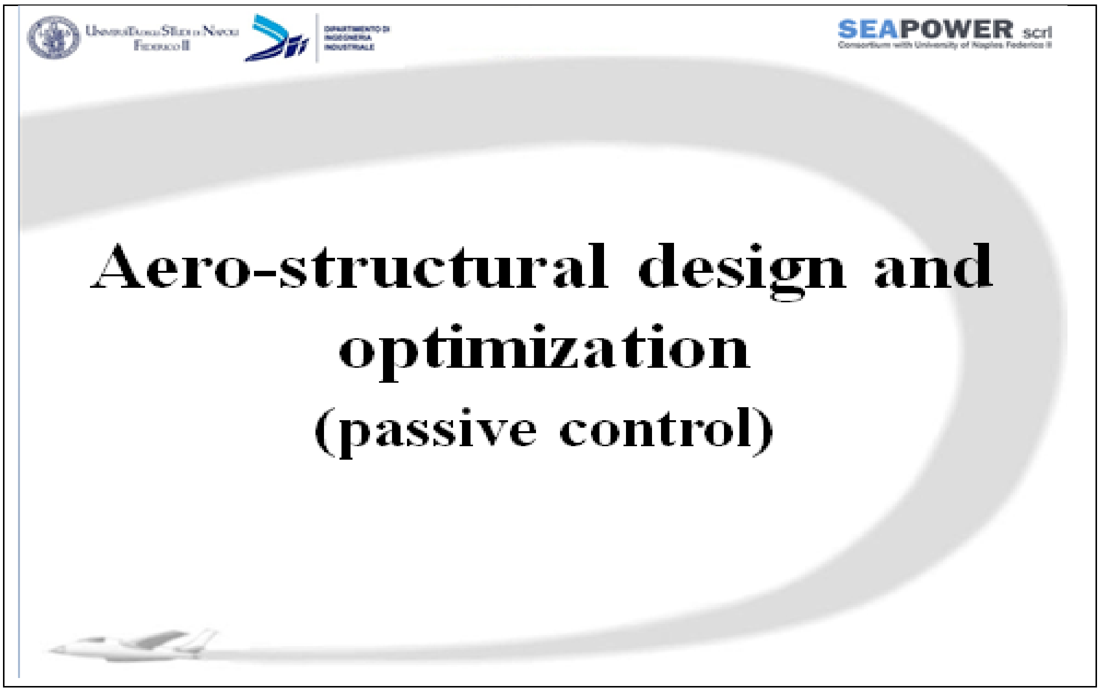
Towing tank dimensions:

- **Length: 120 m**
- **Width: 10 m**
- **Depth: 4.5 m**

Maximum towing speed 10 m/s

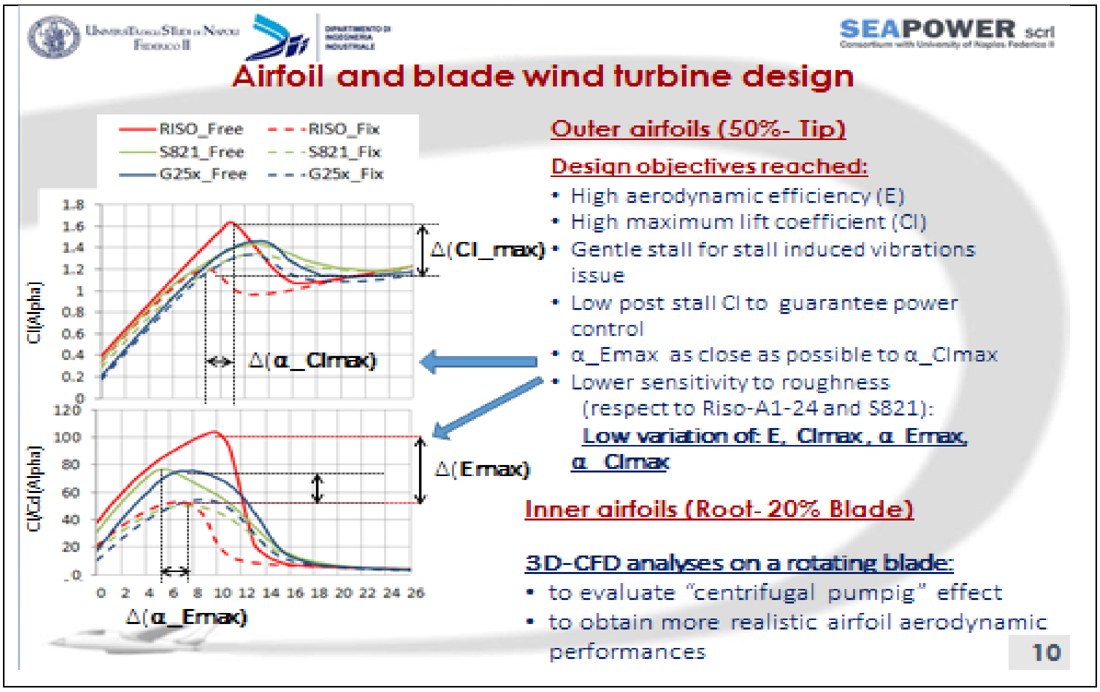
Wave generator available

Projects developed in mini-wind turbines field



Aero-structural design and optimization

(passive control)



Airfoil and blade wind turbine design

Outer airfoils (50%- Tip)

Design objectives reached:

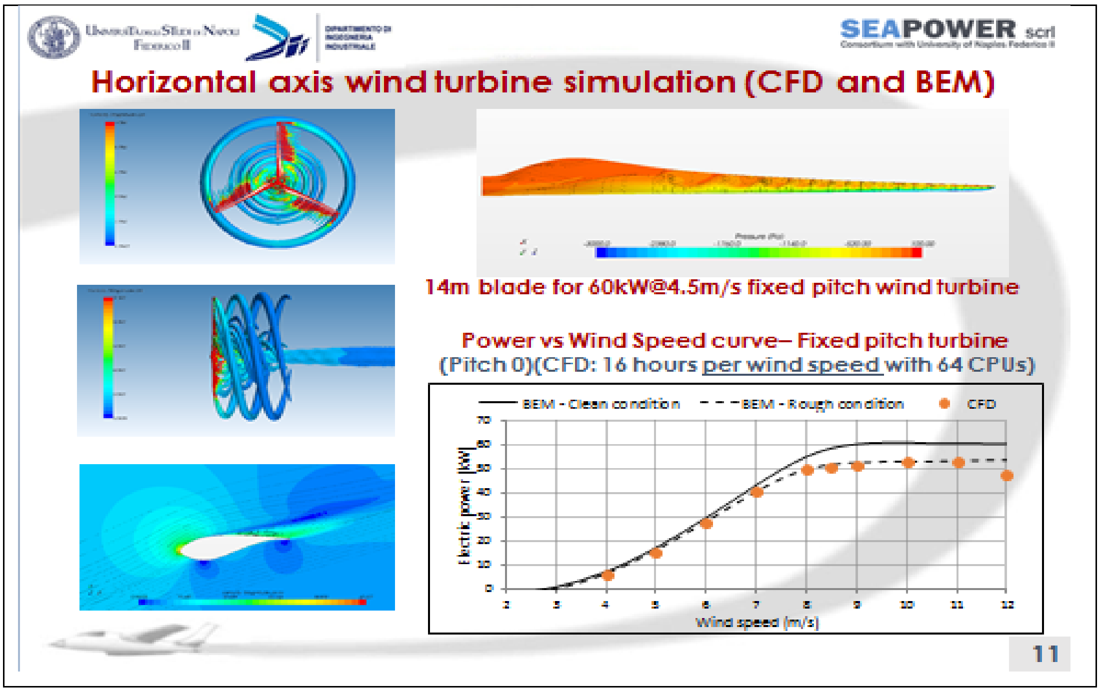
- High aerodynamic efficiency (E)
- High maximum lift coefficient (Cl)
- Gentle stall for stall induced vibrations issue
- Low post stall Cl to guarantee power control
- α_Emax as close as possible to α_Clmax
- Lower sensitivity to roughness (respect to Riso-A1-24 and S821): **Low variation of: E, Clmax, α_Emax, α_Clmax**

Inner airfoils (Root- 20% Blade)

3D-CFD analyses on a rotating blade:

- to evaluate "centrifugal pumpig" effect
- to obtain more realistic airfoil aerodynamic performances

10



Horizontal axis wind turbine simulation (CFD and BEM)

14m blade for 60kW@4.5m/s fixed pitch wind turbine

Power vs Wind Speed curve– Fixed pitch turbine (Pitch 0)(CFD: 16 hours per wind speed with 64 CPUs)

11

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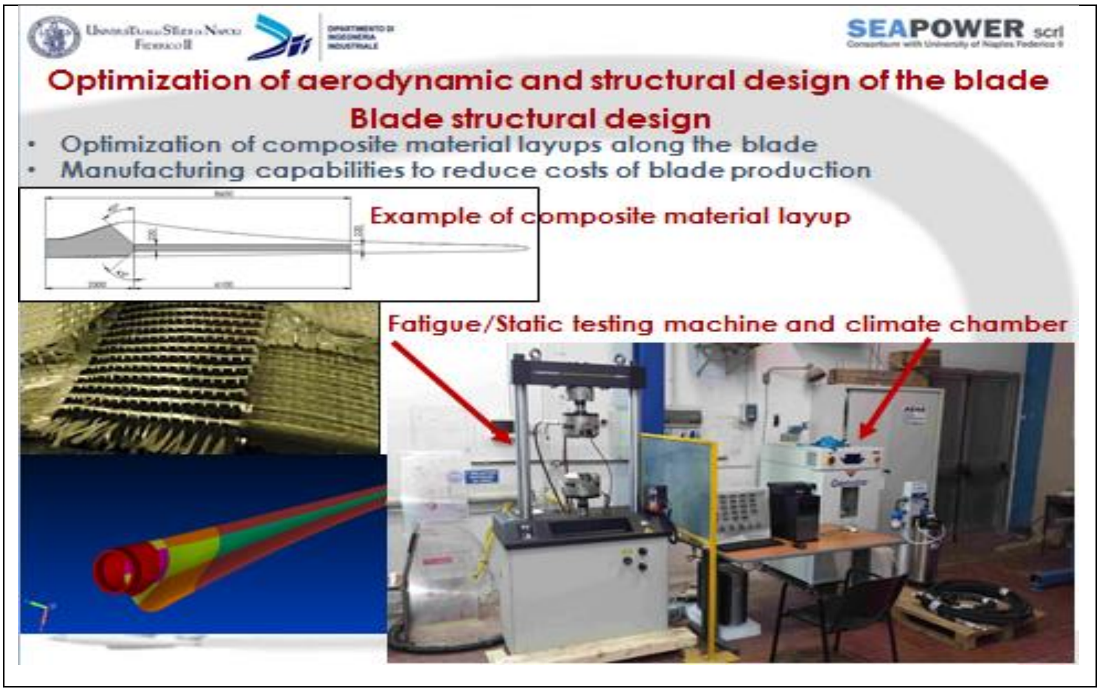
LOW WIND SPEED 60 kW Wind Turbine: SIMPLY 60

14 m blade (about same cost of 9 m blade!!)

Nacelle (reduction of assembling time of more than 50%)

12



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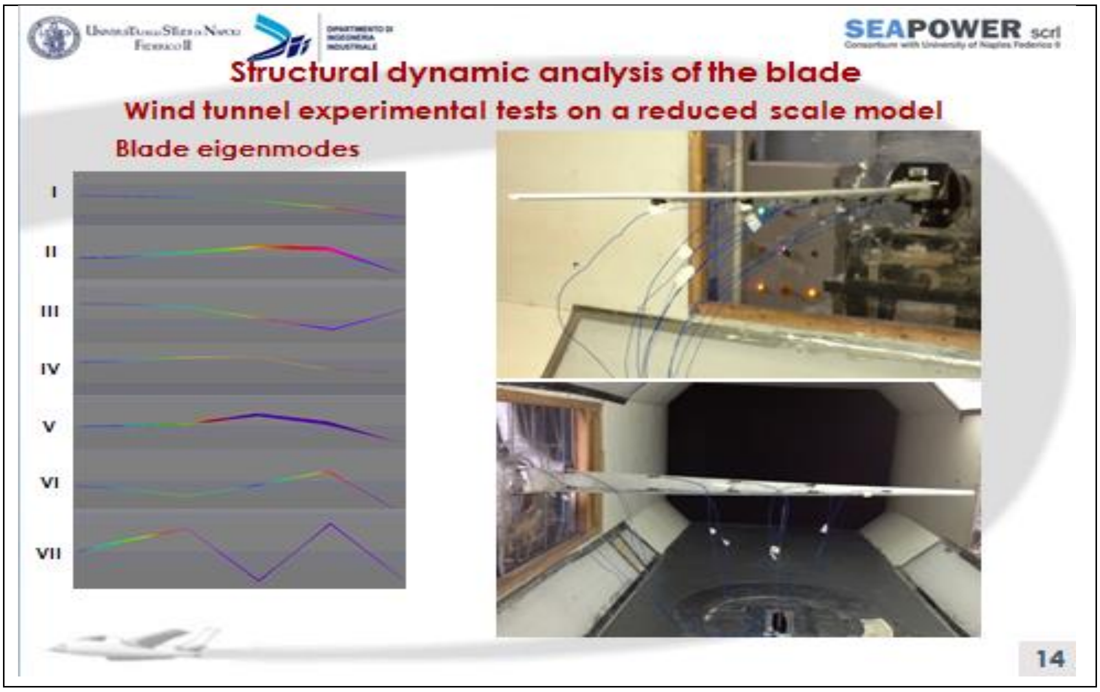
Optimization of aerodynamic and structural design of the blade

Blade structural design

- Optimization of composite material layups along the blade
- Manufacturing capabilities to reduce costs of blade production

Example of composite material layup

Fatigue/Static testing machine and climate chamber



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Structural dynamic analysis of the blade

Wind tunnel experimental tests on a reduced scale model

Blade eigenmodes

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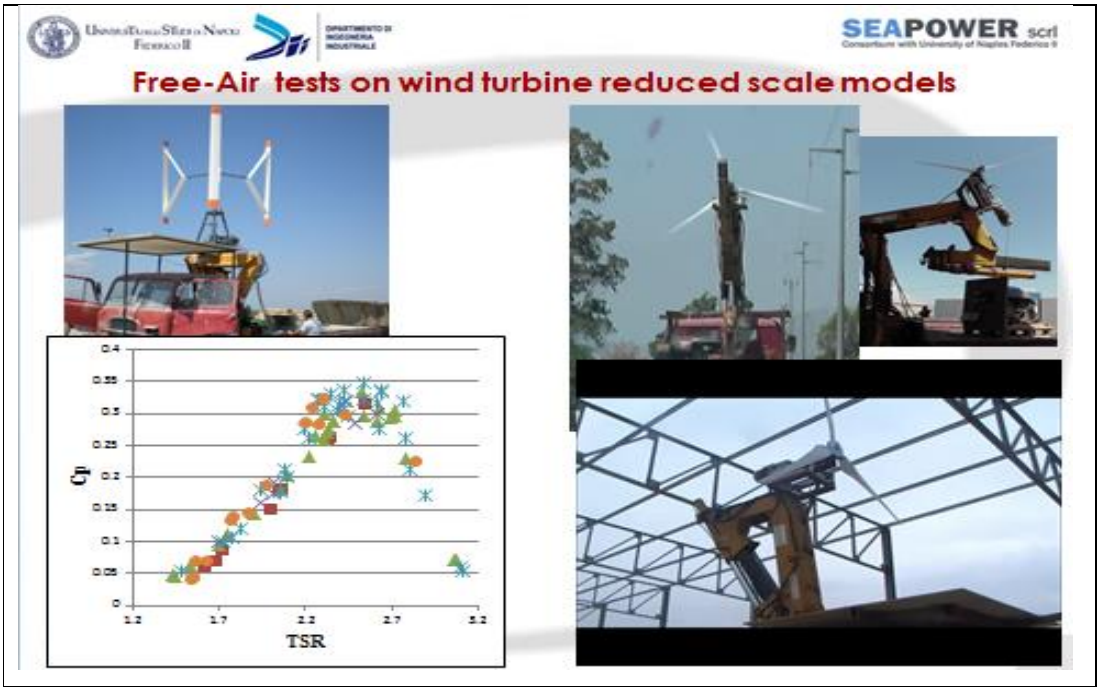
Free air test: wind tunnel blockage correction

Wind tunnel test section area = 2.8 sq m
Rotor area = .28 sq m



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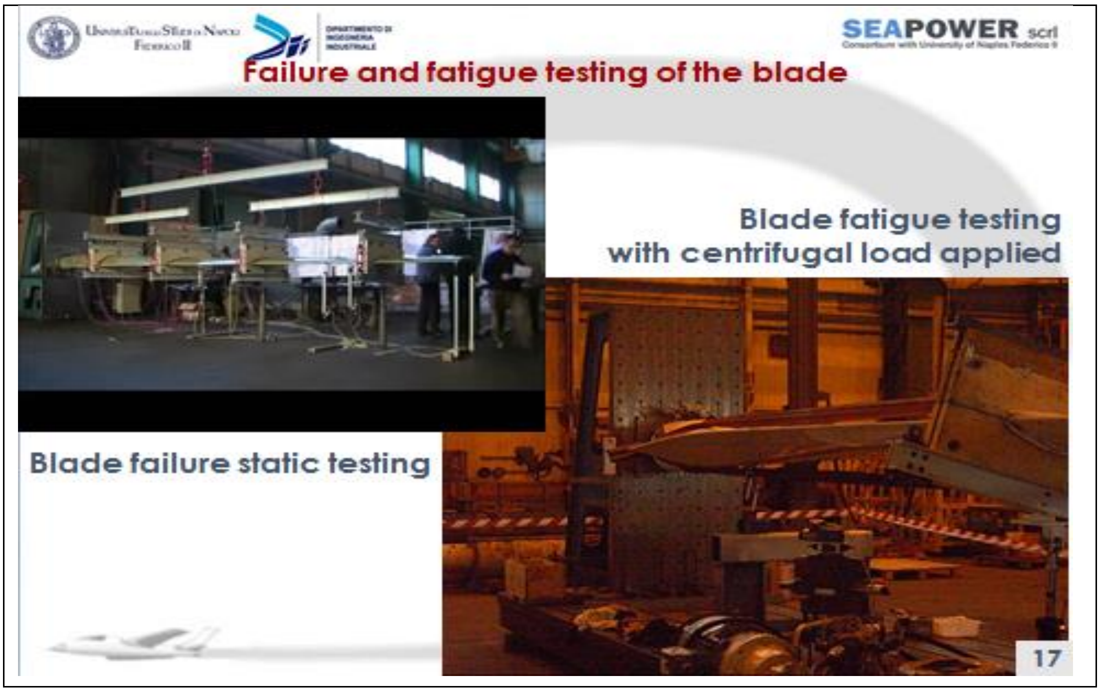
Free-Air tests on wind turbine reduced scale models



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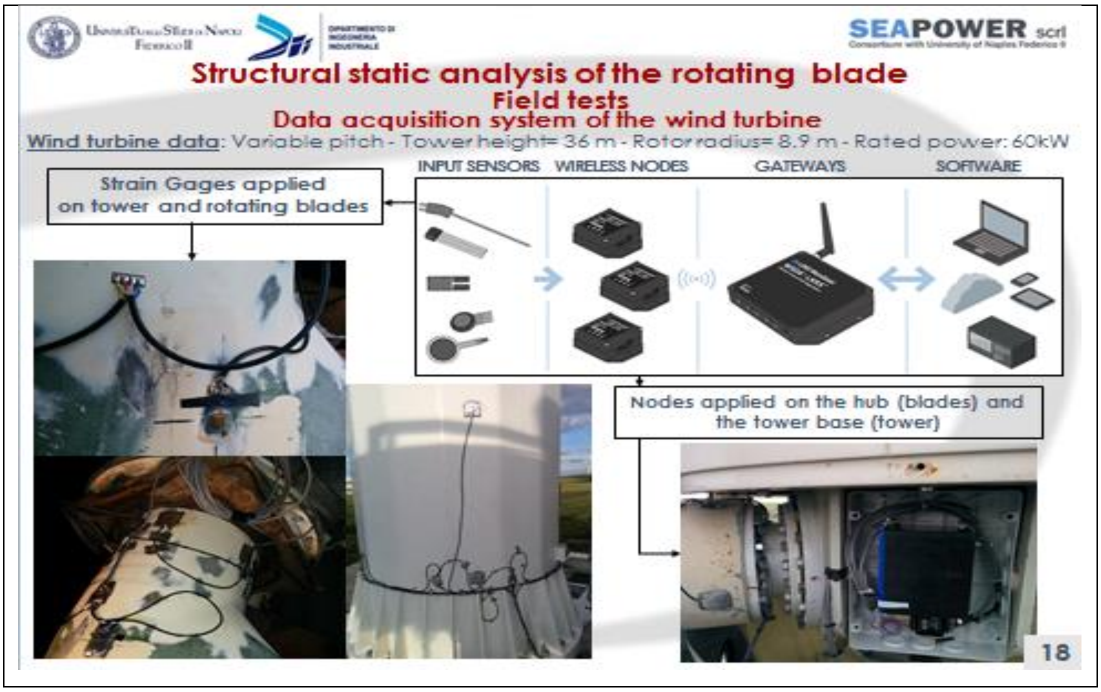
Failure and fatigue testing of the blade

Blade fatigue testing
with centrifugal load applied

Blade failure static testing



Structural static analysis of the rotating blade

Field tests

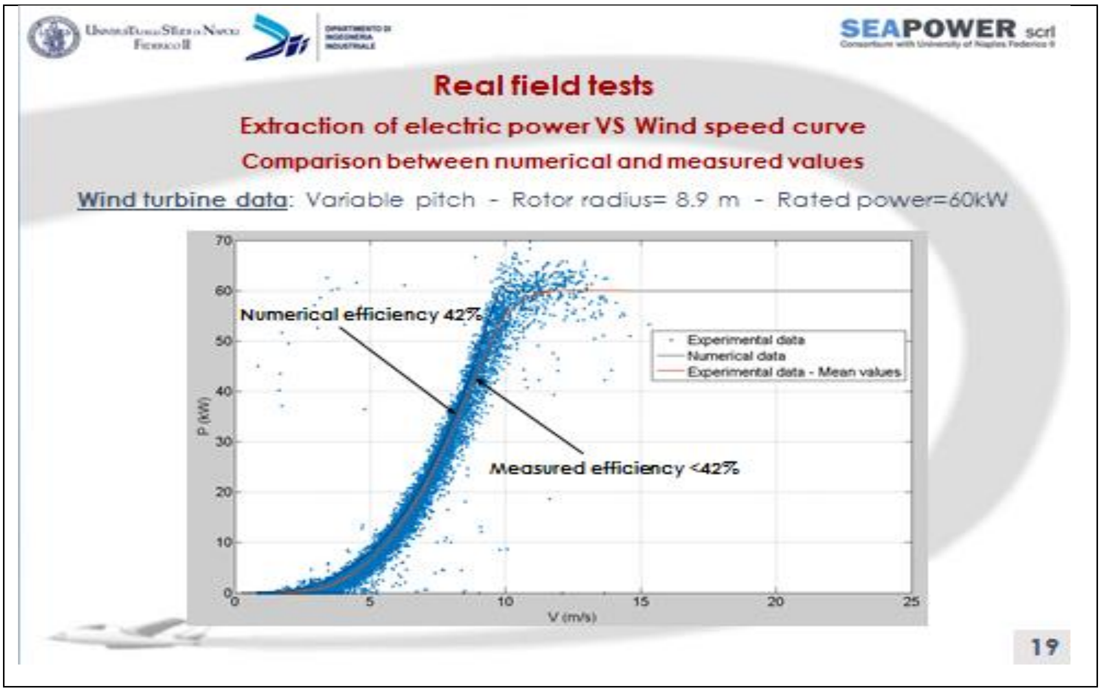
Data acquisition system of the wind turbine

Wind turbine data: Variable pitch - Tower height= 36 m - Rotor radius= 8.9 m - Rated power: 60kW

INPUT SENSORS WIRELESS NODES GATEWAYS SOFTWARE

Strain Gages applied on tower and rotating blades

Nodes applied on the hub (blades) and the tower base (tower)

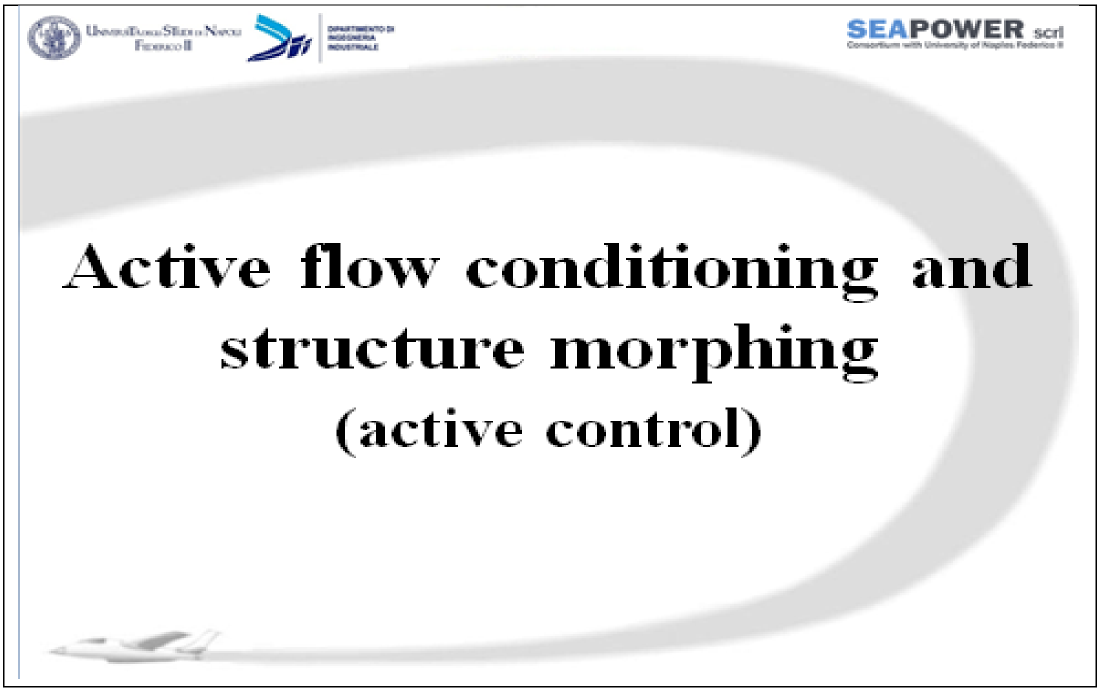


Real field tests

Extraction of electric power VS Wind speed curve

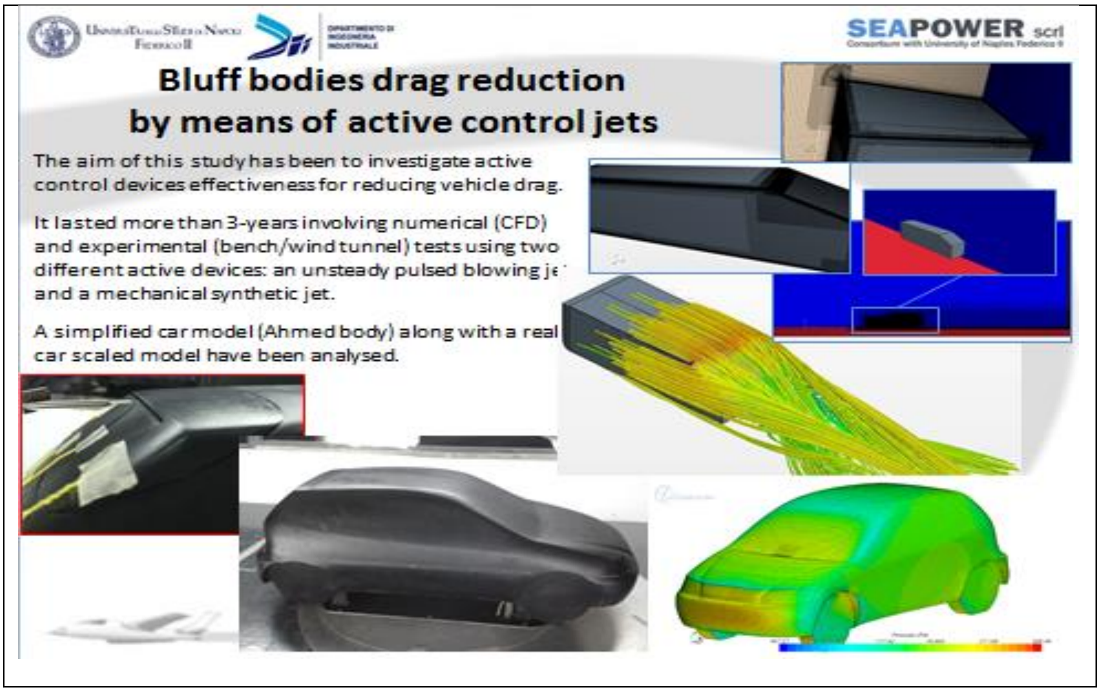
Comparison between numerical and measured values

Wind turbine data: Variable pitch - Rotor radius= 8.9 m - Rated power=60kW



Active flow conditioning and structure morphing

(active control)

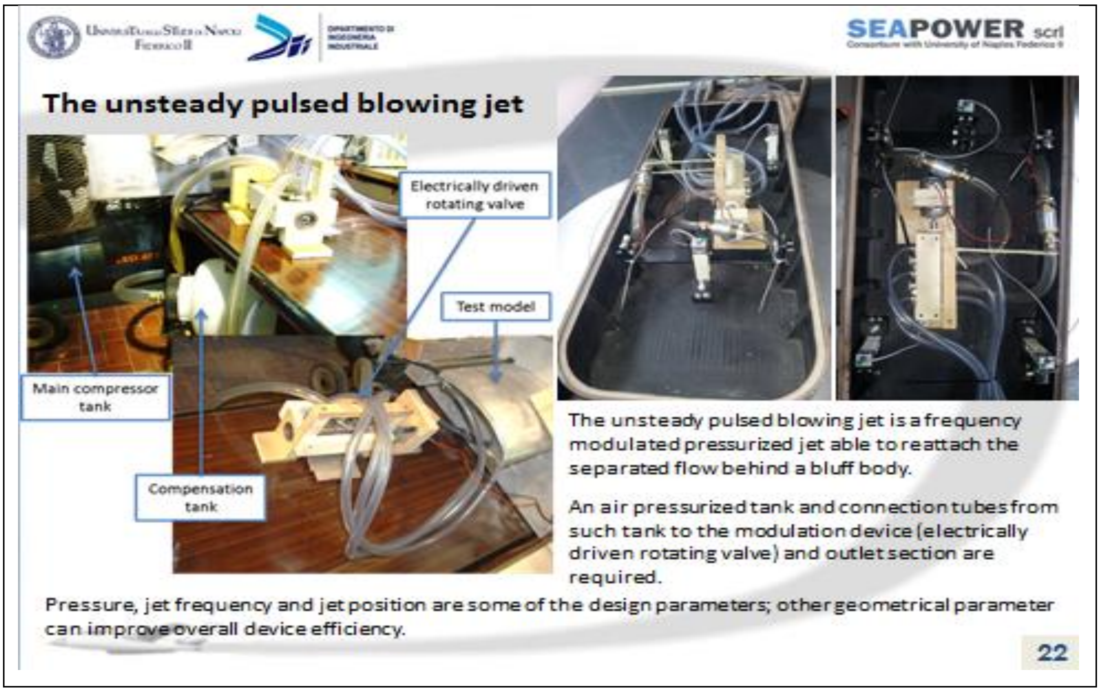


Bluff bodies drag reduction by means of active control jets

The aim of this study has been to investigate active control devices effectiveness for reducing vehicle drag.

It lasted more than 3-years involving numerical (CFD) and experimental (bench/wind tunnel) tests using two different active devices: an unsteady pulsed blowing je and a mechanical synthetic jet.

A simplified car model (Ahmed body) along with a real car scaled model have been analysed.



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The unsteady pulsed blowing jet

Electrically driven rotating valve

Test model

Main compressor tank

Compensation tank

The unsteady pulsed blowing jet is a frequency modulated pressurized jet able to reattach the separated flow behind a bluff body.

An air pressurized tank and connection tubes from such tank to the modulation device (electrically driven rotating valve) and outlet section are required.

Pressure, jet frequency and jet position are some of the design parameters; other geometrical parameter can improve overall device efficiency.

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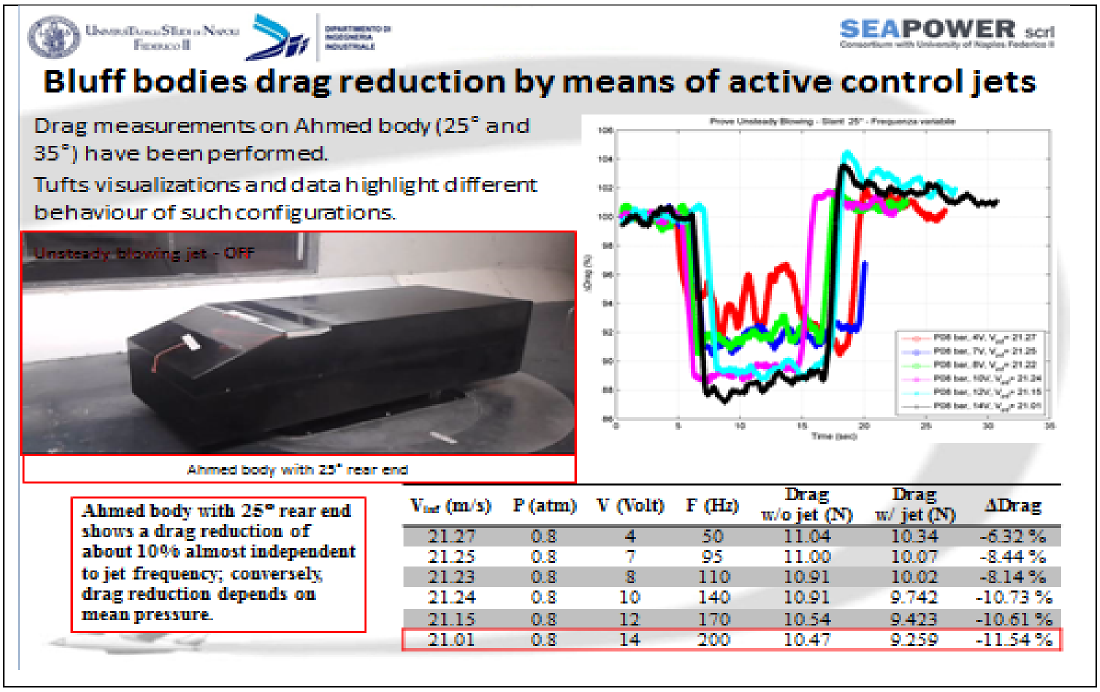
The mechanical synthetic jet

The mechanical synthetic jet is a synthethic jet type device made up of modified ICE driven by an electrical motor working similarly to the unsteady pulsed jets (in theory, with less power demand).

ICEs outlets can be directly connected to the jet outlet section and, in case of different ICEs phases, could generate particular span velocity distributions.

Jet frequency and velocity are not independent when the ICE dimensions are chosen. Jet position and ICE characteristics are crucial design parameters.



Bluff bodies drag reduction by means of active control jets

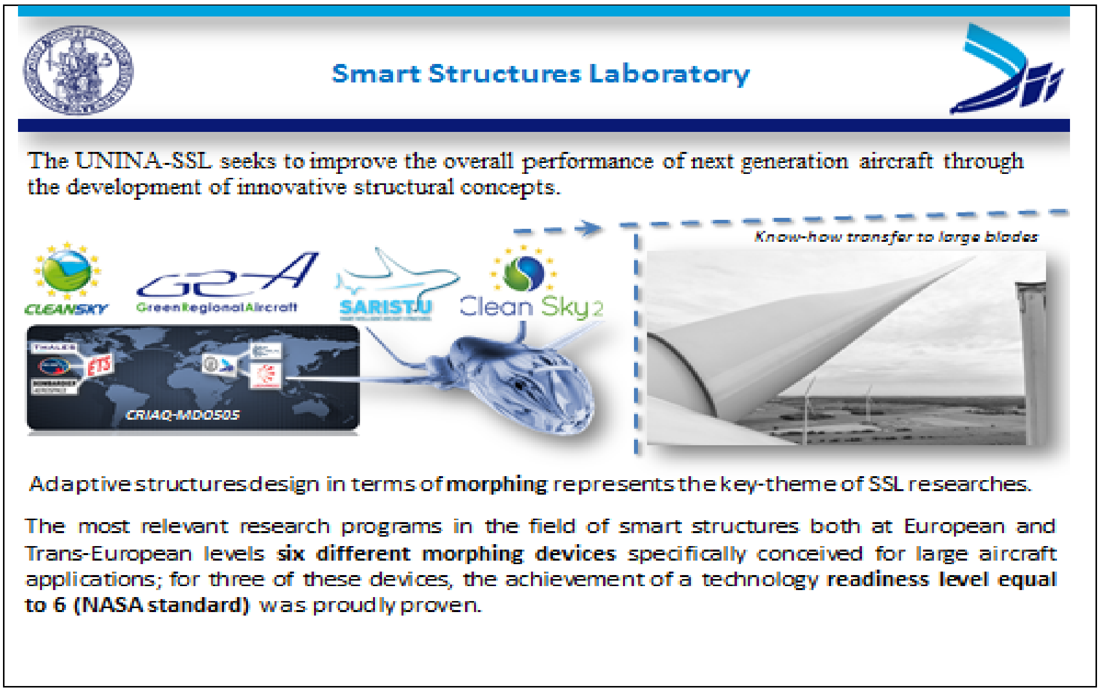
Drag measurements on Ahmed body (25° and 35°) have been performed.

Tufts visualizations and data highlight different behaviour of such configurations.

Ahmed body with 25° rear end

Ahmed body with 25° rear end shows a drag reduction of about 10% almost independent to jet frequency; conversely, drag reduction depends on mean pressure.

V_{inf} (m/s)	P (atm)	V (Volt)	F (Hz)	Drag w/o jet (N)	Drag w/ jet (N)	ΔDrag
21.27	0.8	4	50	11.04	10.34	-6.32 %
21.25	0.8	7	95	11.00	10.07	-8.44 %
21.23	0.8	8	110	10.91	10.02	-8.14 %
21.24	0.8	10	140	10.91	9.742	-10.73 %
21.15	0.8	12	170	10.54	9.423	-10.61 %
21.01	0.8	14	200	10.47	9.259	-11.54 %



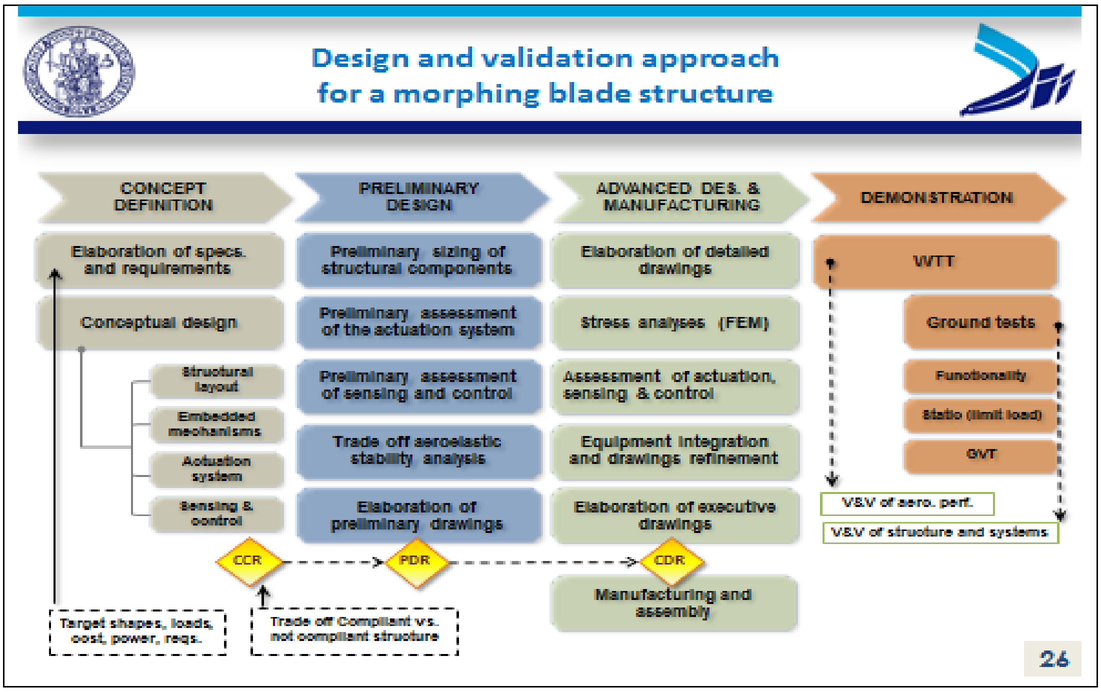
Smart Structures Laboratory

The UNINA-SSL seeks to improve the overall performance of next generation aircraft through the development of innovative structural concepts.

Know-how transfer to large blades

Adaptive structures design in terms of **morphing** represents the key-theme of SSL researches.

The most relevant research programs in the field of smart structures both at European and Trans-European levels **six different morphing devices** specifically conceived for large aircraft applications; for three of these devices, the achievement of a technology **readiness level equal to 6 (NASA standard)** was proudly proven.



Design and validation approach for a morphing blade structure

CONCEPT DEFINITION

Elaboration of specs. and requirements

Conceptual design

- Structural layout
- Embedded mechanisms
- Actuation system
- Sensing & control

Target shapes, loads, cost, power, reqs.

PRELIMINARY DESIGN

Preliminary sizing of structural components

Preliminary assessment of the actuation system

Preliminary assessment of sensing and control

Trade off aeroelastic stability analysis

Elaboration of preliminary drawings

Trade off Compliant vs. not compliant structure

ADVANCED DES. & MANUFACTURING

Elaboration of detailed drawings

Stress analyses (FEM)

Assessment of actuation, sensing & control

Equipment integration and drawings refinement

Elaboration of executive drawings

Manufacturing and assembly

DEMONSTRATION

WTT

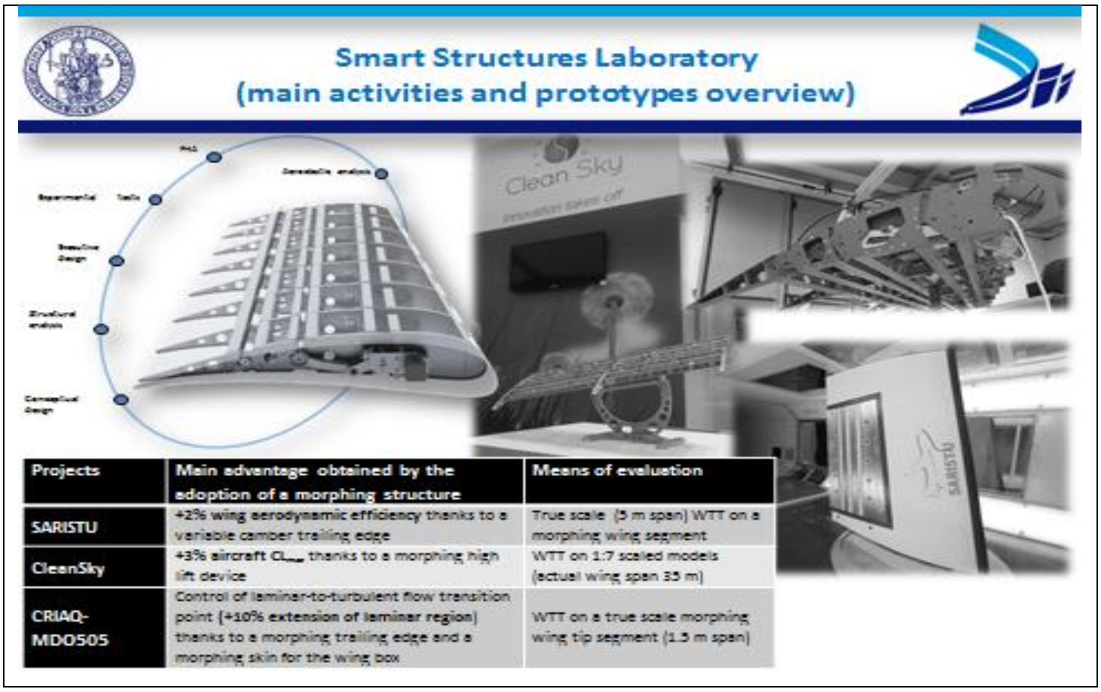
Ground tests

- Functionality
- Static (limit load)
- GVT

V&V of aero. perf.

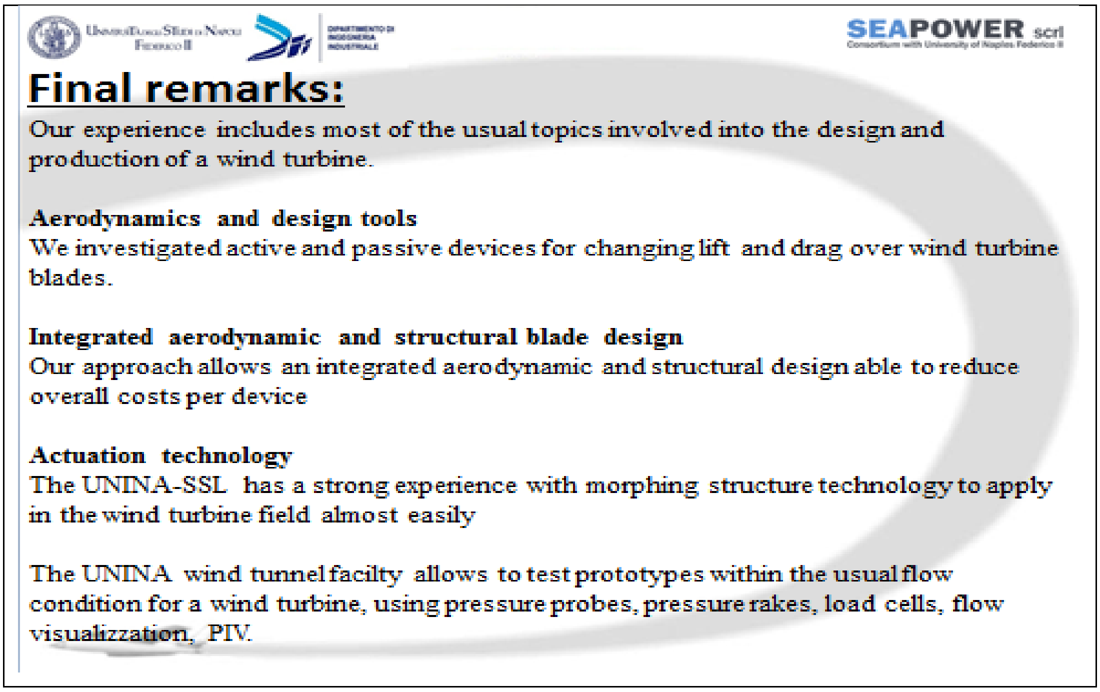
V&V of structure and systems

CCR → PDR → CDR



Smart Structures Laboratory (main activities and prototypes overview)

Projects	Main advantage obtained by the adoption of a morphing structure	Means of evaluation
SARISTU	+2% wing aerodynamic efficiency thanks to a variable camber trailing edge	True scale (5 m span) WTT on a morphing wing segment
CleanSky	+3% aircraft CL_{max} thanks to a morphing high lift device	WTT on 1:7 scaled models (actual wing span 35 m)
CRIAQ-MDO505	Control of laminar-to-turbulent flow transition point (+10% extension of laminar region) thanks to a morphing trailing edge and a morphing skin for the wing box	WTT on a true scale morphing wing tip segment (1.5 m span)



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Final remarks:

Our experience includes most of the usual topics involved into the design and production of a wind turbine.

Aerodynamics and design tools
We investigated active and passive devices for changing lift and drag over wind turbine blades.

Integrated aerodynamic and structural blade design
Our approach allows an integrated aerodynamic and structural design able to reduce overall costs per device

Actuation technology
The UNINA-SSL has a strong experience with morphing structure technology to apply in the wind turbine field almost easily

The UNINA wind tunnel facilty allows to test prototypes within the usual flow condition for a wind turbine, using pressure probes, pressure rakes, load cells, flow visualizzation, PIV.

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Pozzuoli Bay

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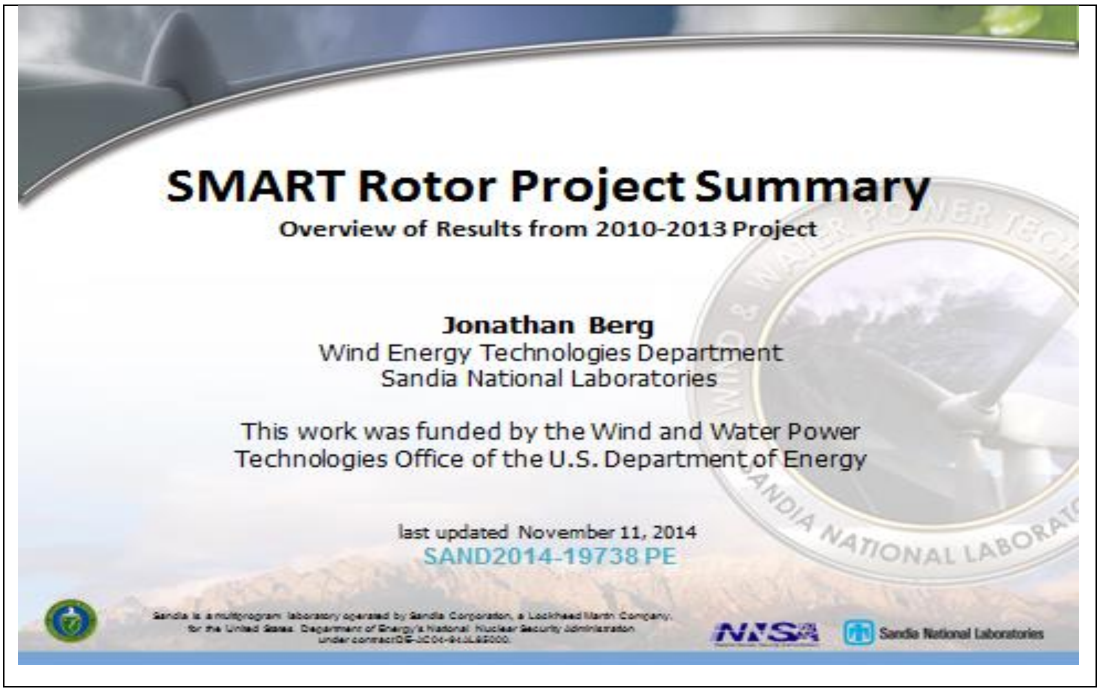
Thanks for the attention!



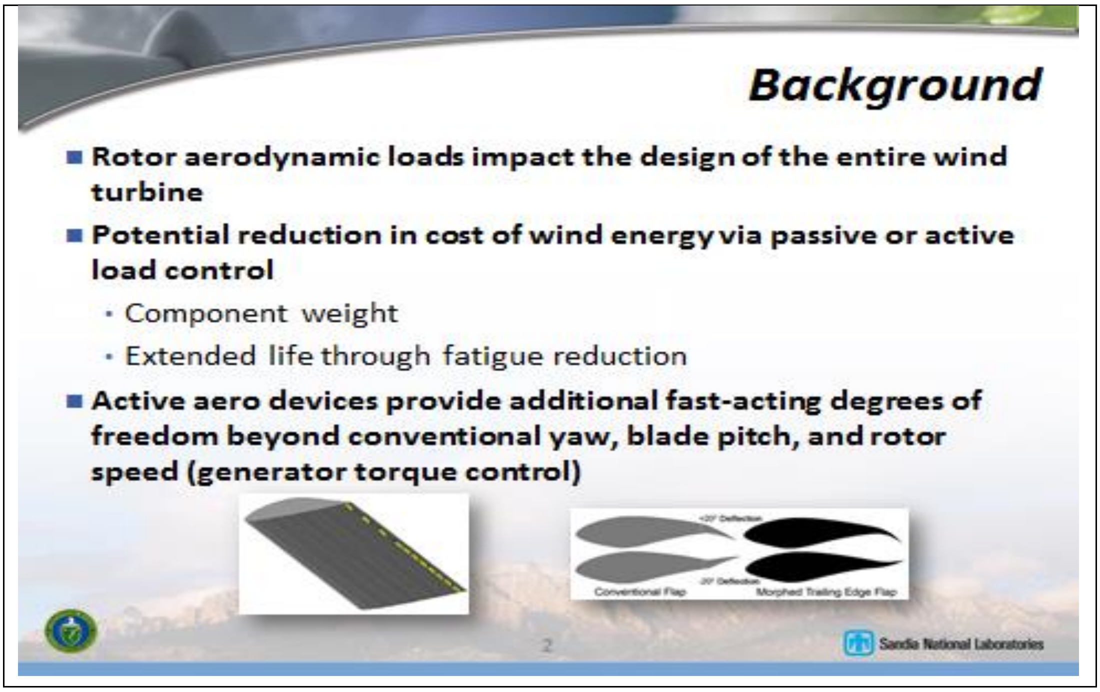
SMART Rotor Project Summary

Overview of Results from 2010-2013 Project

Jonathan Berg
Wind Energy Technologies Department
Sandia National Laboratories

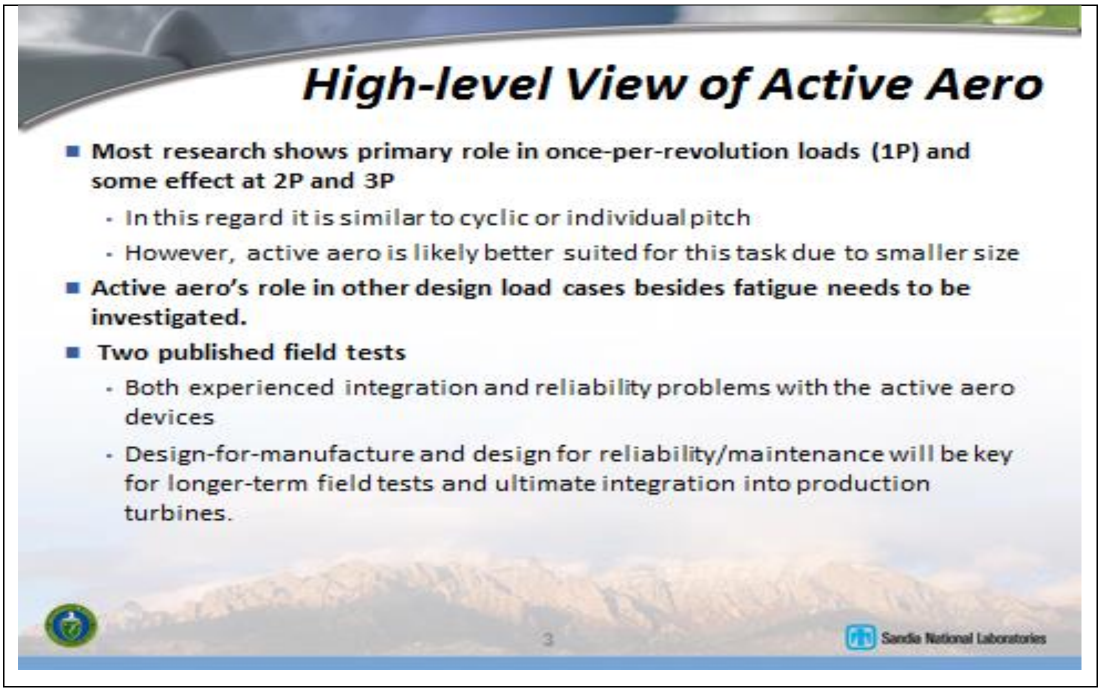
This work was funded by the Wind and Water Power
Technologies Office of the U.S. Department of Energy

last updated November 11, 2014
SAND2014-19738 PE



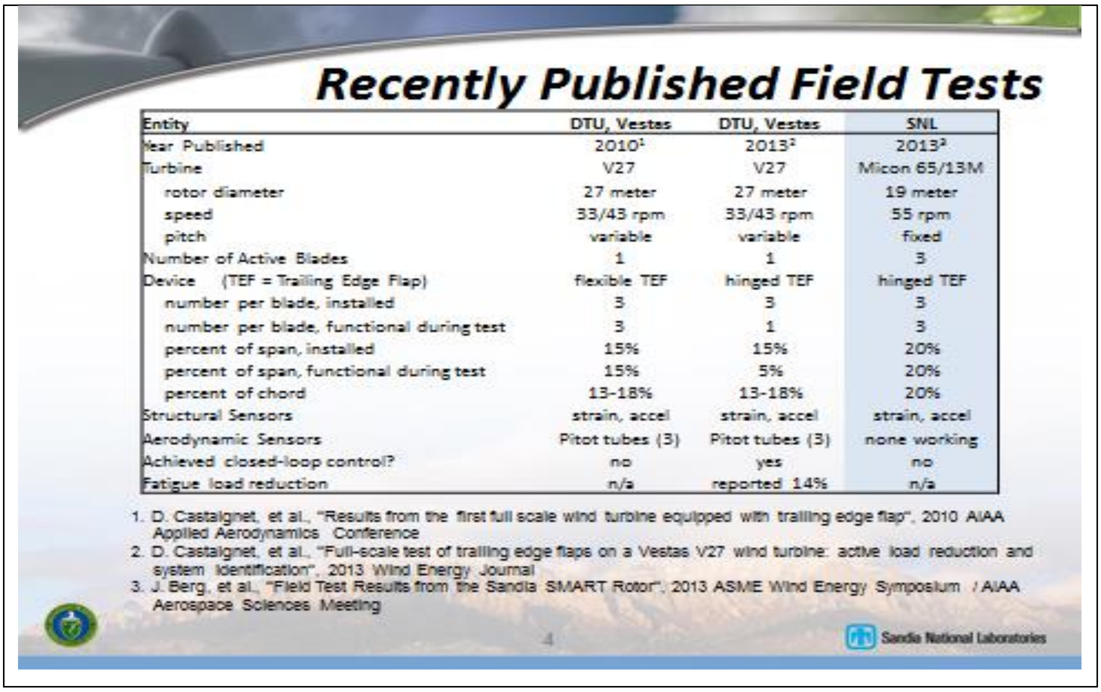
Background

- **Rotor aerodynamic loads impact the design of the entire wind turbine**
- **Potential reduction in cost of wind energy via passive or active load control**
  - Component weight
  - Extended life through fatigue reduction
- **Active aero devices provide additional fast-acting degrees of freedom beyond conventional yaw, blade pitch, and rotor speed (generator torque control)**



High-level View of Active Aero

- Most research shows primary role in once-per-revolution loads (1P) and some effect at 2P and 3P
  - In this regard it is similar to cyclic or individual pitch
  - However, active aero is likely better suited for this task due to smaller size
- Active aero's role in other design load cases besides fatigue needs to be investigated.
- Two published field tests
  - Both experienced integration and reliability problems with the active aero devices
  - Design-for-manufacture and design for reliability/maintenance will be key for longer-term field tests and ultimate integration into production turbines.



Recently Published Field Tests

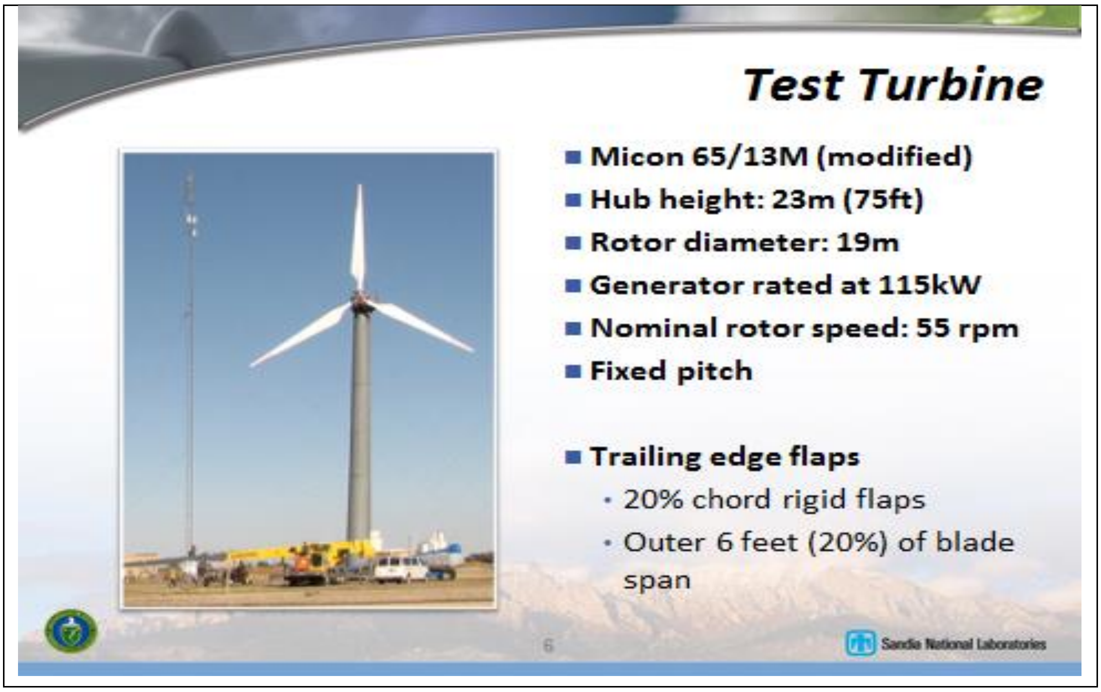
Entity	DTU, Vestas	DTU, Vestas	SNL
Year Published	2010[1]	2013[2]	2013[3]
Turbine	V27	V27	Micon 65/13M
rotor diameter	27 meter	27 meter	19 meter
speed	33/43 rpm	33/43 rpm	55 rpm
pitch	variable	variable	fixed
Number of Active Blades	1	1	3
Device (TEF = Trailing Edge Flap)	flexible TEF	hinged TEF	hinged TEF
number per blade, installed	3	3	3
number per blade, functional during test	3	1	3
percent of span, installed	15%	15%	20%
percent of span, functional during test	15%	5%	20%
percent of chord	13-18%	13-18%	20%
Structural Sensors	strain, accel	strain, accel	strain, accel
Aerodynamic Sensors	Pitot tubes (3)	Pitot tubes (3)	none working
Achieved closed-loop control?	no	yes	no
Fatigue load reduction	n/a	reported 14%	n/a

1. D. Castaignet, et al., "Results from the first full scale wind turbine equipped with trailing edge flap", 2010 AIAA Applied Aerodynamics Conference
2. D. Castaignet, et al., "Full-scale test of trailing edge flaps on a Vestas V27 wind turbine: active load reduction and system identification", 2013 Wind Energy Journal
3. J. Berg, et al., "Field Test Results from the Sandia SMART Rotor", 2013 ASME Wind Energy Symposium / AIAA Aerospace Sciences Meeting

Project Overview

SMART rotor project goals
- Evaluate adequacy of simulation tools for active aerodynamic load control
- Gain insight into the challenges of integration

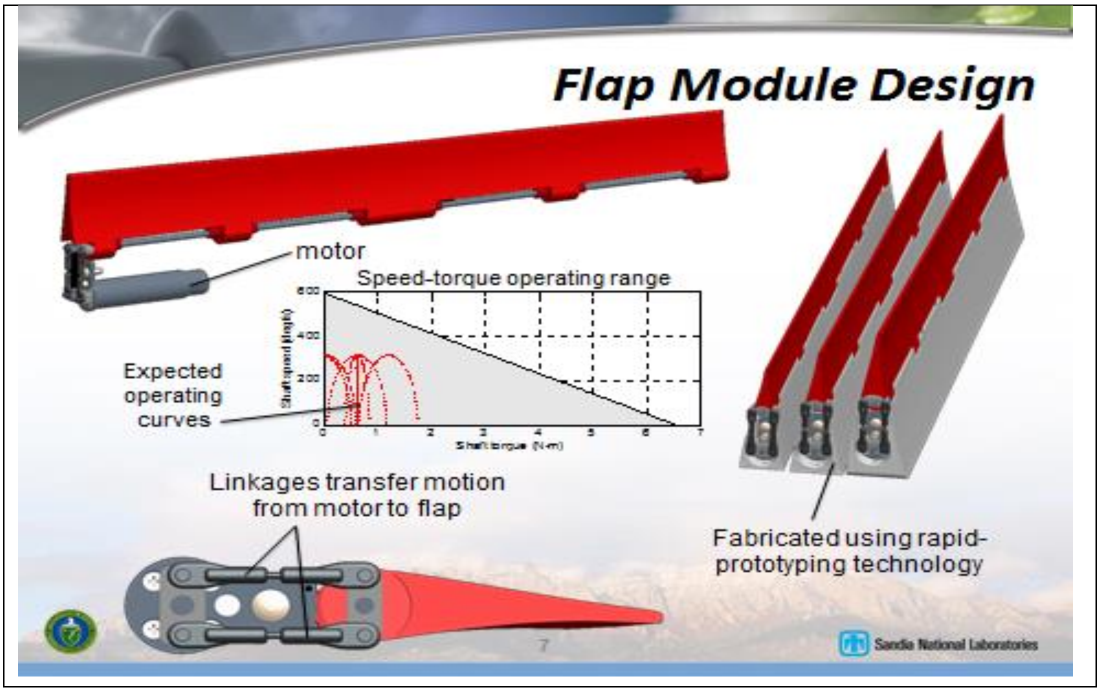
Conventional hinged flaps chosen
- expectation of good aerodynamic control authority
- relative simplicity of integration
- but not necessary the ideal actuator for active aero



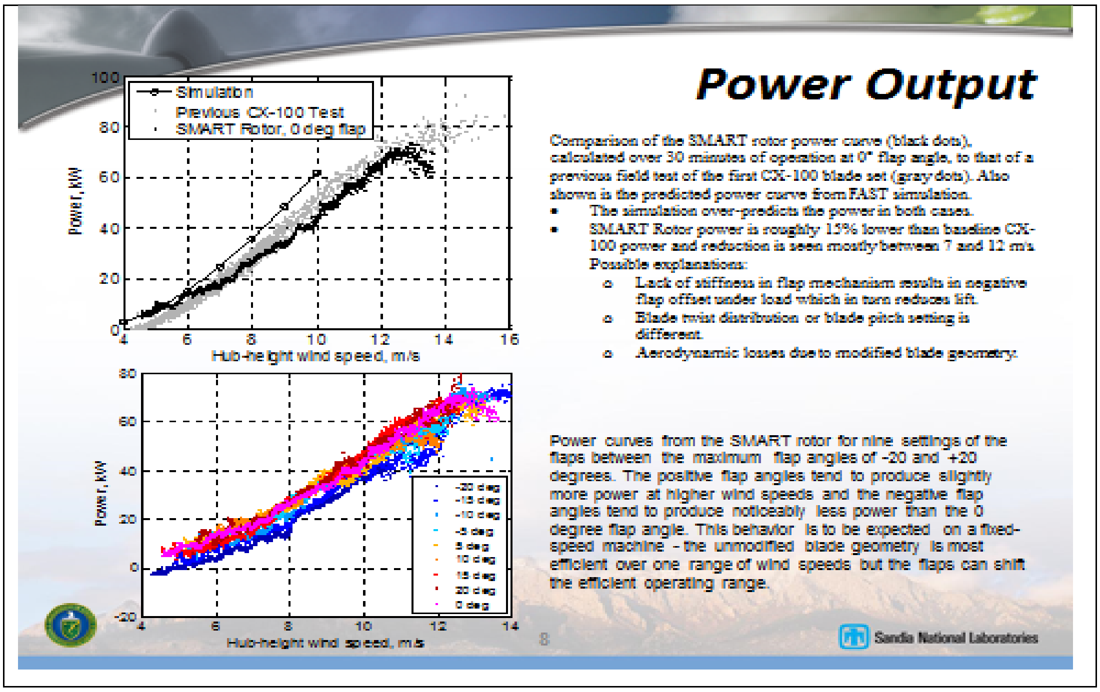
Test Turbine

- Micon 65/13M (modified)
- Hub height: 23m (75ft)
- Rotor diameter: 19m
- Generator rated at 115kW
- Nominal rotor speed: 55 rpm
- Fixed pitch

- Trailing edge flaps
  - 20% chord rigid flaps
  - Outer 6 feet (20%) of blade span



Flap Module Design

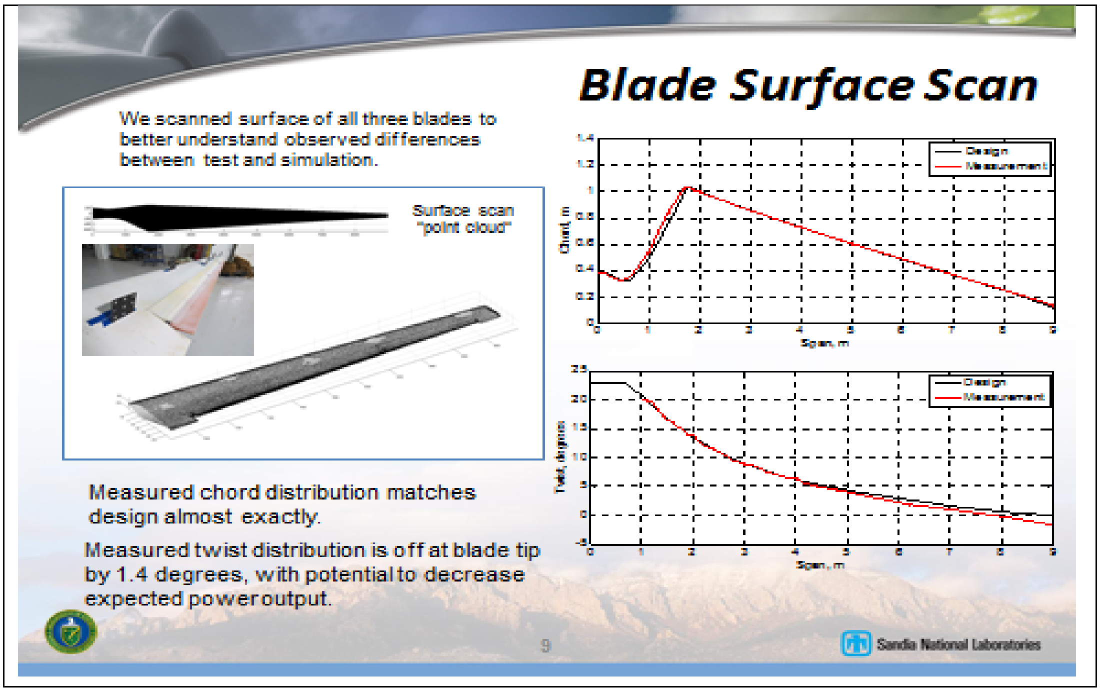


Power Output

Comparison of the SMART rotor power curve (black dots), calculated over 30 minutes of operation at 0° flap angle, to that of a previous field test of the first CX-100 blade set (gray dots). Also shown is the predicted power curve from FAST simulation.

- The simulation over-predicts the power in both cases.
- SMART Rotor power is roughly 15% lower than baseline CX-100 power and reduction is seen mostly between 7 and 12 m/s. Possible explanations:
  - Lack of stiffness in flap mechanism results in negative flap offset under load which in turn reduces lift.
  - Blade twist distribution or blade pitch setting is different.
  - Aerodynamic losses due to modified blade geometry.

Power curves from the SMART rotor for nine settings of the flaps between the maximum flap angles of -20 and +20 degrees. The positive flap angles tend to produce slightly more power at higher wind speeds and the negative flap angles tend to produce noticeably less power than the 0 degree flap angle. This behavior is to be expected on a fixed-speed machine - the unmodified blade geometry is most efficient over one range of wind speeds but the flaps can shift the efficient operating range.



Blade Surface Scan

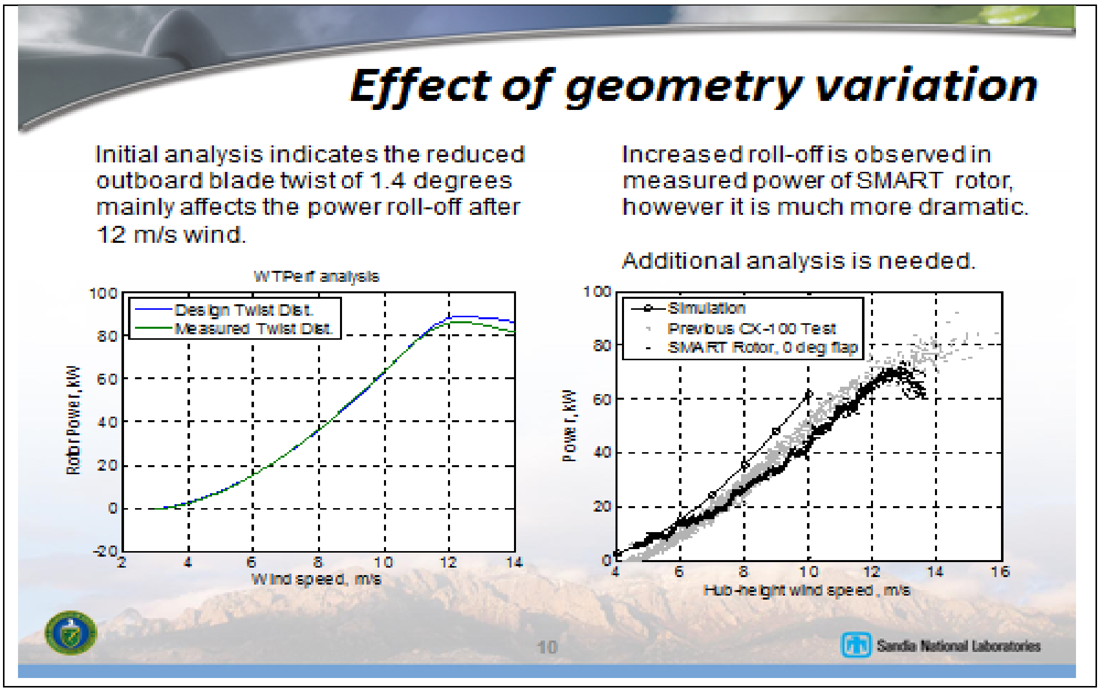
We scanned surface of all three blades to better understand observed differences between test and simulation.

Surface scan "point cloud"

Measured chord distribution matches design almost exactly.

Measured twist distribution is off at blade tip by 1.4 degrees, with potential to decrease expected power output.

Sandia National Laboratories



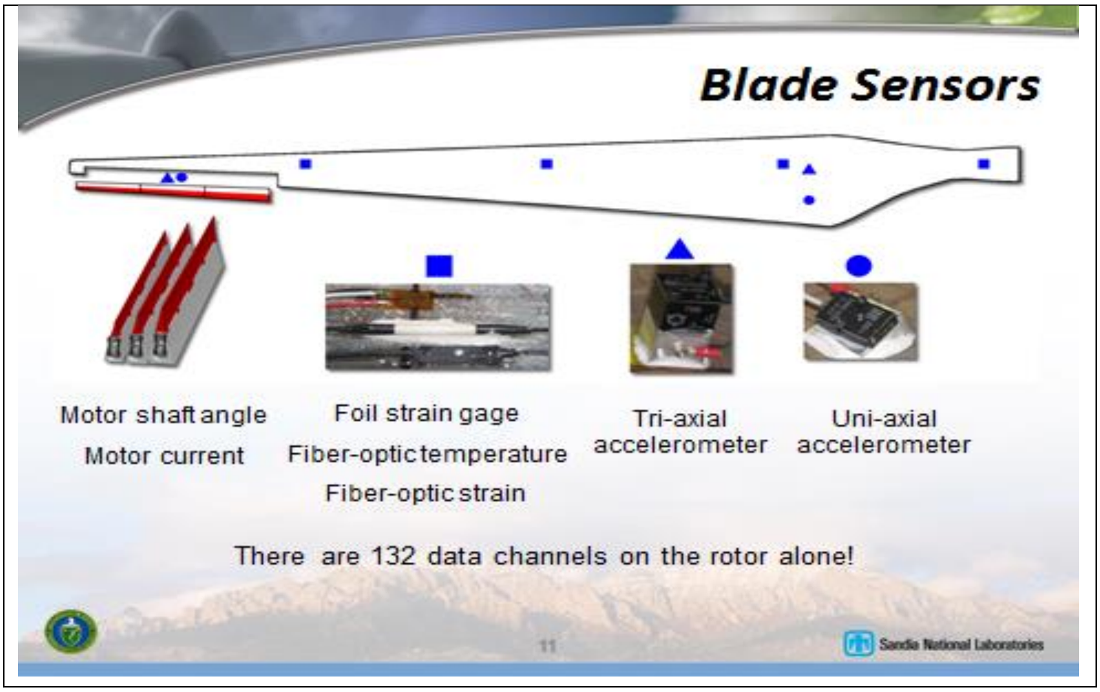
Effect of geometry variation

Initial analysis indicates the reduced outboard blade twist of 1.4 degrees mainly affects the power roll-off after 12 m/s wind.

Increased roll-off is observed in measured power of SMART rotor, however it is much more dramatic.

Additional analysis is needed.

Sandia National Laboratories



Blade Sensors

Motor shaft angle
Motor current

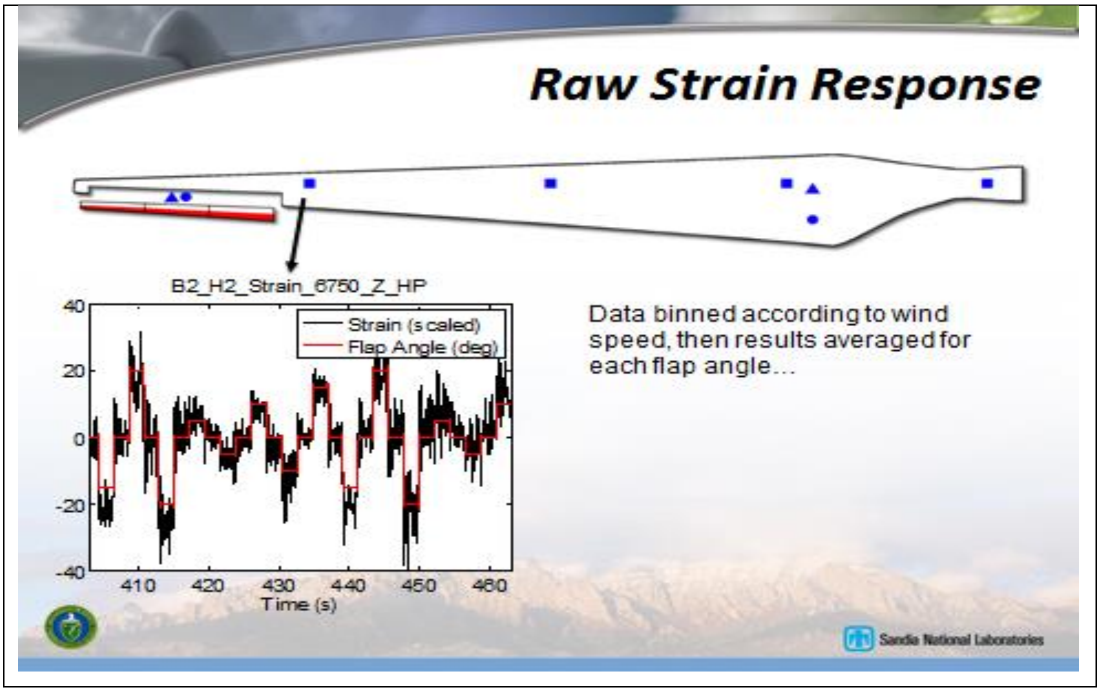
Foil strain gage
Fiber-optic temperature
Fiber-optic strain

Tri-axial accelerometer

Uni-axial accelerometer

There are 132 data channels on the rotor alone!

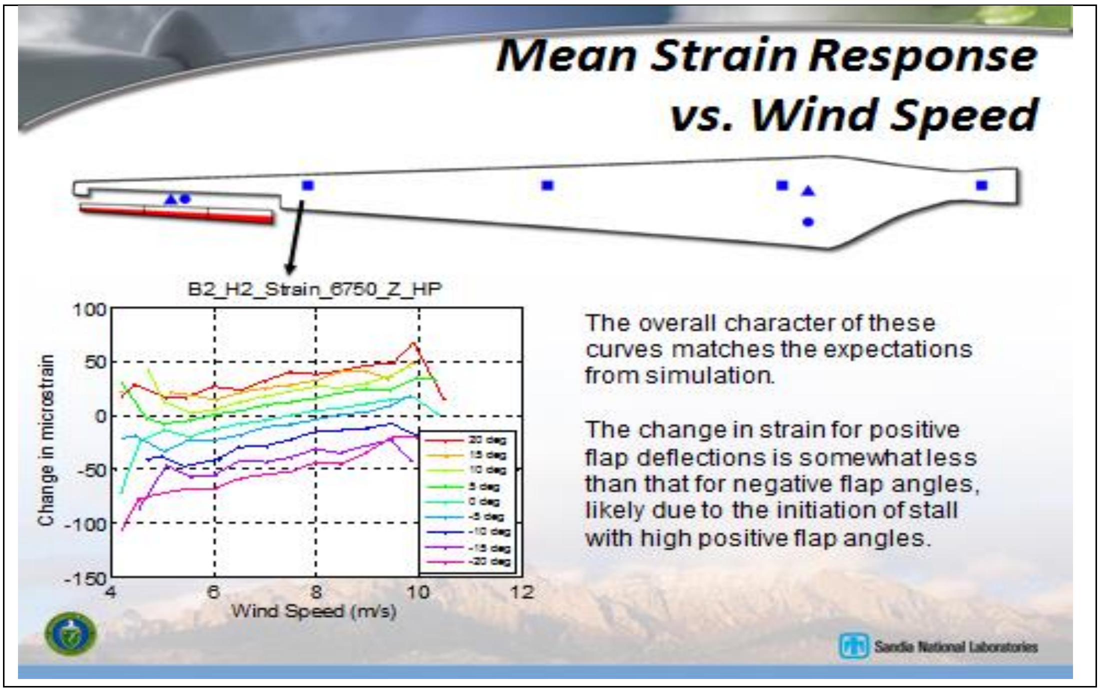
Sandia National Laboratories



Raw Strain Response

Data binned according to wind speed, then results averaged for each flap angle...

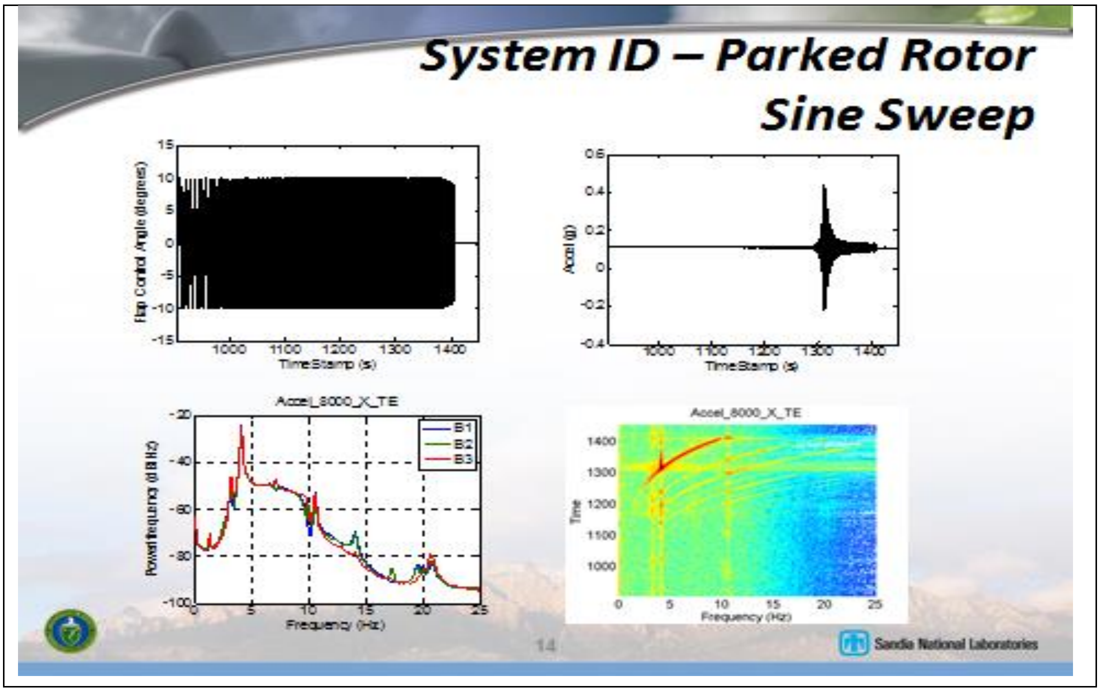
Sandia National Laboratories



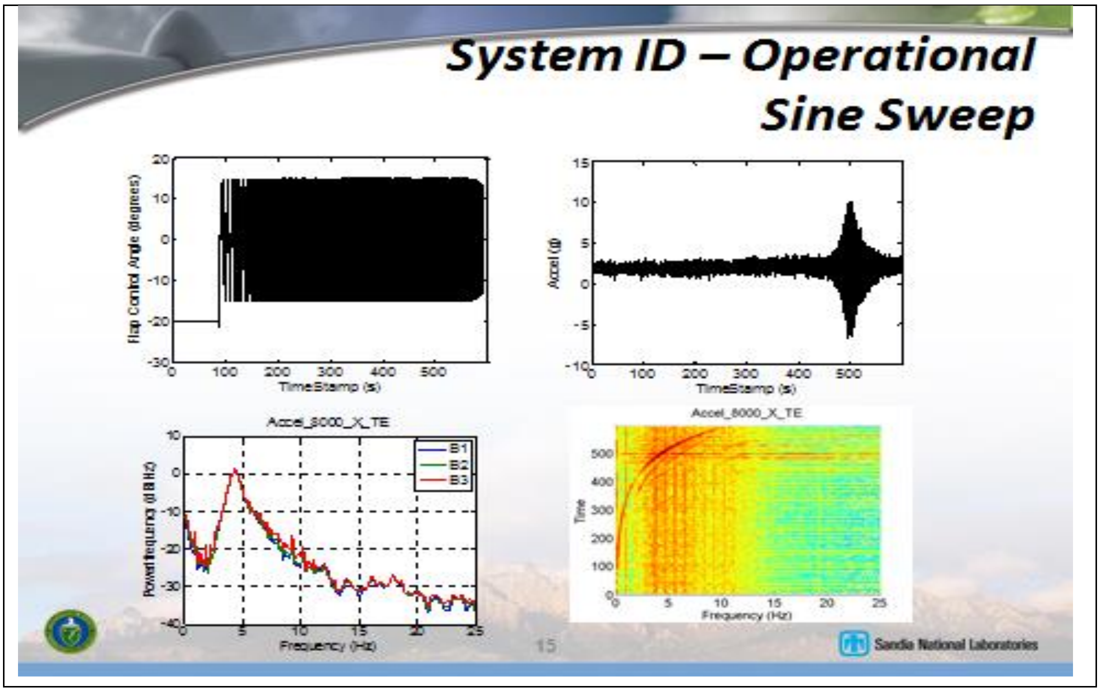
Mean Strain Response vs. Wind Speed

The overall character of these curves matches the expectations from simulation.

The change in strain for positive flap deflections is somewhat less than that for negative flap angles, likely due to the initiation of stall with high positive flap angles.

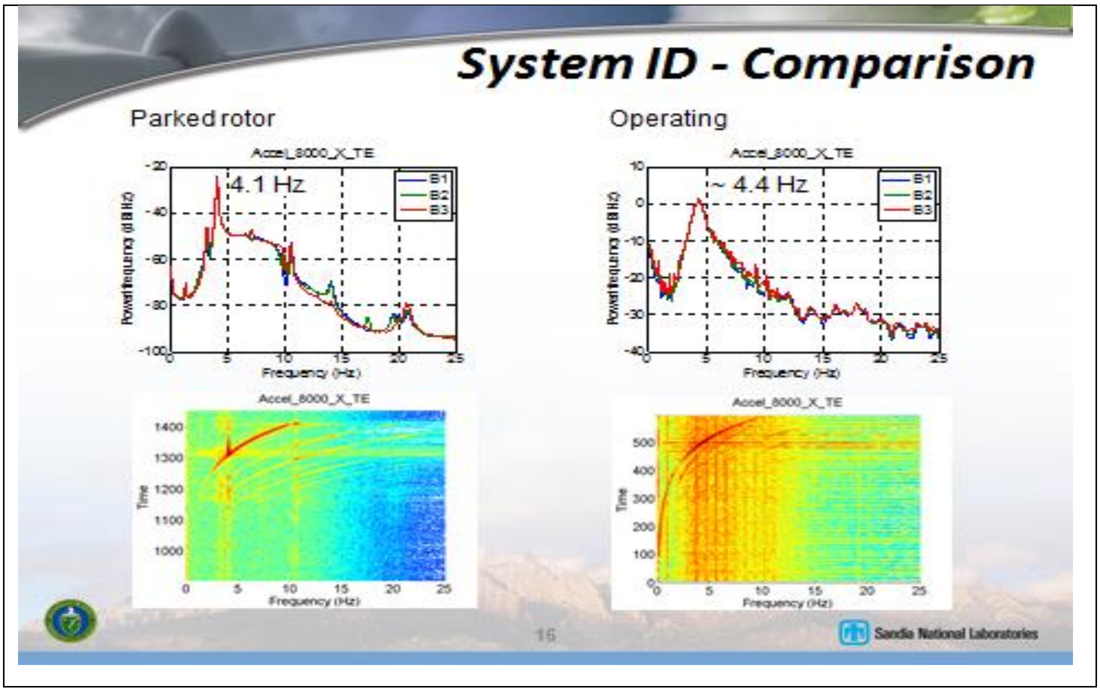


System ID – Parked Rotor Sine Sweep



System ID – Operational Sine Sweep

Sandia National Laboratories

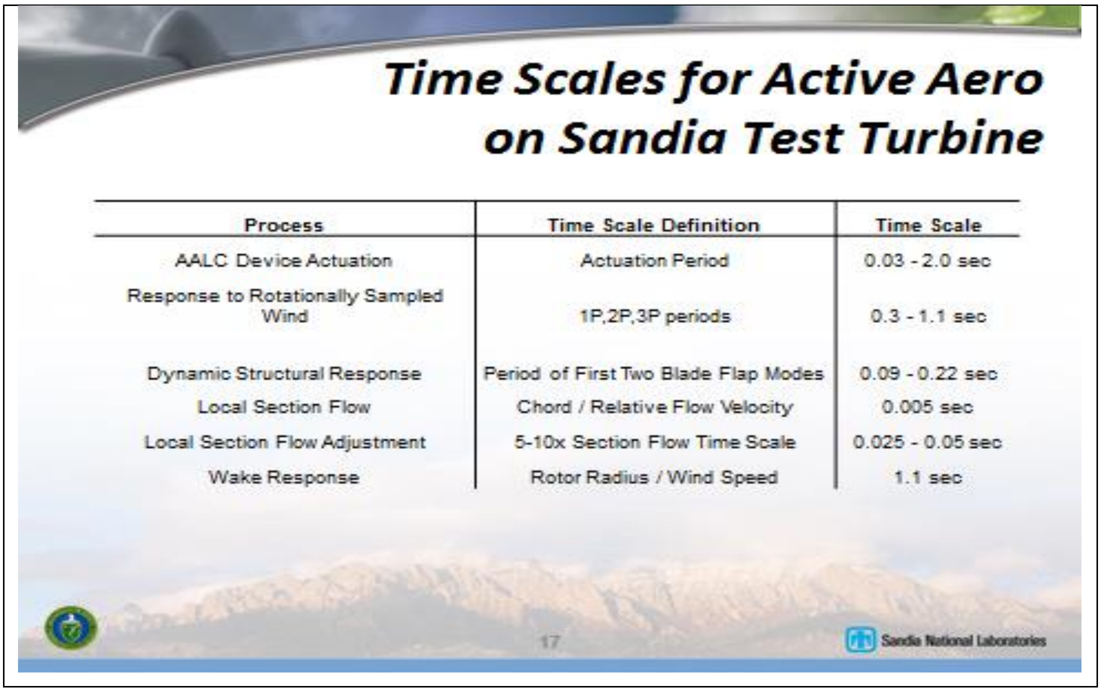


System ID - Comparison

Parked rotor

Operating

Sandia National Laboratories



Time Scales for Active Aero on Sandia Test Turbine

Process	Time Scale Definition	Time Scale
AALC Device Actuation	Actuation Period	0.03 - 2.0 sec
Response to Rotationally Sampled Wind	1P,2P,3P periods	0.3 - 1.1 sec
Dynamic Structural Response	Period of First Two Blade Flap Modes	0.09 - 0.22 sec
Local Section Flow	Chord / Relative Flow Velocity	0.005 sec
Local Section Flow Adjustment	5-10x Section Flow Time Scale	0.025 - 0.05 sec
Wake Response	Rotor Radius / Wind Speed	1.1 sec

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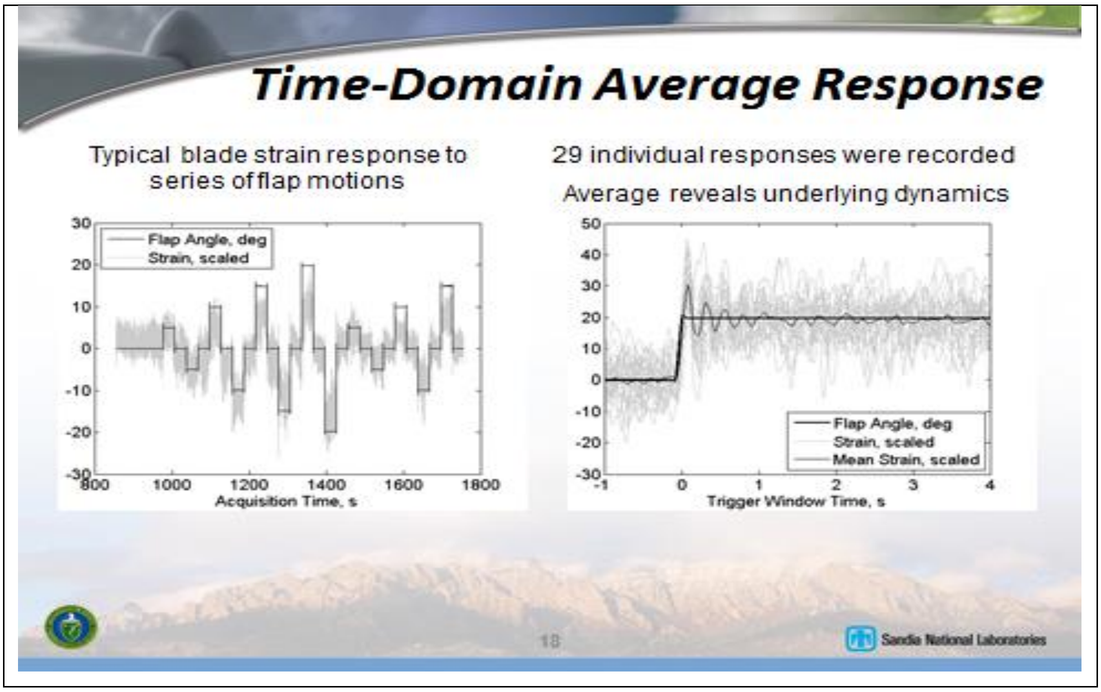

Time-Domain Average Response

Typical blade strain response to series of flap motions

29 individual responses were recorded

Average reveals underlying dynamics

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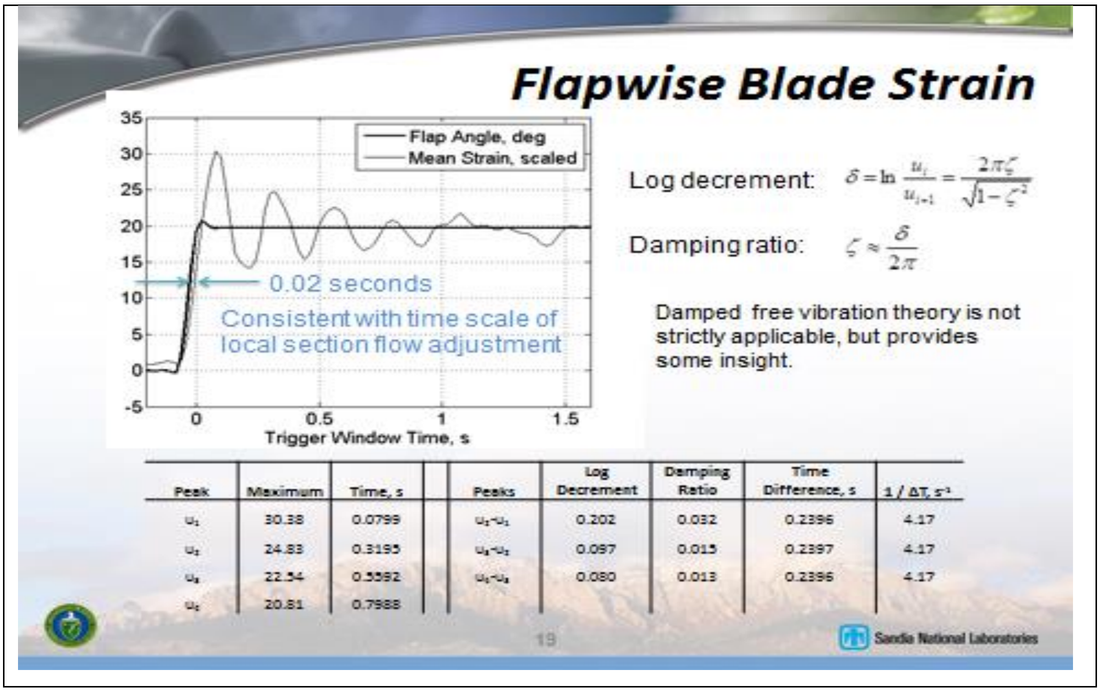

Flapwise Blade Strain

0.02 seconds

Consistent with time scale of local section flow adjustment

Log decrement: $\delta = \ln \frac{u_i}{u_{i+1}} = \frac{2\pi\zeta}{\sqrt{1-\zeta^2}}$

Damping ratio: $\zeta \approx \frac{\delta}{2\pi}$

Damped free vibration theory is not strictly applicable, but provides some insight.

Peak	Maximum	Time, s		Peaks	Log Decrement	Damping Ratio	Time Difference, s	1 / ΔT, s⁻¹
u_1	30.38	0.0799		u_1-u_2	0.202	0.032	0.2396	4.17
u_2	24.83	0.3195		u_2-u_3	0.097	0.015	0.2397	4.17
u_3	22.54	0.5592		u_3-u_4	0.080	0.013	0.2396	4.17
u_4	20.81	0.7988						

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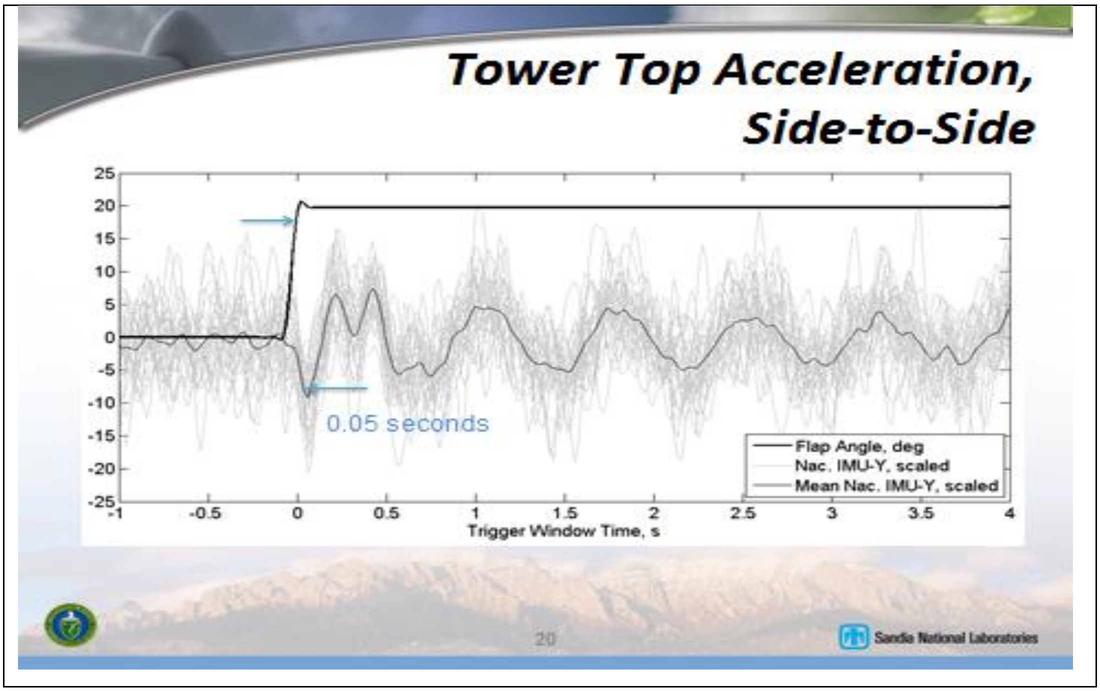

Tower Top Acceleration, Side-to-Side

0.05 seconds

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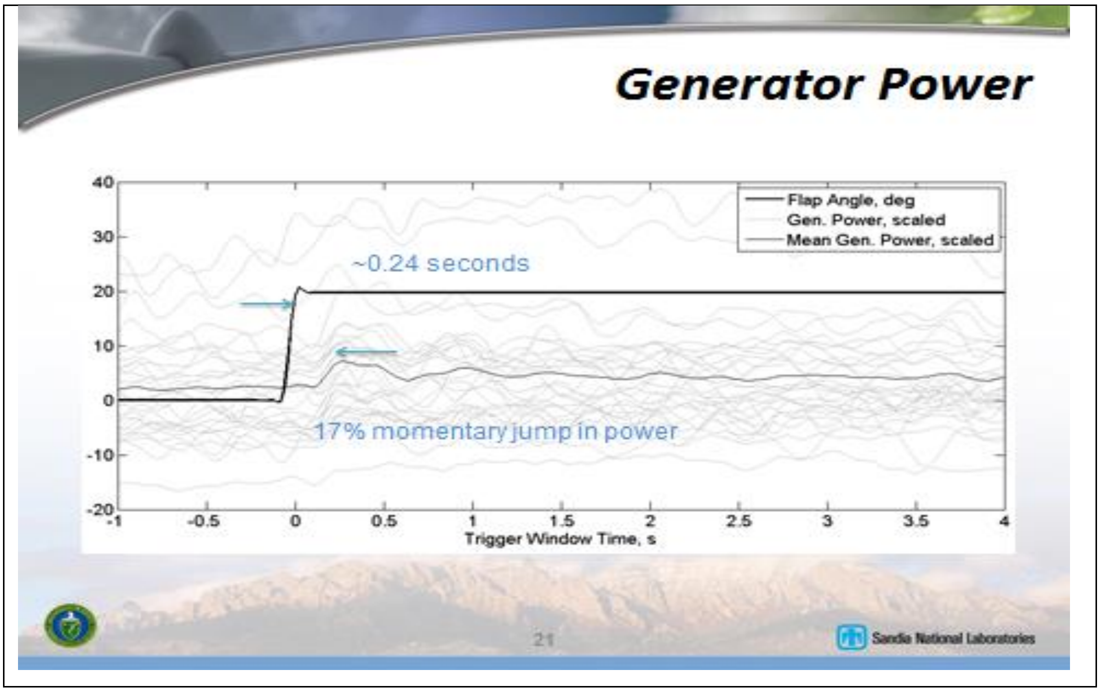


Generator Power

~0.24 seconds

17% momentary jump in power

Sandia National Laboratories

Project Reports

SAND2014-0681

SANDIA REPORT

SMART Wind Turbine Rotor:
Design and Field Test

Sandia National Laboratories

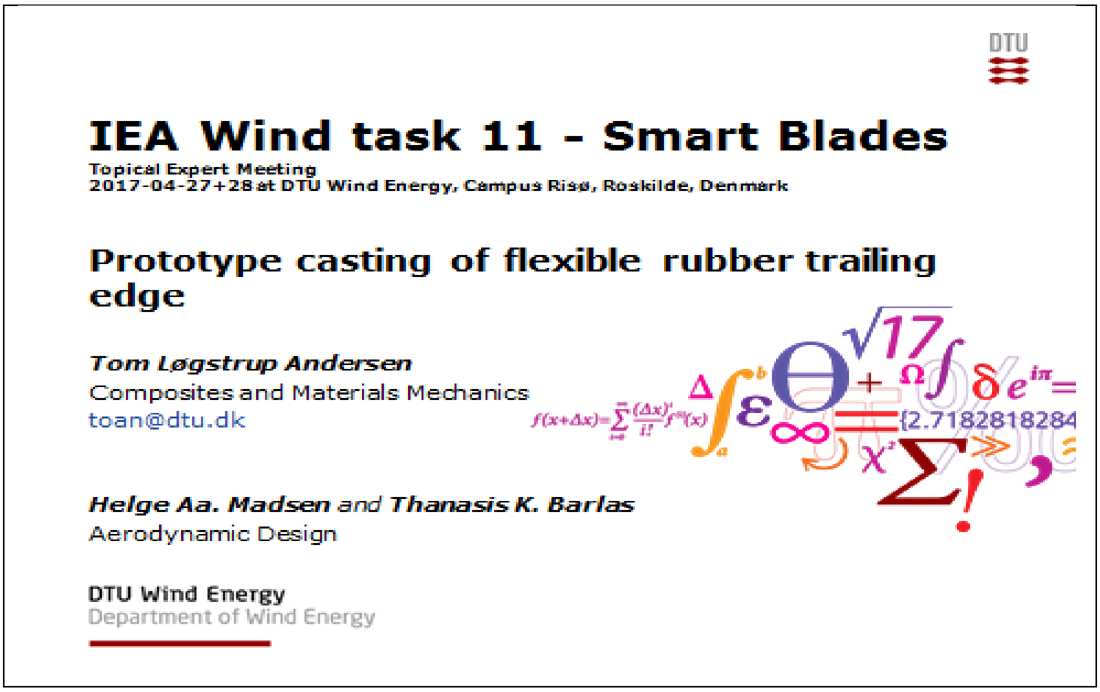
SAND2014-0712

SANDIA REPORT

SMART Wind Turbine Rotor:
Data Analysis and Conclusions

Sandia National Laboratories

Sandia National Laboratories



IEA Wind task 11 - Smart Blades

Topical Expert Meeting
2017-04-27+28 at DTU Wind Energy, Campus Risø, Roskilde, Denmark

Prototype casting of flexible rubber trailing edge

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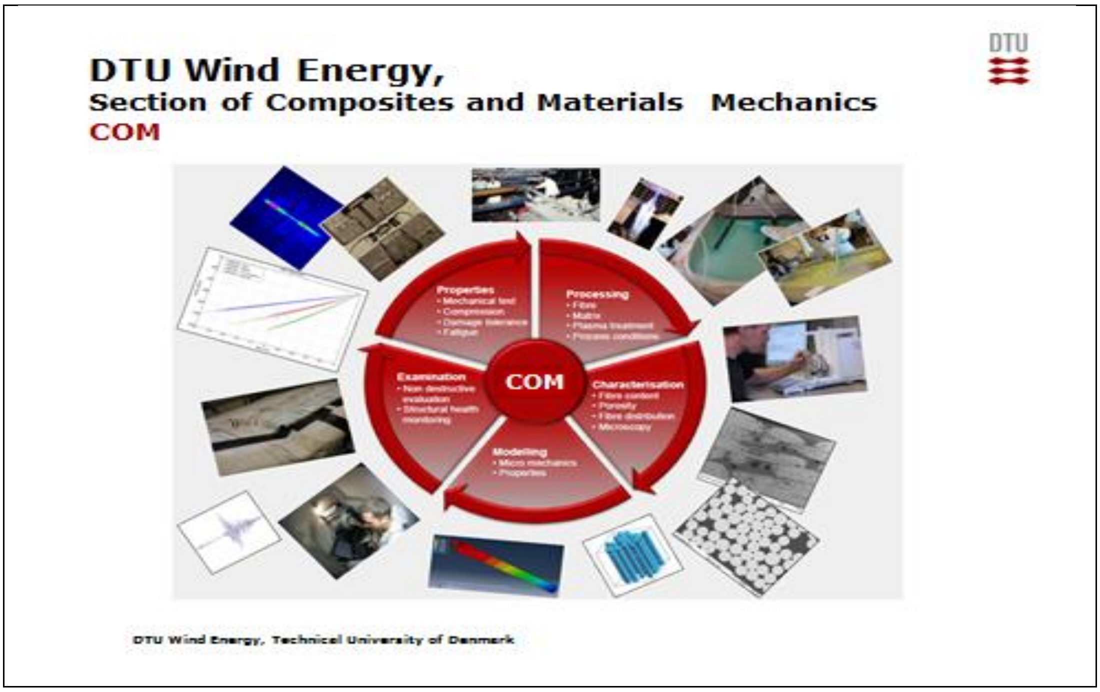
Helge Aa. Madsen *and* ***Thanasis K. Barlas***
Aerodynamic Design

DTU Wind Energy
Department of Wind Energy



DTU Wind Energy,
Section of Composites and Materials Mechanics
COM

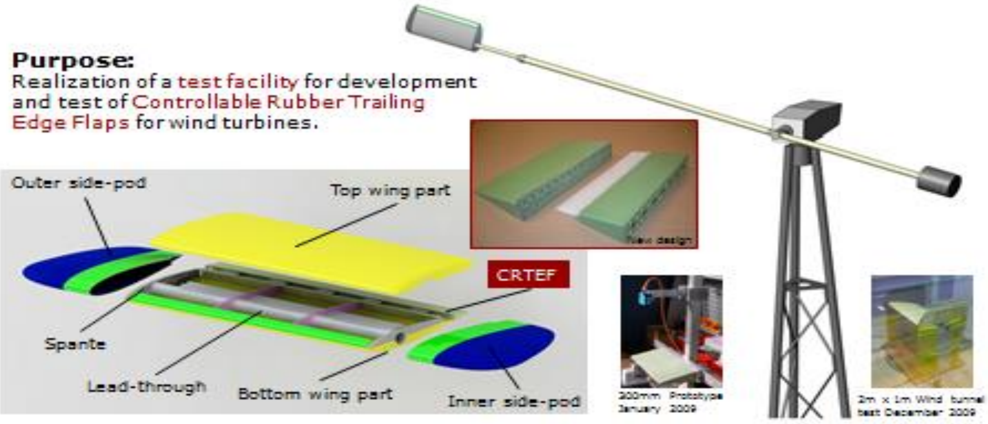
DTU Wind Energy, Technical University of Denmark

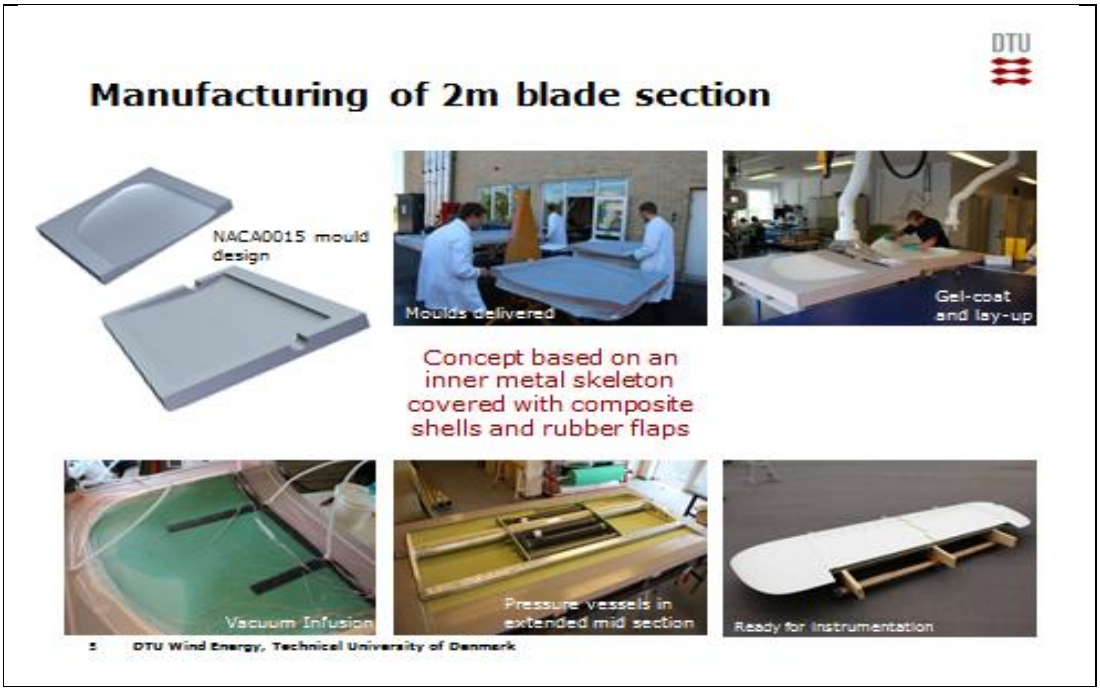
Outline

- Introduction
- Prototype casting of flexible rubber trailing flaps
- Videos of flap test
- Conclusion

RIA and INDUFLAP projects

Purpose:
Realization of a test facility for development and test of Controllable Rubber Trailing Edge Flaps for wind turbines.





Manufacturing of 2m blade section

NACA0015 mould design

Moulds delivered

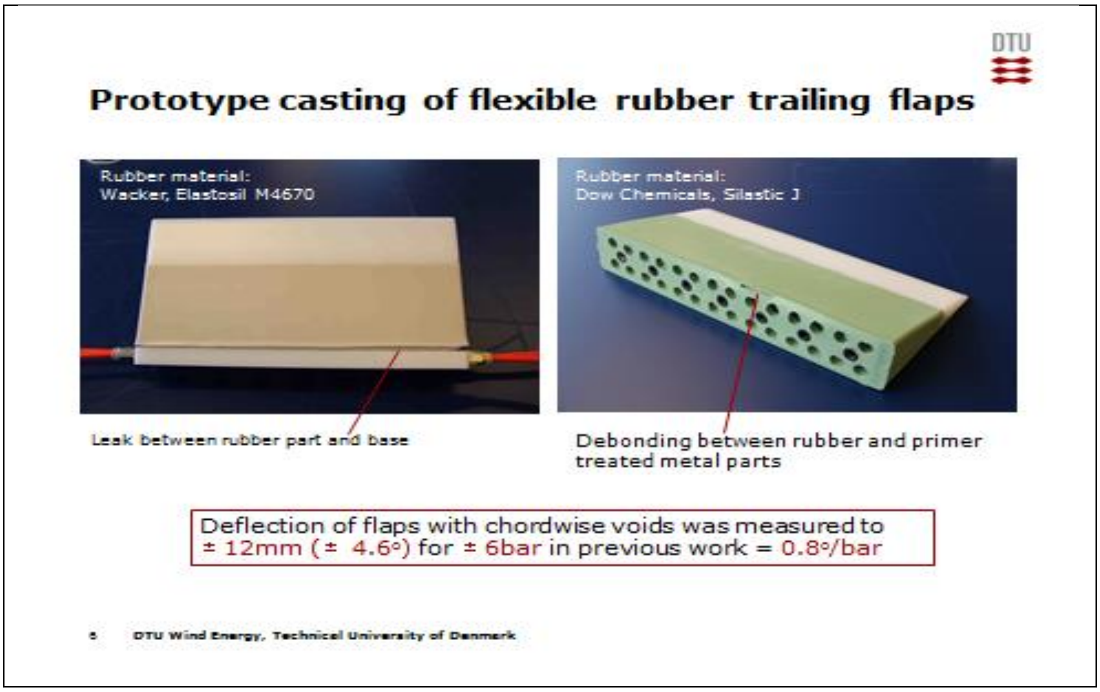
Gel-coat and lay-up

Concept based on an inner metal skeleton covered with composite shells and rubber flaps

Vacuum Infusion

Pressure vessels in extended mid section

Ready for instrumentation



Prototype casting of flexible rubber trailing flaps

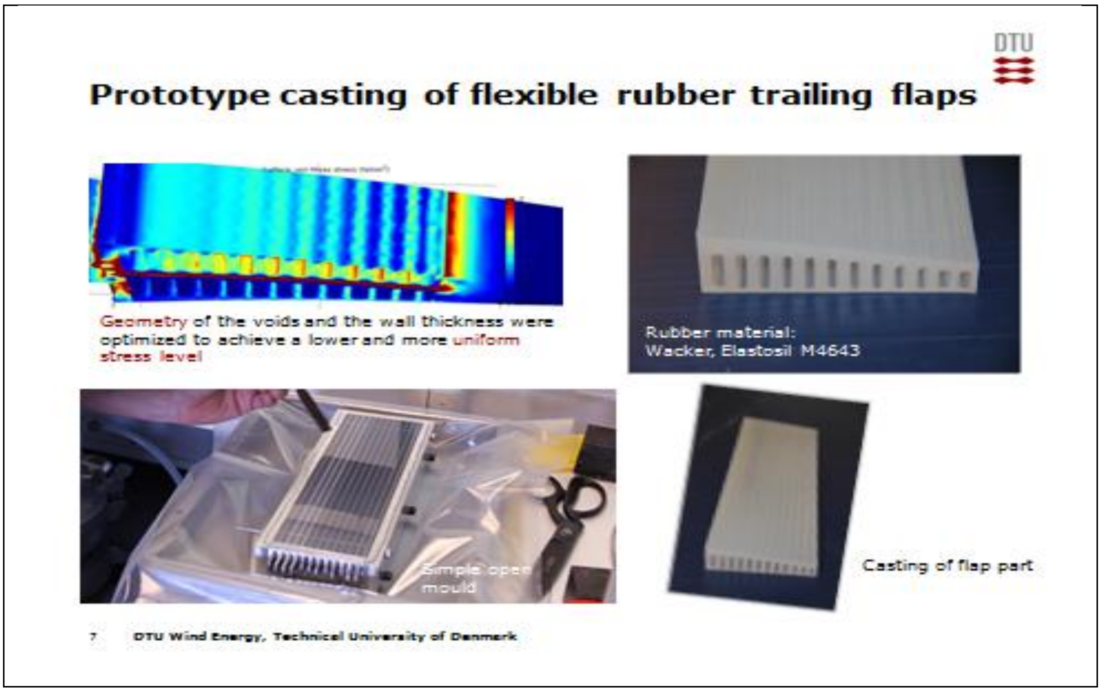
Rubber material:
Wacker, Elastosil M4670

Rubber material:
Dow Chemicals, Silastic J

Leak between rubber part and base

Debonding between rubber and primer treated metal parts

Deflection of flaps with chordwise voids was measured to ± 12mm (± 4.6°) for ± 6bar in previous work = 0.8°/bar



DTU

Prototype casting of flexible rubber trailing flaps

Geometry of the voids and the wall thickness were optimized to achieve a lower and more uniform stress level

Rubber material:
Wacker, Elastosil M4643

Simple open mould

Casting of flap part

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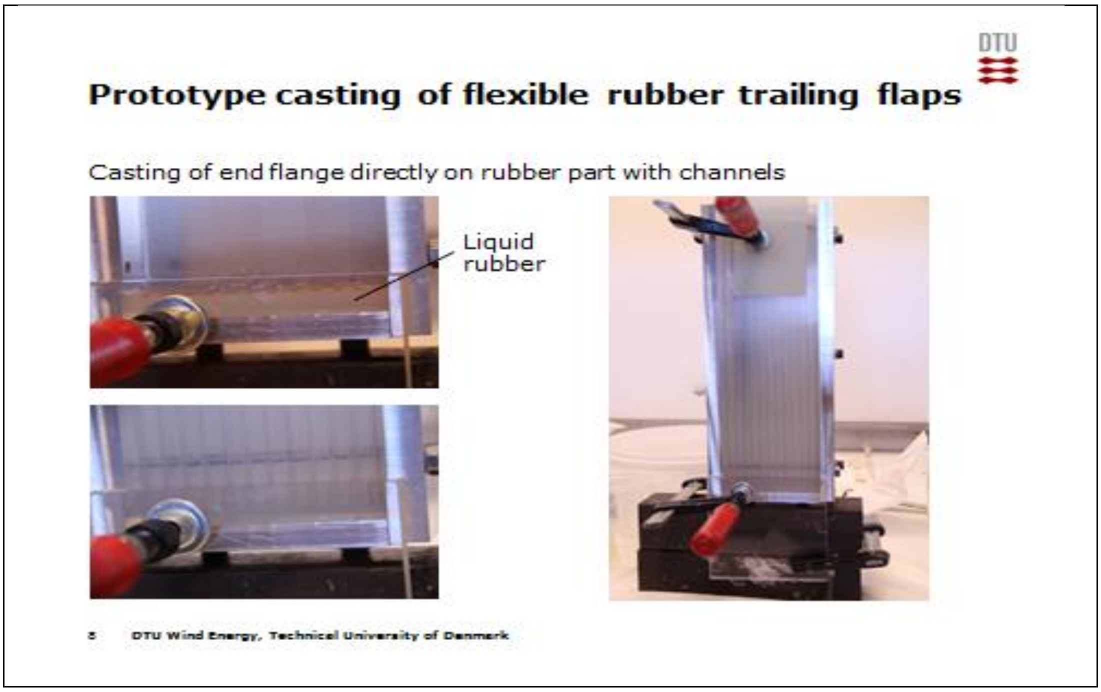

DTU

Prototype casting of flexible rubber trailing flaps

Casting of end flange directly on rubber part with channels

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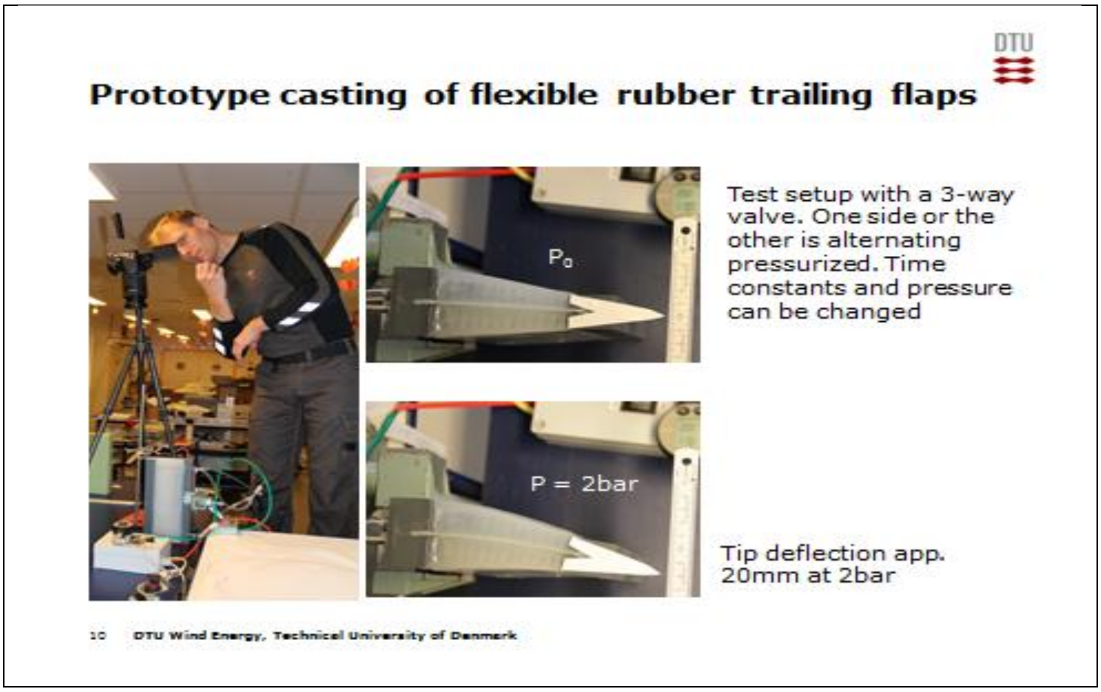
Prototype casting of flexible rubber trailing flaps

Rubber part with casted end flange – casting repeated in the other end



Prototype casting of flexible rubber trailing flaps

Test setup with a 3-way valve. One side or the other is alternating pressurized. Time constants and pressure can be changed

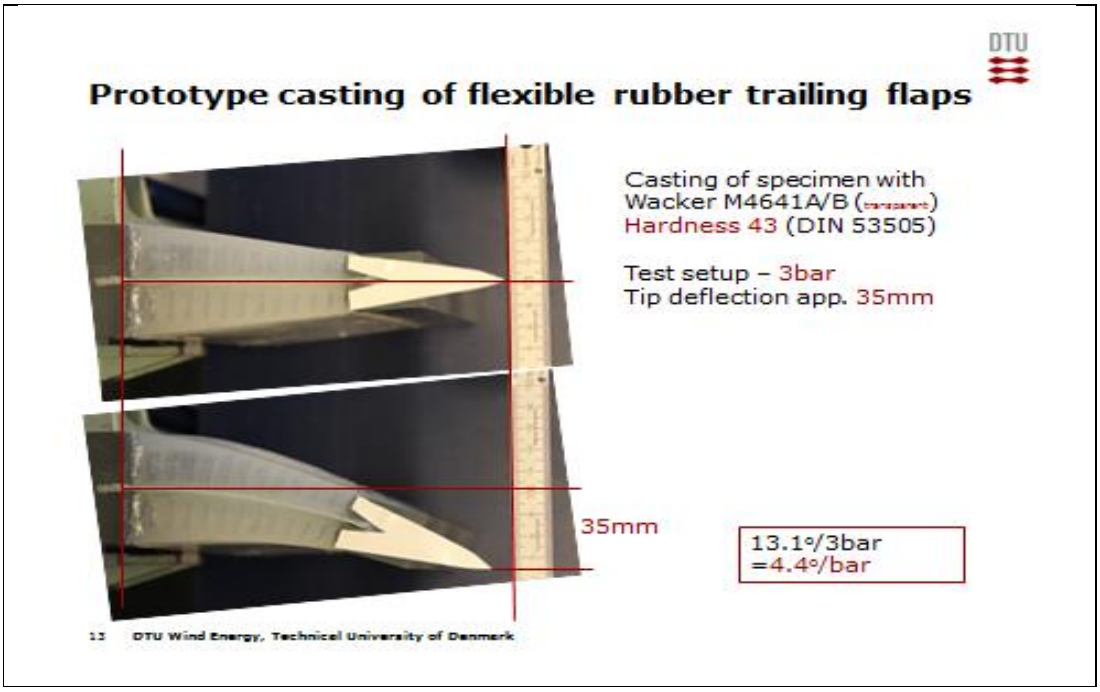
Tip deflection app. 20mm at 2bar

Prototype casting of flexible rubber trailing flaps

Video 1

Prototype casting of flexible rubber trailing flaps

Video 2

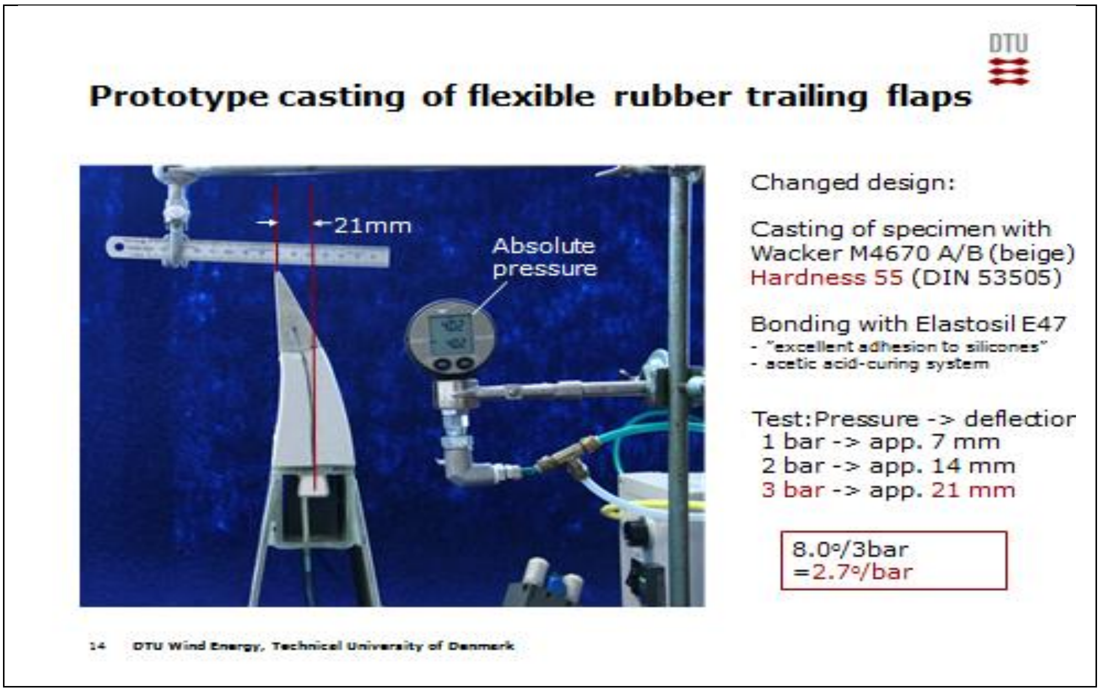


Prototype casting of flexible rubber trailing flaps

Casting of specimen with
Wacker M4641A/B (transparent)
Hardness 43 (DIN 53505)

Test setup – 3bar
Tip deflection app. 35mm

13.1°/3bar
=4.4°/bar



Prototype casting of flexible rubber trailing flaps

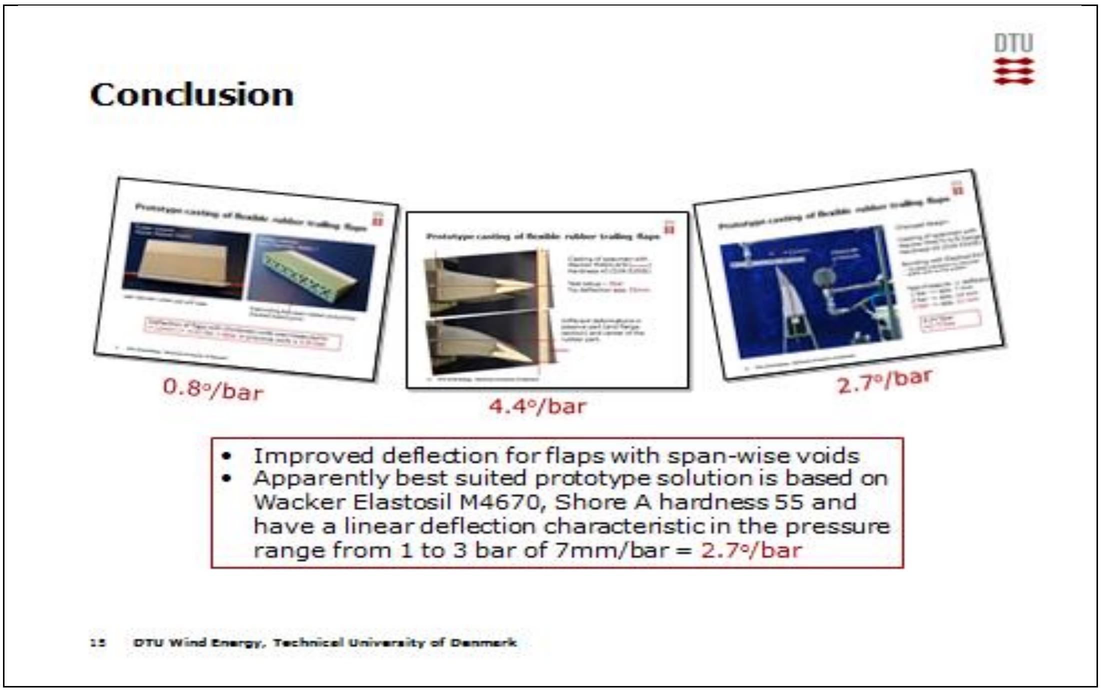
Changed design:

Casting of specimen with
Wacker M4670 A/B (beige)
Hardness 55 (DIN 53505)

Bonding with Elastosil E47
- "excellent adhesion to silicones"
- acetic acid-curing system

Test:Pressure -> deflectior
1 bar -> app. 7 mm
2 bar -> app. 14 mm
3 bar -> app. 21 mm

8.0°/3bar
=2.7°/bar



Conclusion

0.8°/bar

4.4°/bar

2.7°/bar

- Improved deflection for flaps with span-wise voids
- Apparently best suited prototype solution is based on Wacker Elastosil M4670, Shore A hardness 55 and have a linear deflection characteristic in the pressure range from 1 to 3 bar of 7mm/bar = 2.7°/bar

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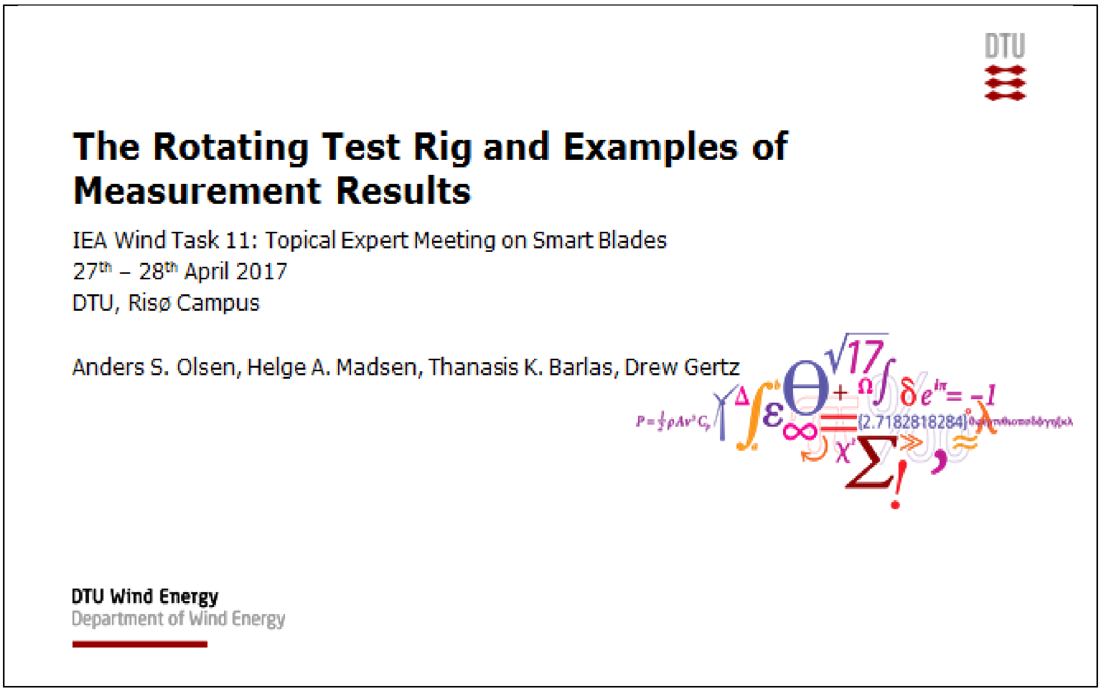


The Rotating Test Rig and Examples of Measurement Results

IEA Wind Task 11: Topical Expert Meeting on Smart Blades
27th – 28th April 2017
DTU, Risø Campus

Anders S. Olsen, Helge A. Madsen, Thanasis K. Barlas, Drew Gertz

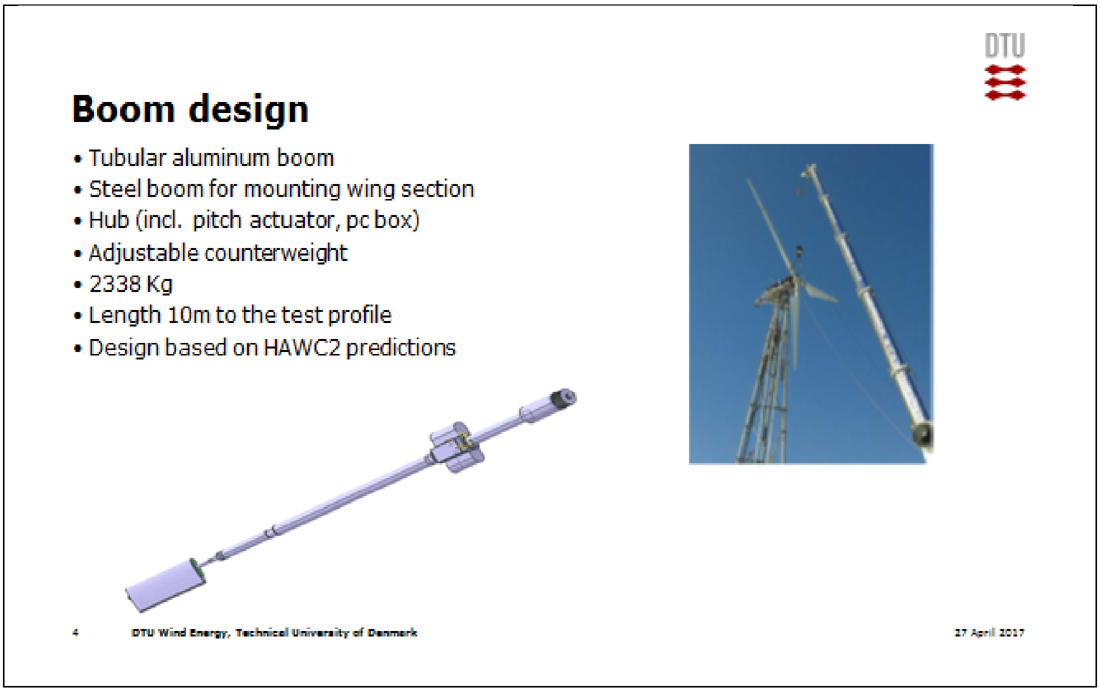
DTU Wind Energy
Department of Wind Energy

Content

- Introduction
- Boom Design
- Section Design
- Instrumentation
- Test Methods
- Corrections
- Analysis
- Results from the summer 2016 campaign with INDUFLAP1 flap (NACA0015 +15%c flap)
- Link to the National Wind Tunnel and DTU Test Turbine
- Conclusions

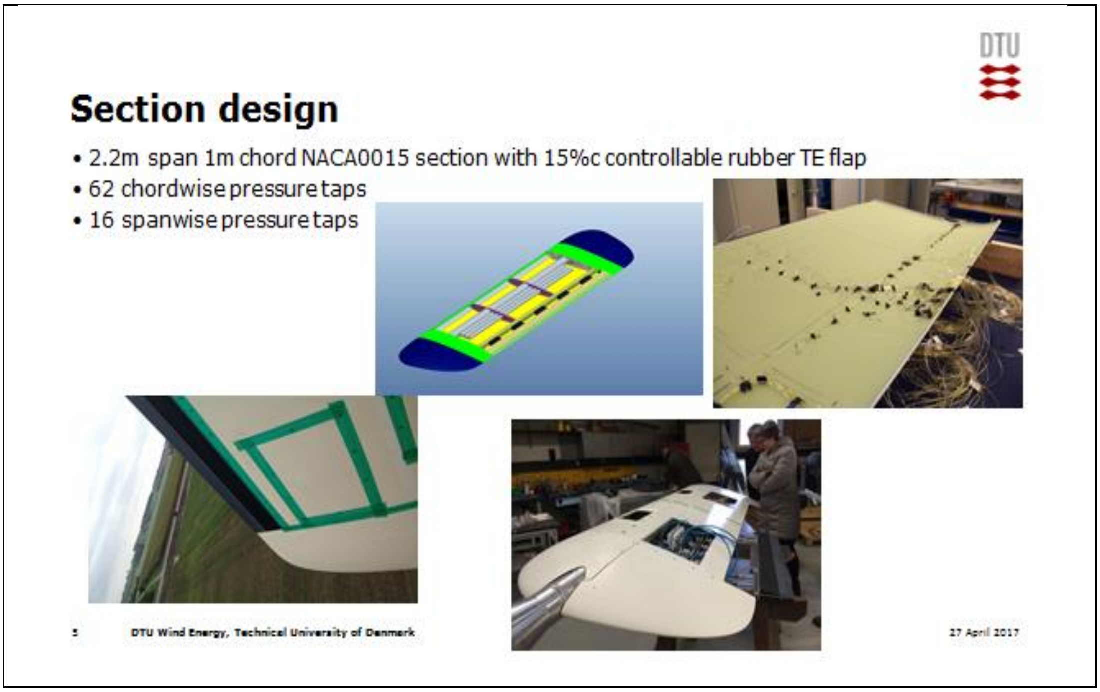
Introduction

- Established during the INDUFLAP project in 2014
- 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 (2.2m spanwise length and 1m chord) is rotated by a 10m boom mounted on the shaft of the Tellus 100kW turbine. Upgraded with a fully variable speed drive.
- Detailed measurements of the aerodynamic loading on the blade section, inflow and structural response



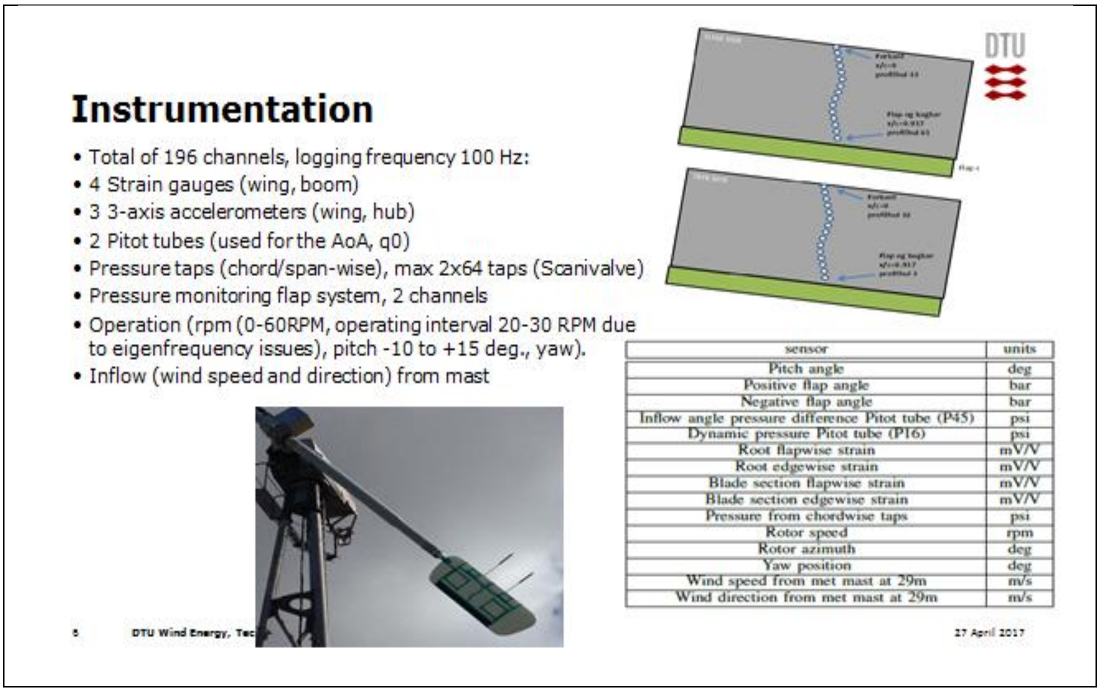
Boom design

- Tubular aluminum boom
- Steel boom for mounting wing section
- Hub (incl. pitch actuator, pc box)
- Adjustable counterweight
- 2338 Kg
- Length 10m to the test profile
- Design based on HAWC2 predictions



Section design

- 2.2m span 1m chord NACA0015 section with 15%c controllable rubber TE flap
- 62 chordwise pressure taps
- 16 spanwise pressure taps



Instrumentation

- Total of 196 channels, logging frequency 100 Hz:
- 4 Strain gauges (wing, boom)
- 3 3-axis accelerometers (wing, hub)
- 2 Pitot tubes (used for the AoA, q0)
- Pressure taps (chord/span-wise), max 2x64 taps (Scanivalve)
- Pressure monitoring flap system, 2 channels
- Operation (rpm (0-60RPM, operating interval 20-30 RPM due to eigenfrequency issues), pitch -10 to +15 deg., yaw).
- Inflow (wind speed and direction) from mast

sensor	units
Pitch angle	deg
Positive flap angle	bar
Negative flap angle	bar
Inflow angle pressure difference Pitot tube (P45)	psi
Dynamic pressure Pitot tube (P16)	psi
Root flapwise strain	mV/V
Root edgewise strain	mV/V
Blade section flapwise strain	mV/V
Blade section edgewise strain	mV/V
Pressure from chordwise taps	psi
Rotor speed	rpm
Rotor azimuth	deg
Yaw position	deg
Wind speed from met mast at 29m	m/s
Wind direction from met mast at 29m	m/s

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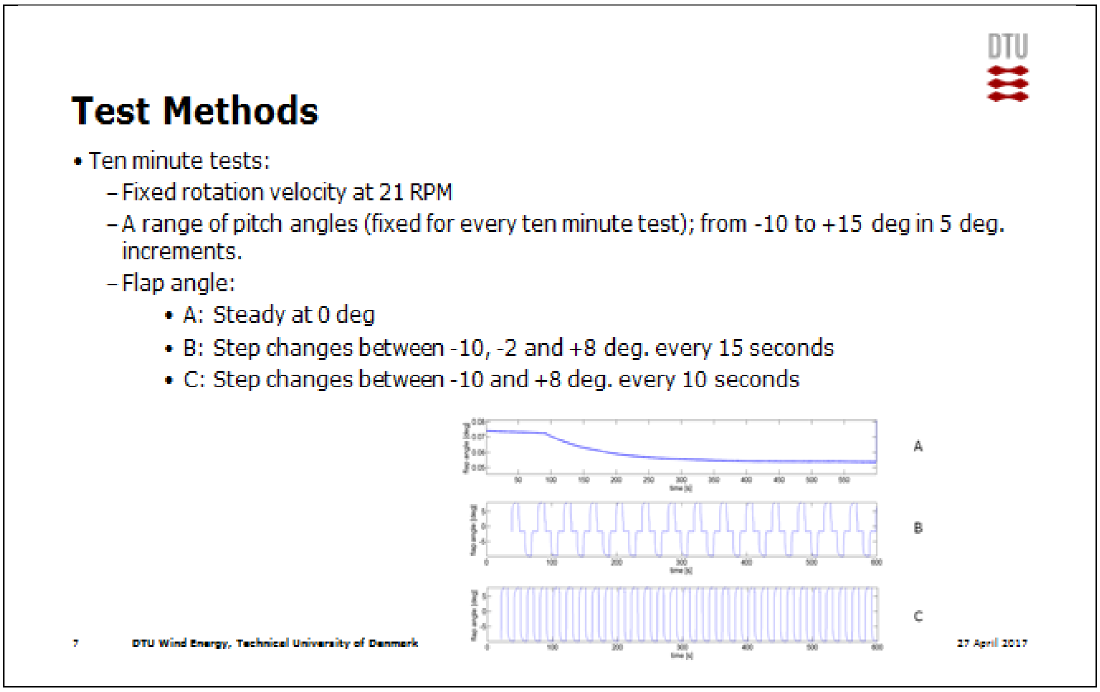
27 April 2017



Test Methods

- Ten minute tests:
  - Fixed rotation velocity at 21 RPM
  - A range of pitch angles (fixed for every ten minute test); from -10 to +15 deg in 5 deg. increments.
  - Flap angle:
    - A: Steady at 0 deg
    - B: Step changes between -10, -2 and +8 deg. every 15 seconds
    - C: Step changes between -10 and +8 deg. every 10 seconds

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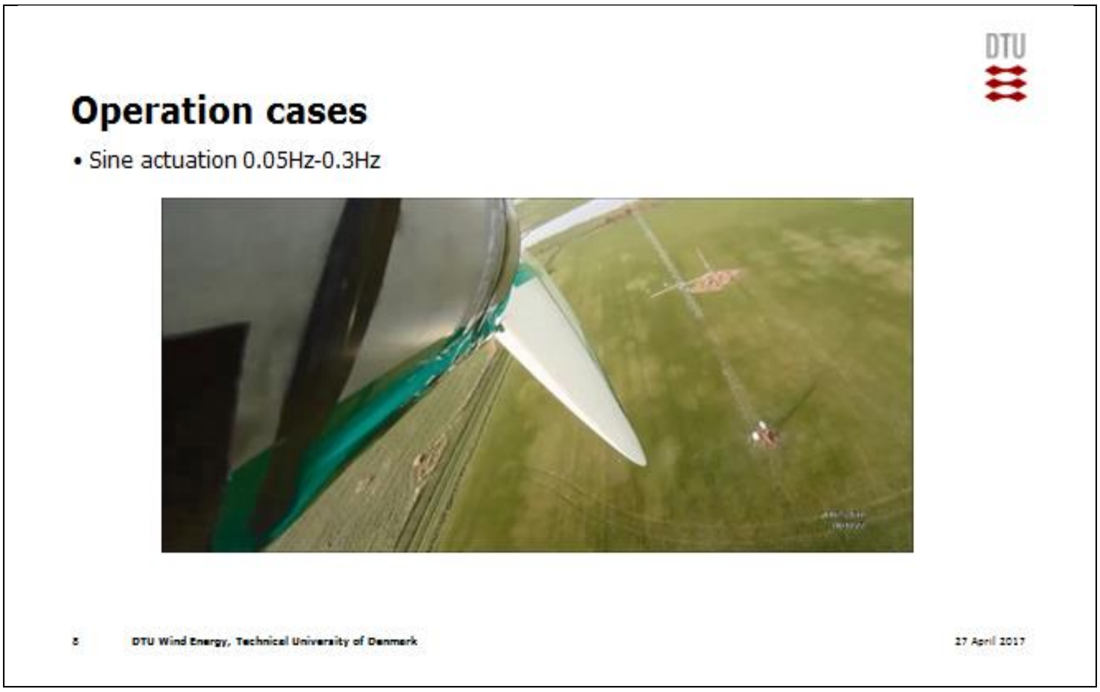
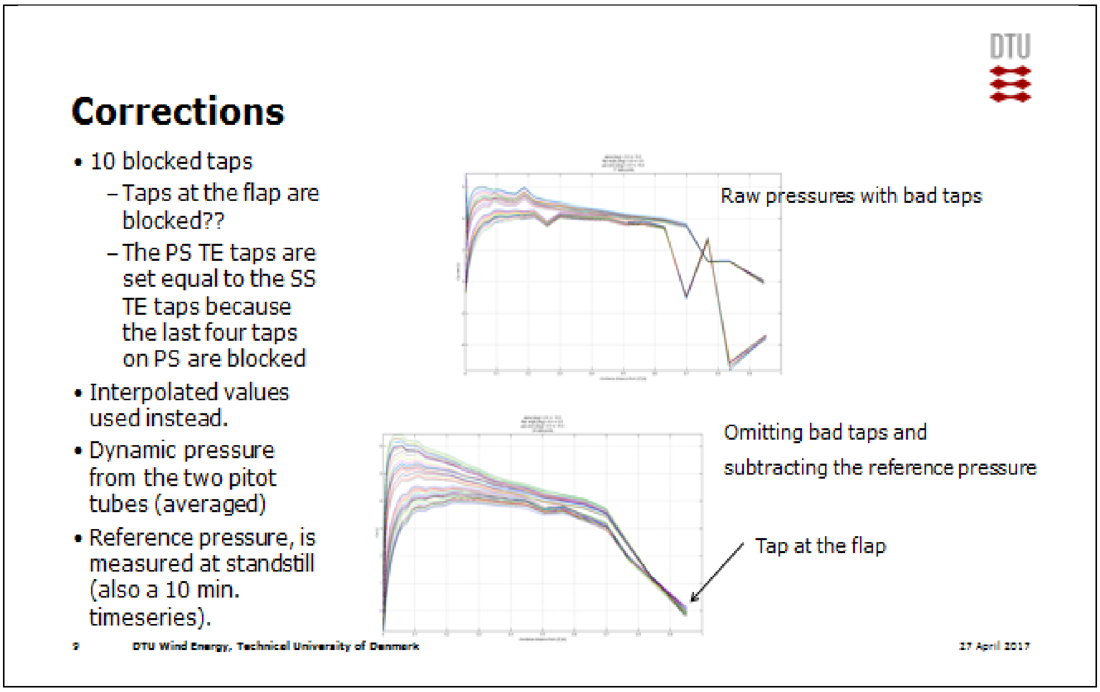


Operation cases

- Sine actuation 0.05Hz-0.3Hz



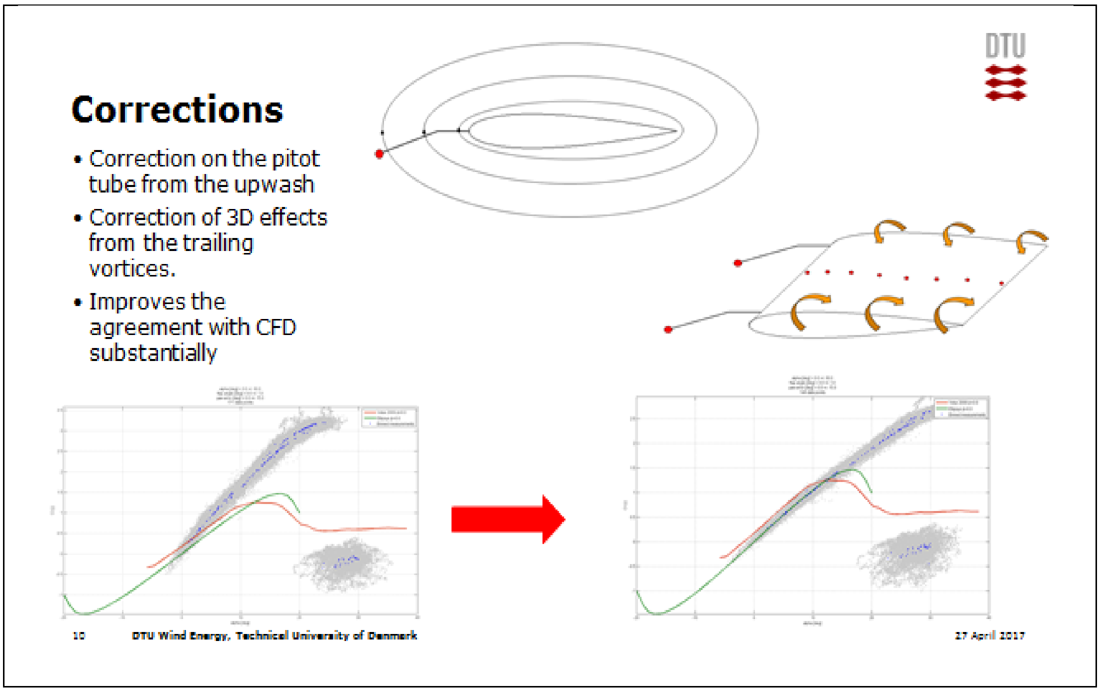
Corrections

- 10 blocked taps
  - Taps at the flap are blocked??
  - The PS TE taps are set equal to the SS TE taps because the last four taps on PS are blocked
- Interpolated values used instead.
- Dynamic pressure from the two pitot tubes (averaged)
- Reference pressure, is measured at standstill (also a 10 min. timeseries).

Raw pressures with bad taps

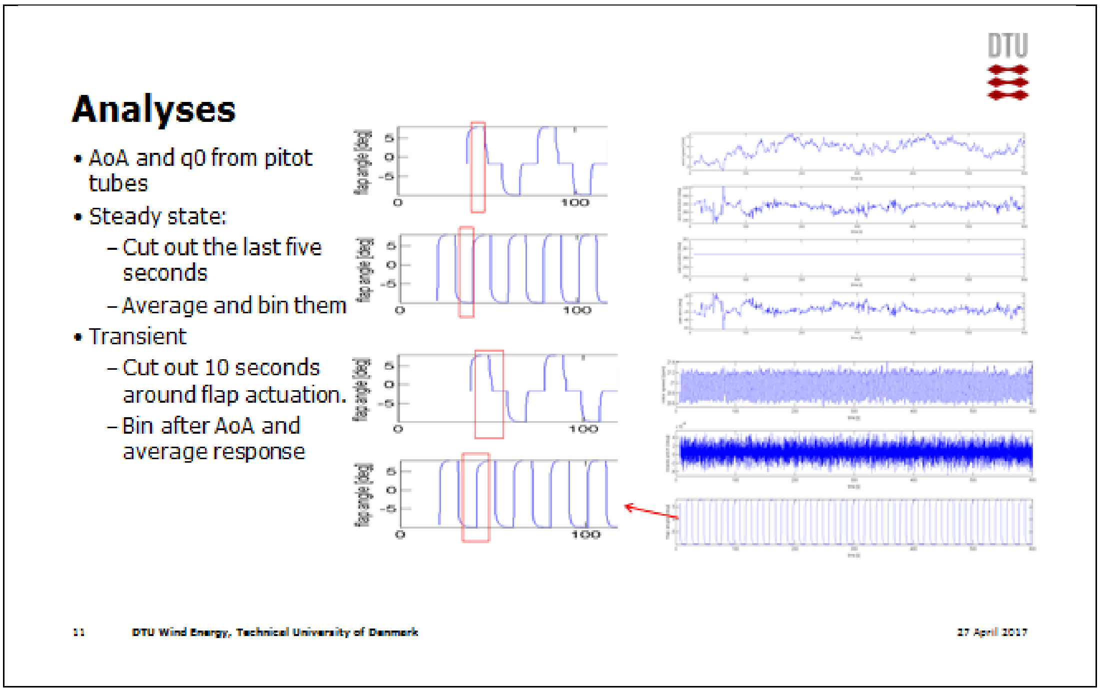
Omitting bad taps and subtracting the reference pressure

Tap at the flap



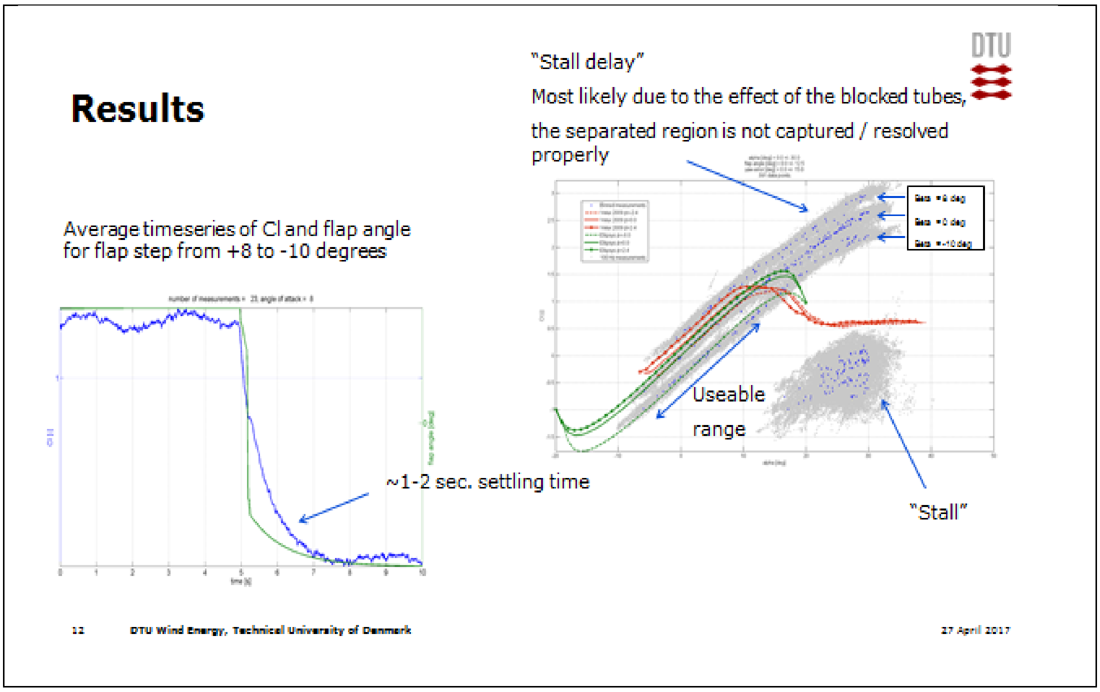
Corrections

- Correction on the pitot tube from the upwash
- Correction of 3D effects from the trailing vortices.
- Improves the agreement with CFD substantially



Analyses

- AoA and q0 from pitot tubes
- Steady state:
  - Cut out the last five seconds
  - Average and bin them
- Transient
  - Cut out 10 seconds around flap actuation.
  - Bin after AoA and average response



Results

Average timeseries of Cl and flap angle for flap step from +8 to -10 degrees

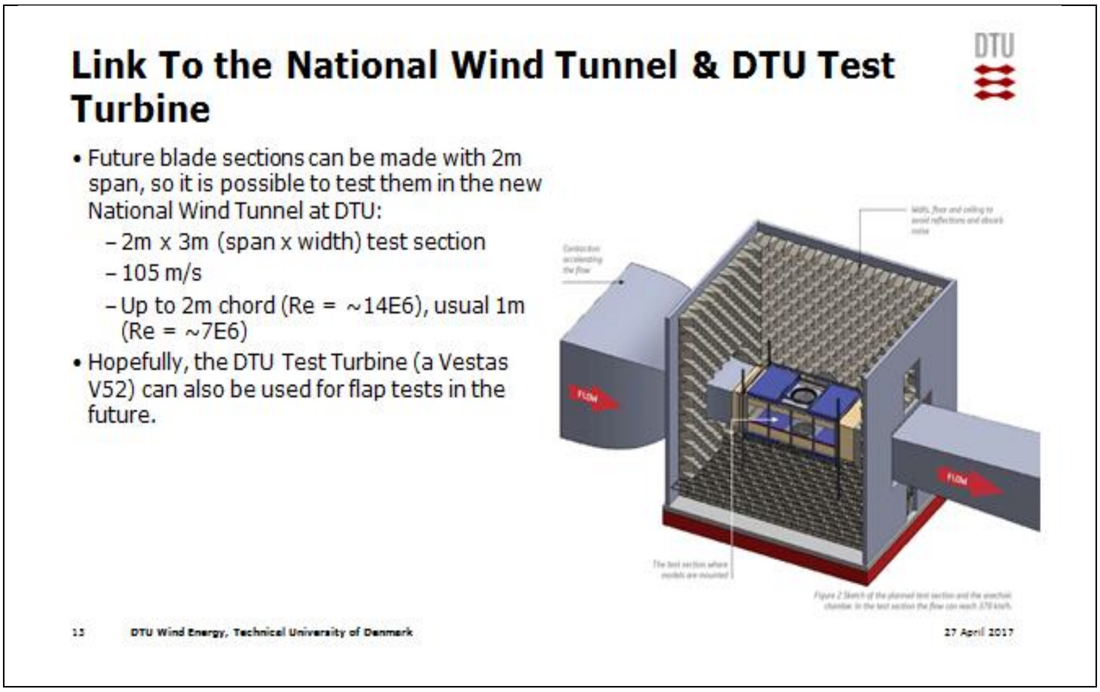
~1-2 sec. settling time

"Stall delay"

Most likely due to the effect of the blocked tubes, the separated region is not captured / resolved properly

Useable range

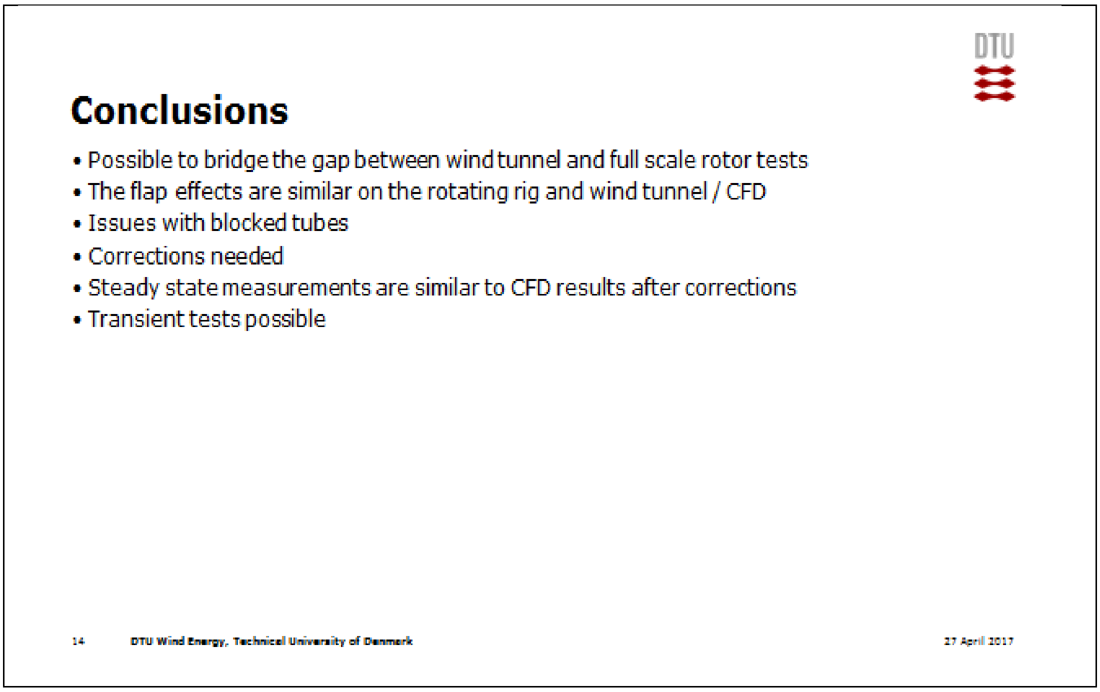
"Stall"



Link To the National Wind Tunnel & DTU Test Turbine

- Future blade sections can be made with 2m span, so it is possible to test them in the new National Wind Tunnel at DTU:
  - 2m x 3m (span x width) test section
  - 105 m/s
  - Up to 2m chord (Re = ~14E6), usual 1m (Re = ~7E6)
- Hopefully, the DTU Test Turbine (a Vestas V52) can also be used for flap tests in the future.

Figure 2 Sketch of the planned test section and the anechoic chamber. In the test section the flow can reach 370 km/h.



Conclusions

- Possible to bridge the gap between wind tunnel and full scale rotor tests
- The flap effects are similar on the rotating rig and wind tunnel / CFD
- Issues with blocked tubes
- Corrections needed
- Steady state measurements are similar to CFD results after corrections
- Transient tests possible

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Your energy. Our passion.

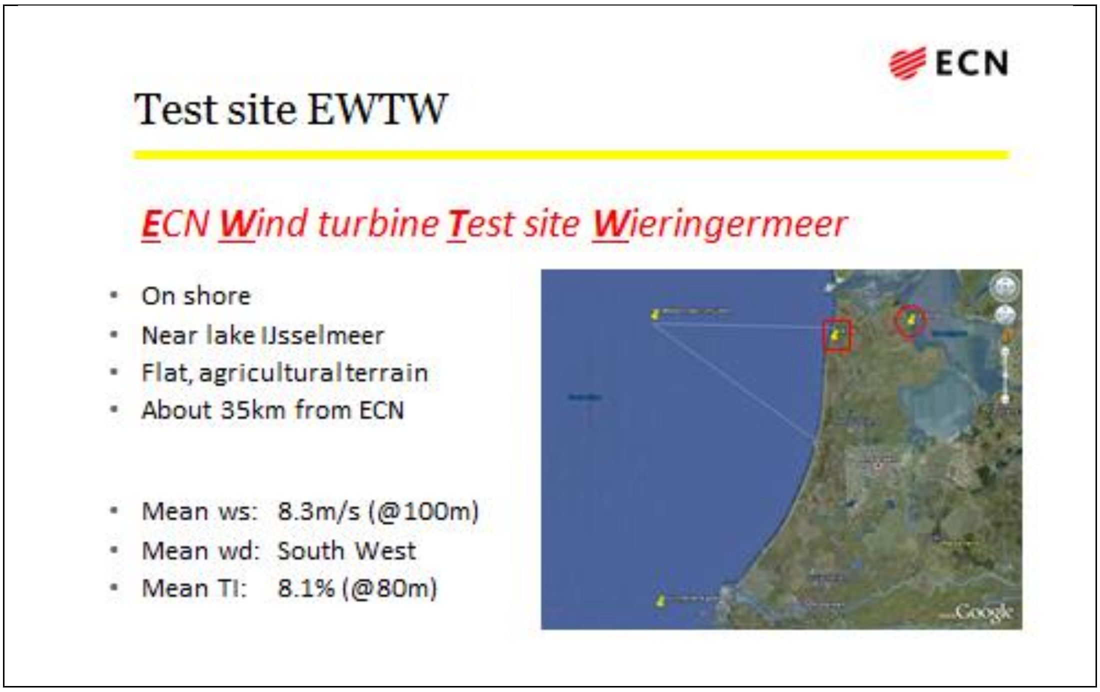
Development of blade response measurements

Smart blades – IEA Topical Expert Meeting

Marcel Poodt, ECN

Roskilde, Denmark
27-28 April 2017

www.ecn.nl

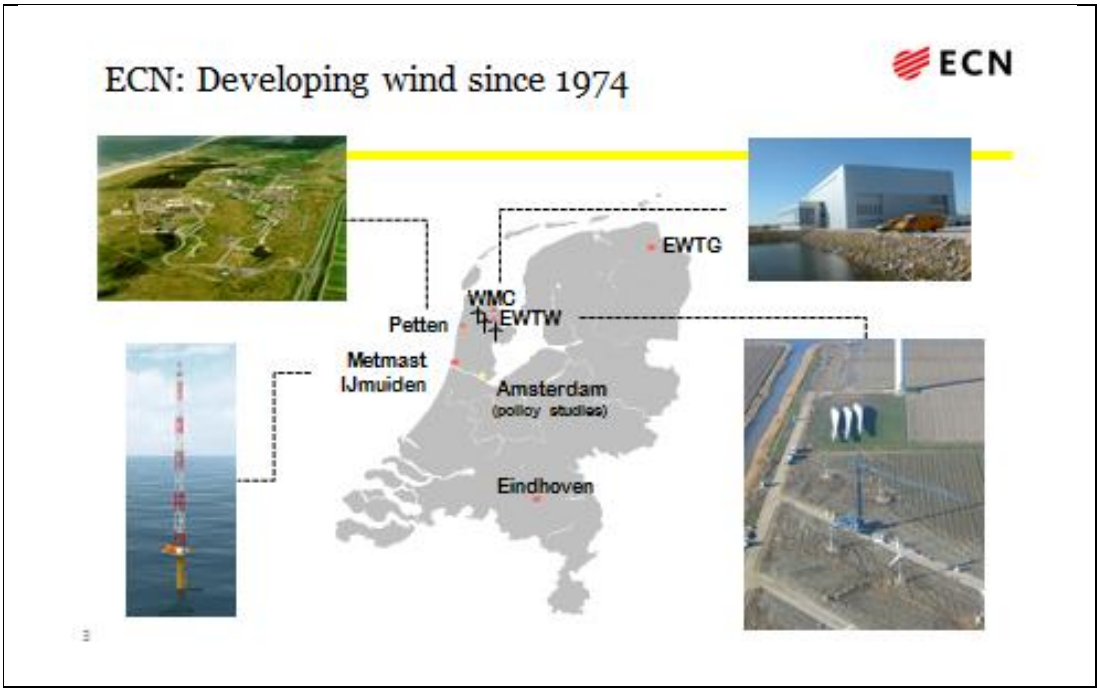


Test site EWTW

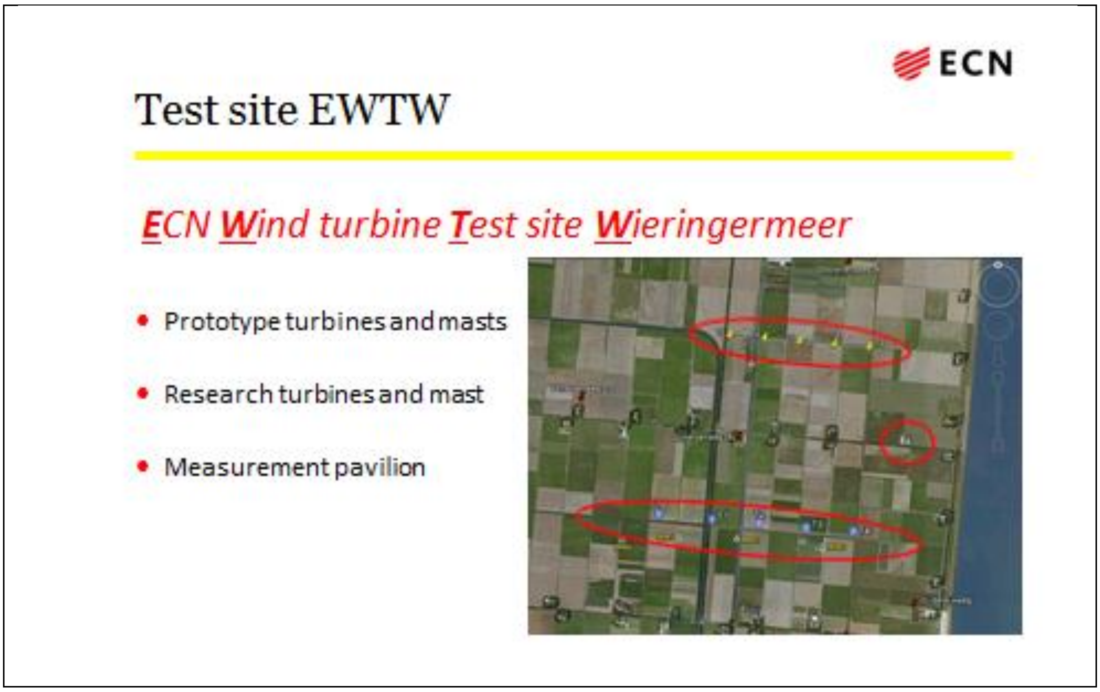
ECN Wind turbine Test site Wieringermeer

- On shore
- Near lake IJsselmeer
- Flat, agricultural terrain
- About 35km from ECN

- Mean ws: 8.3m/s (@100m)
- Mean wd: South West
- Mean TI: 8.1% (@80m)



ECN: Developing wind since 1974



Test site EWTW

ECN Wind turbine Test site Wieringermeer

- Prototype turbines and masts
- Research turbines and mast
- Measurement pavilion

Prototype turbine measurements

ECN is ISO 17025 certified for measurements on:

- Power performance
  - IEC 61400-12-1, 12-2
  - MEASNET
- Mechanical loads
  - IEC 61400-13
- Meteorological measurements
  - LiDAR/SoDAR validation

ECN is active in a standardization /working groups (quality):

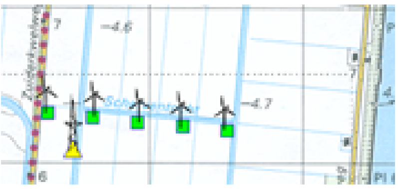
- MEASNET expert groups
- IEC/TC88, IECRE

Dedicated campaigns are organized as well

Dedicated measurement campaigns

- Validation measurements for LM iRotor
  - iRotor developed by LM: blade tip response measurement system
  - Validation measurement by ECN
  - two high frequency lasers on tower surface
  - accurate measurement of distance to passing tip

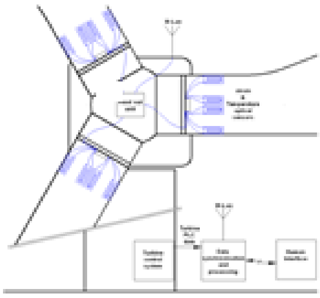
- Innotip
  - design, build and validate innovative offshore blade tips for increasing AEP
  - Project partners LM, ECN
  - Funded by Dutch TKI
  - Loads and power curve measurements with various tip shapes on ECN research turbines

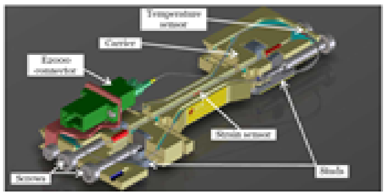


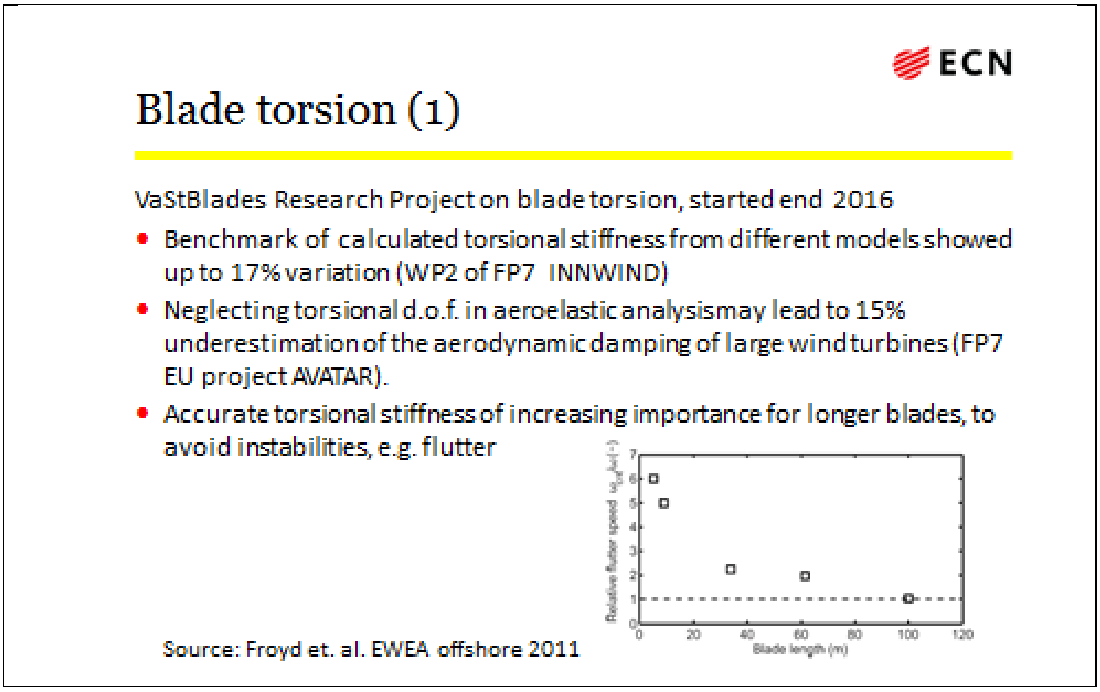
Sensor development

Fibre Optic Blade Load Monitoring (FOBM)

- Patented sensor developed by ECN
- High accuracy and durability
- Mounted on two studs, easy to install and replace
- Sensing over inhomogeneous strained surface
- Initially developed for CBM, also suitable for load based control
- Demonstration project “LoadWatch” with OEM (Dutch TKI project).







ECN

Blade torsion (1)

VaStBlades Research Project on blade torsion, started end 2016

- Benchmark of calculated torsional stiffness from different models showed up to 17% variation (WP2 of FP7 INNWIND)
- Neglecting torsional d.o.f. in aeroelastic analysis may lead to 15% underestimation of the aerodynamic damping of large wind turbines (FP7 EU project AVATAR).
- Accurate torsional stiffness of increasing importance for longer blades, to avoid instabilities, e.g. flutter

Source: Froyd et. al. EWEA offshore 2011

ECN

Blade torsion (2)

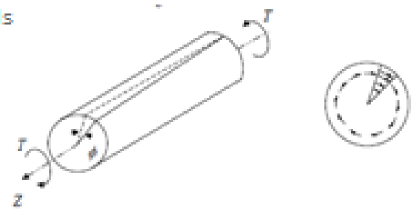
- Video of blade of HAT turbine, rotor diameter 25m

Video by Jos Beurskens

Blade torsion (3)

VaStBlades Research Project on blade torsion

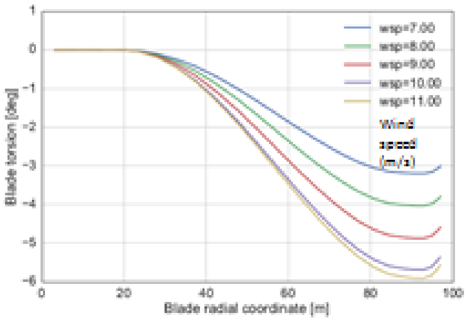
- Dutch TKI project with WMC and industrial partners
- Work packages:
  - WP1 Structural blade model improvement
  - WP2 Laboratory tests at component level
  - WP3 On-site turbine measurements
  - WP4 Validation of models and tools
  - WP5 10MW blade design using improved tools
- Torsion order of magnitude:
  1 degree/10m span, outer blade area



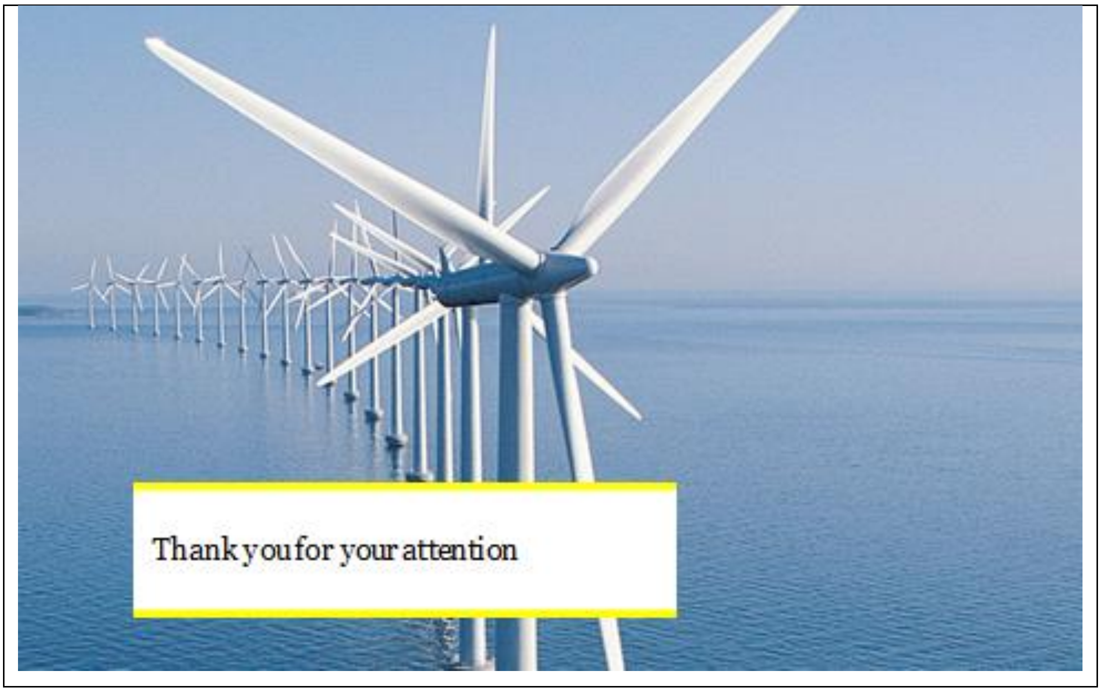
Blade torsion (4)

VaStBlades Project on blade torsion

- Target to measure outer 1/3 of span
- Measurement system development
  - Optical
  - Fiber optic
    - Strain spatial resolution, frequency
    - Conversion to torsional deformation



Design of an Aeroelastically Tailored 10 MW Wind Turbine Rotor, Frederik Zahle, DTU



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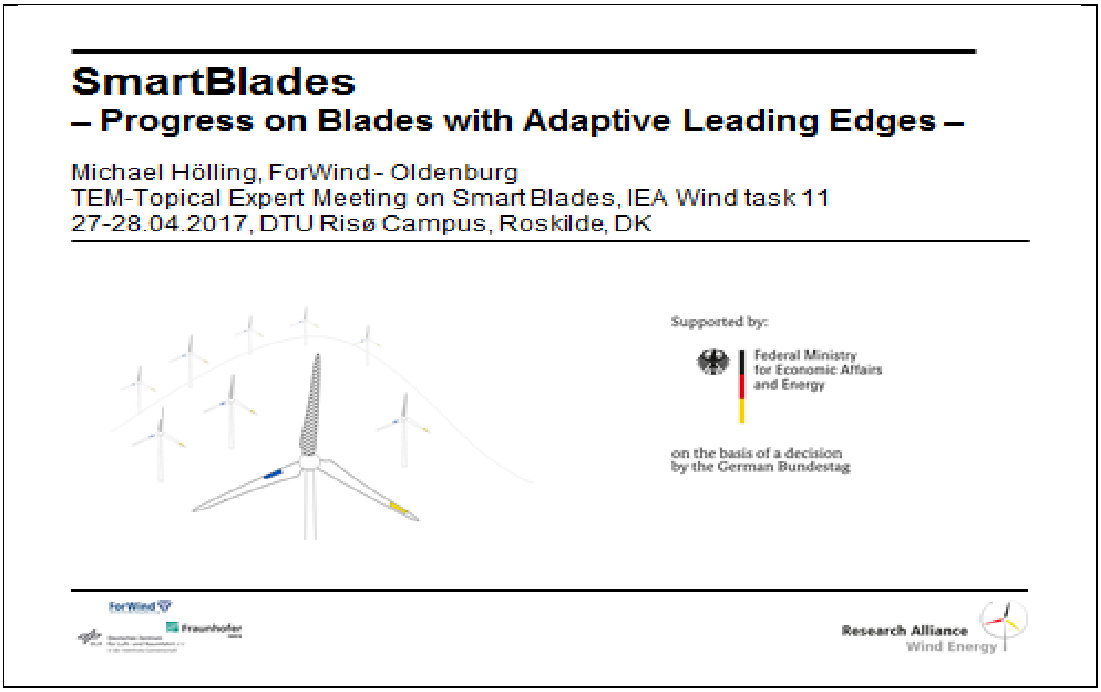

SmartBlades
– Progress on Blades with Adaptive Leading Edges –

Michael Hölling, ForWind - Oldenburg
TEM-Topical Expert Meeting on Smart Blades, IEA Wind task 11
27-28.04.2017, DTU Risø Campus, Roskilde, DK

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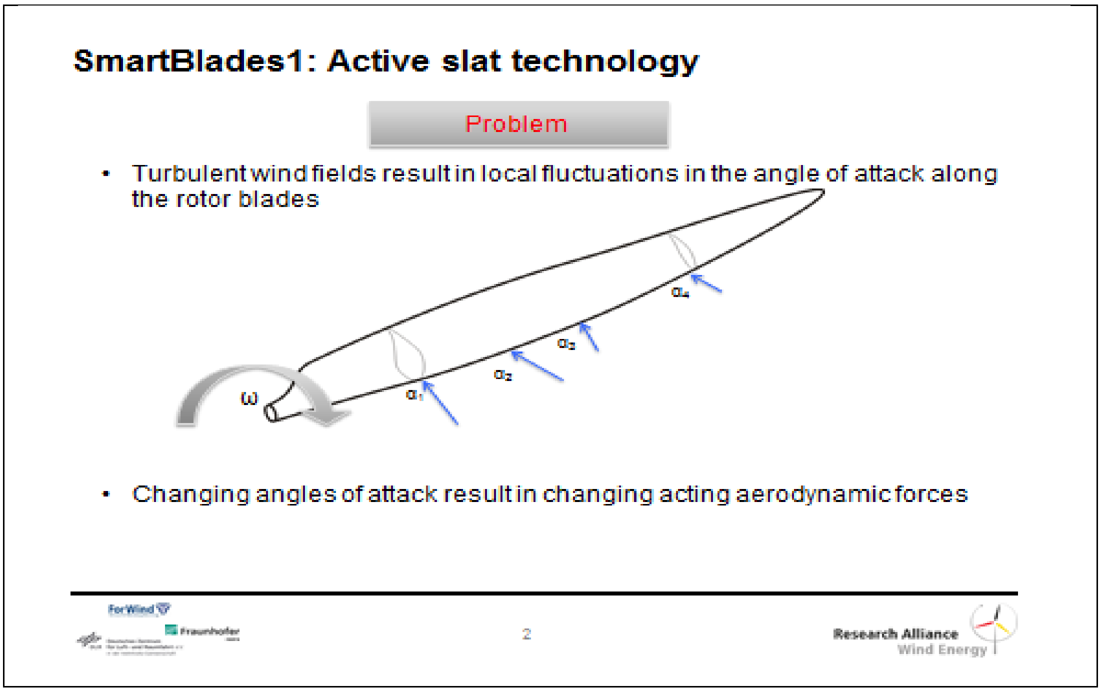


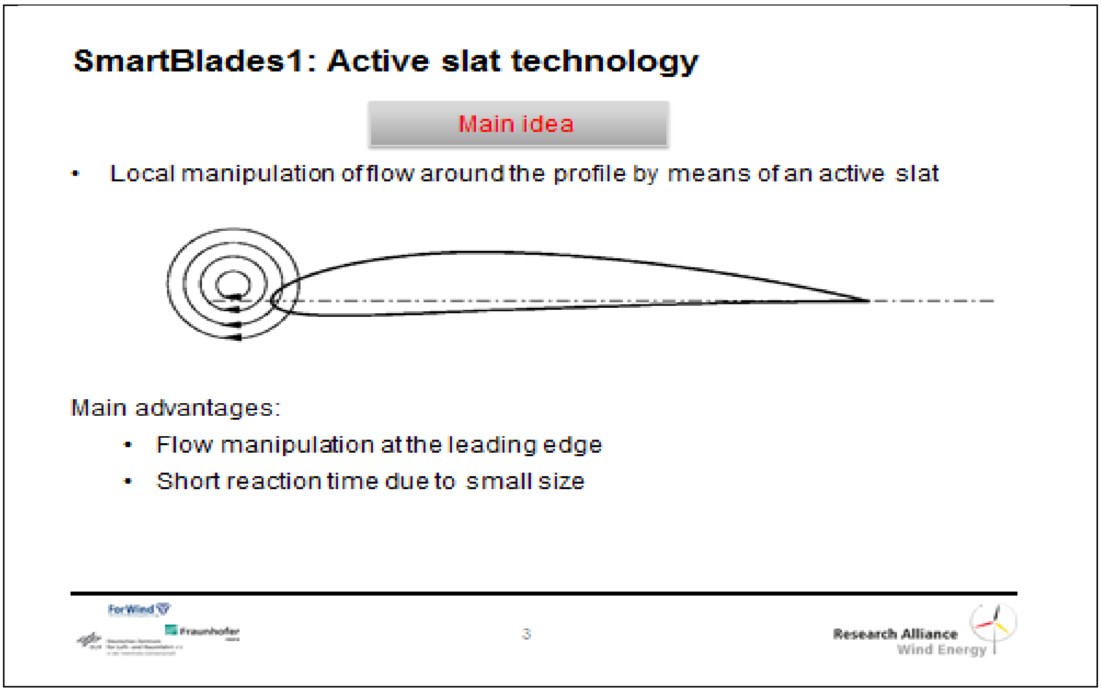
SmartBlades1: Active slat technology

Problem

- Turbulent wind fields result in local fluctuations in the angle of attack along the rotor blades

- Changing angles of attack result in changing acting aerodynamic forces

Research Alliance Wind Energy



SmartBlades1: Active slat technology

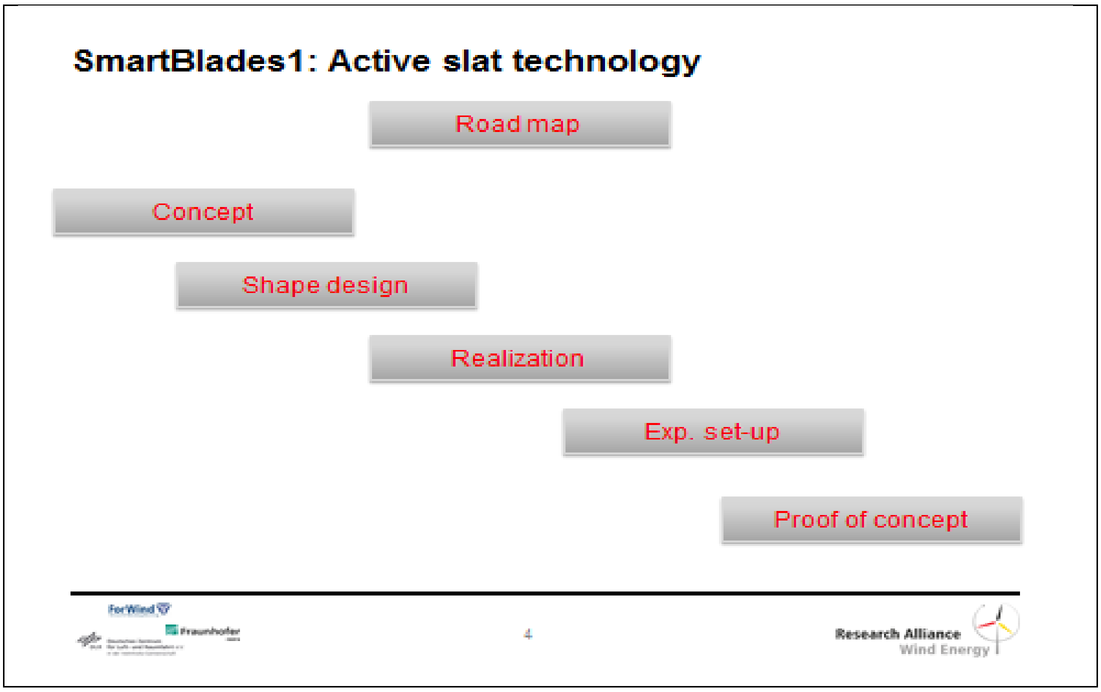
Main idea

- Local manipulation of flow around the profile by means of an active slat

Main advantages:

- Flow manipulation at the leading edge
- Short reaction time due to small size

Research Alliance Wind Energy



SmartBlades1: Active slat technology

Road map

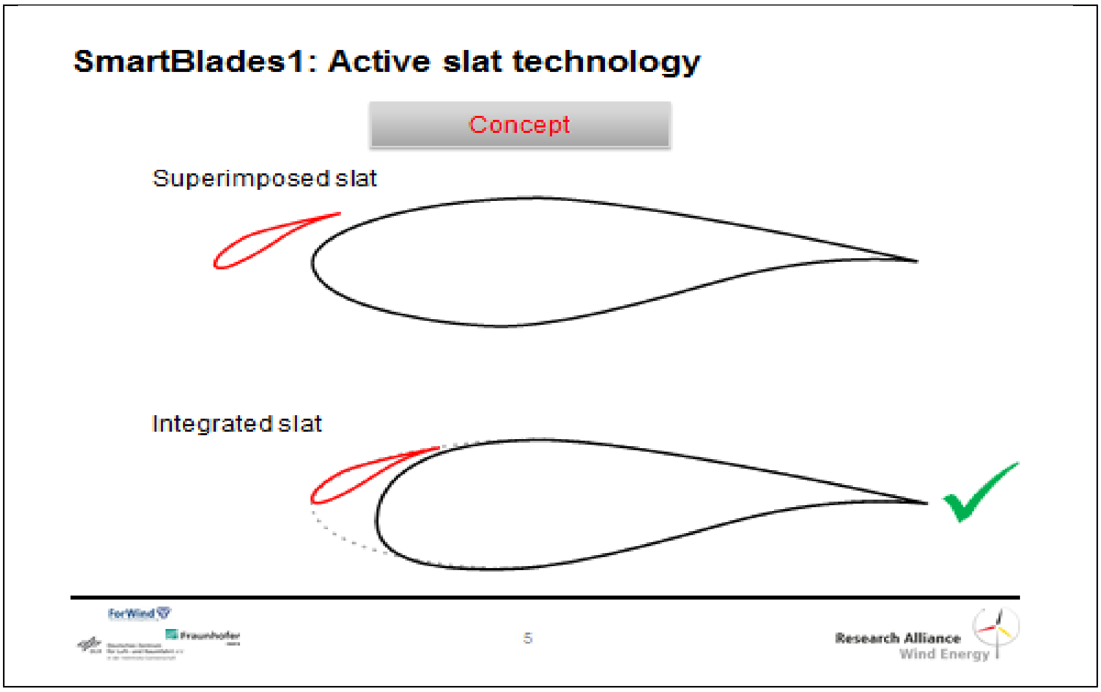
Concept

Shape design

Realization

Exp. set-up

Proof of concept

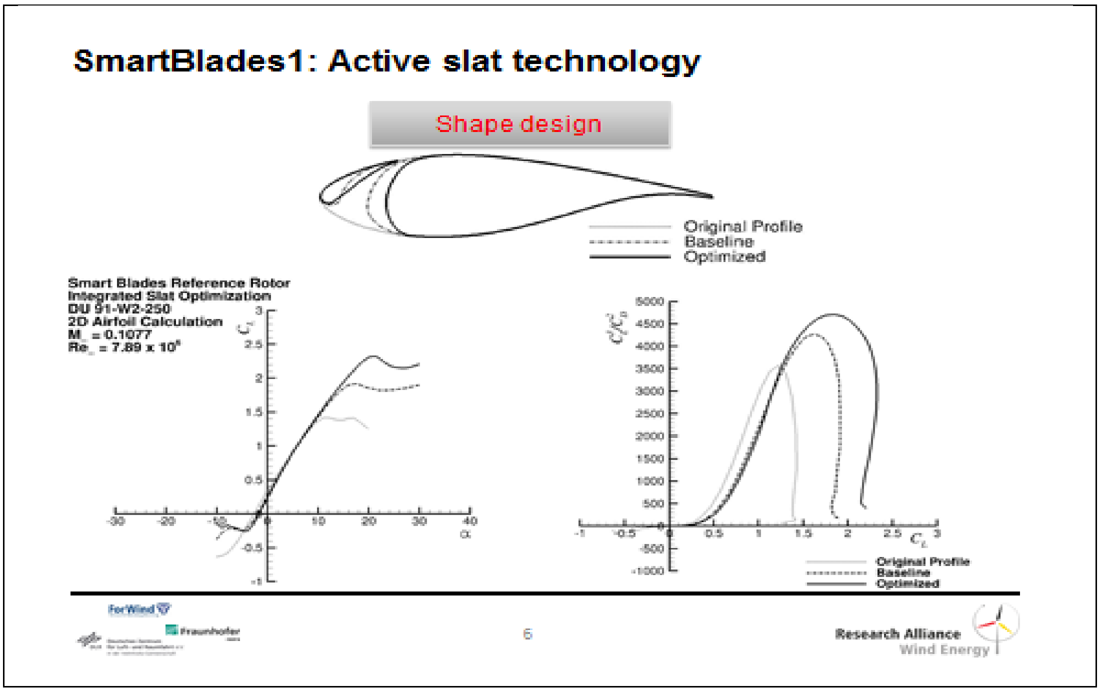


SmartBlades1: Active slat technology

Concept

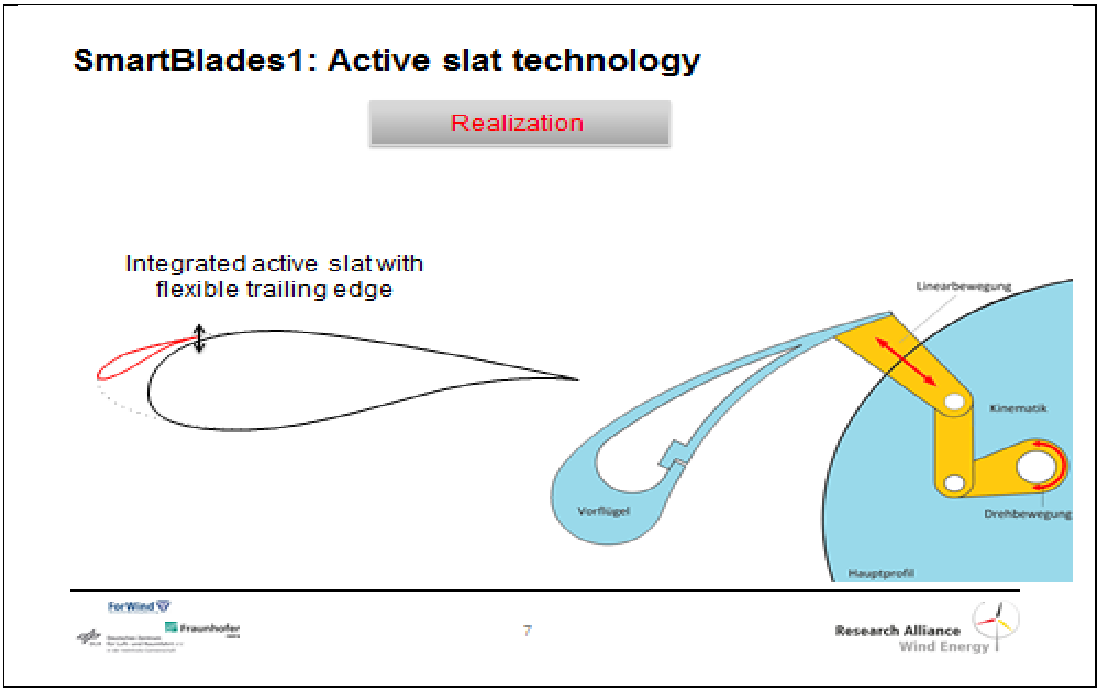
Superimposed slat

Integrated slat ✓



SmartBlades1: Active slat technology

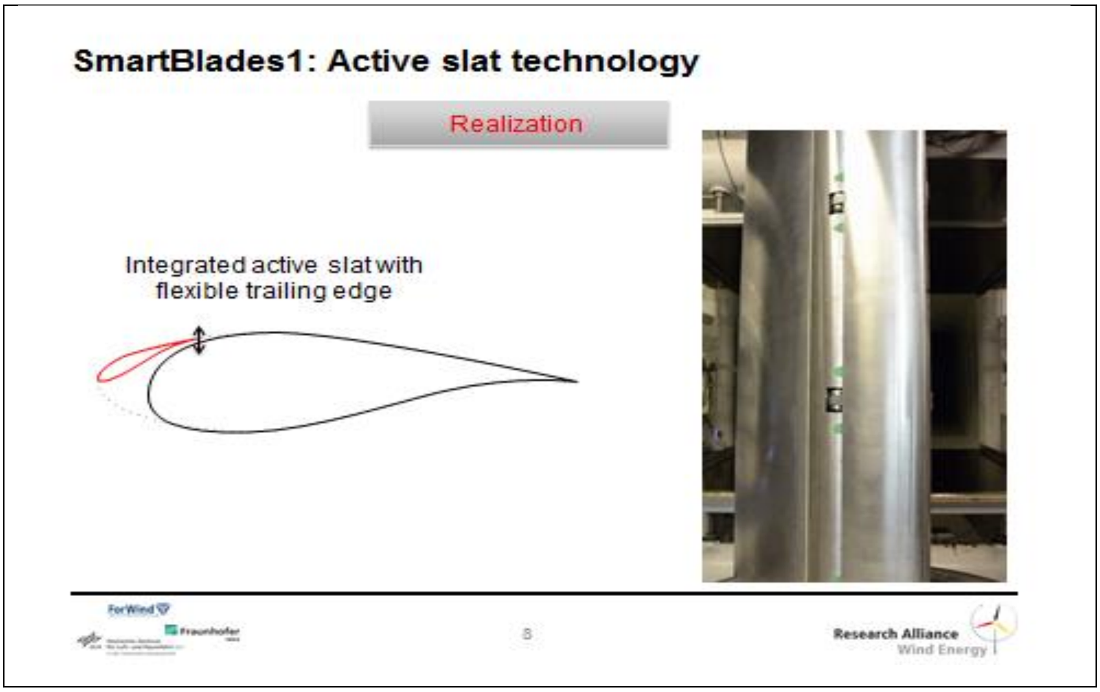
Shape design



SmartBlades1: Active slat technology

Realization

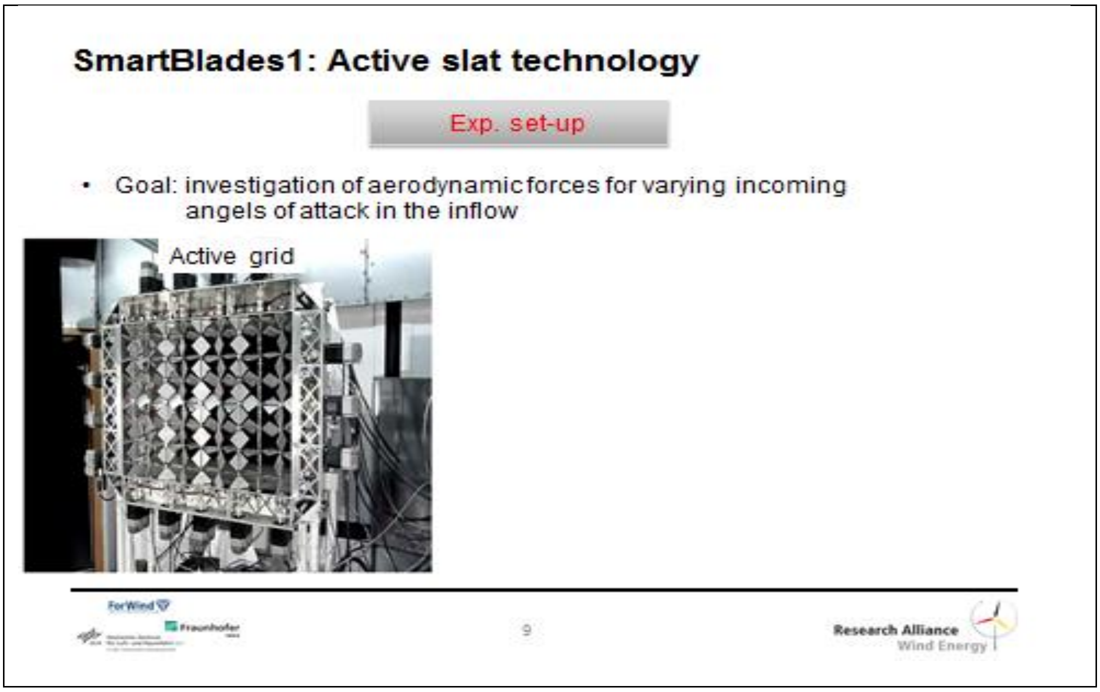
Integrated active slat with flexible trailing edge



SmartBlades1: Active slat technology

Realization

Integrated active slat with flexible trailing edge

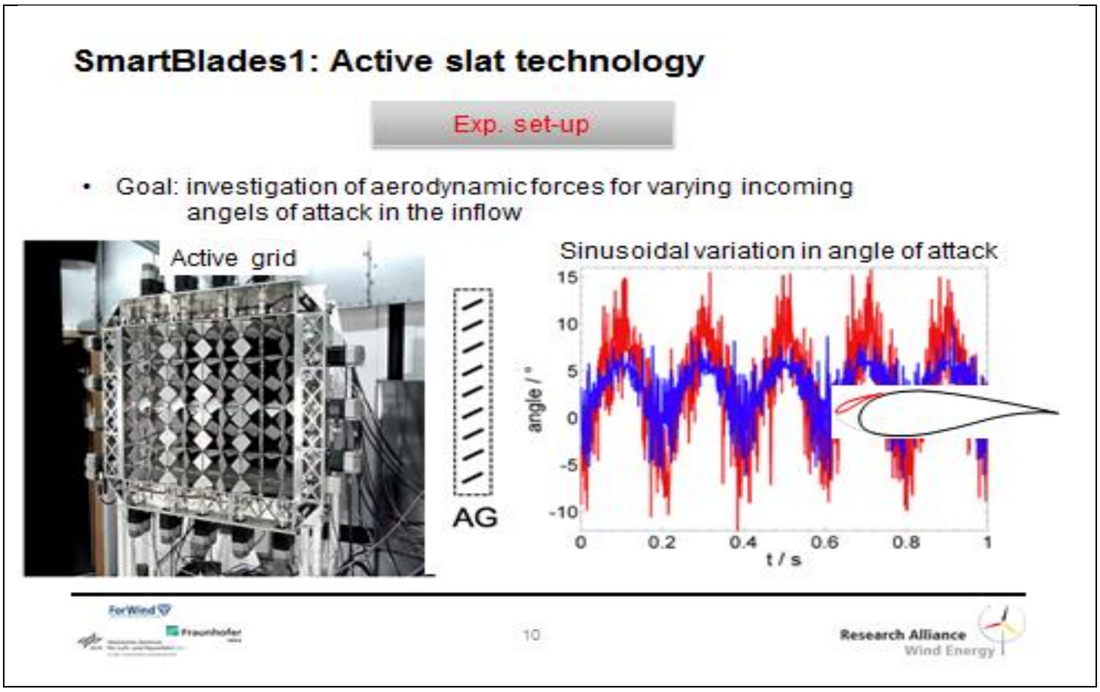


SmartBlades1: Active slat technology

Exp. set-up

- Goal: investigation of aerodynamic forces for varying incoming angels of attack in the inflow

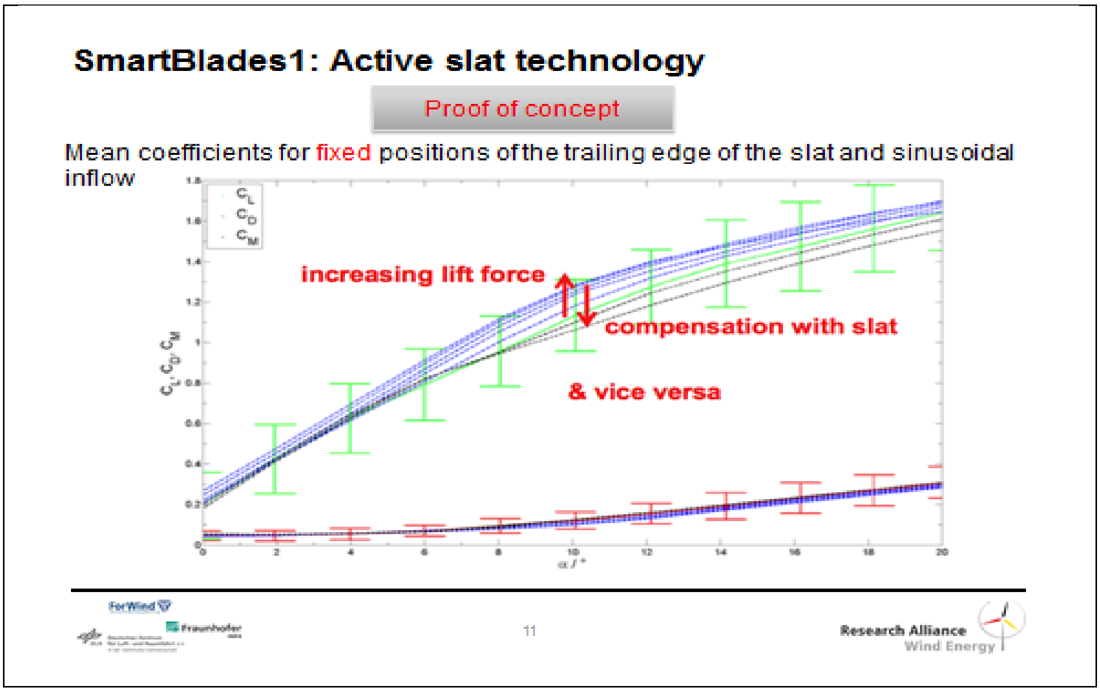
Active grid



SmartBlades1: Active slat technology

Exp. set-up

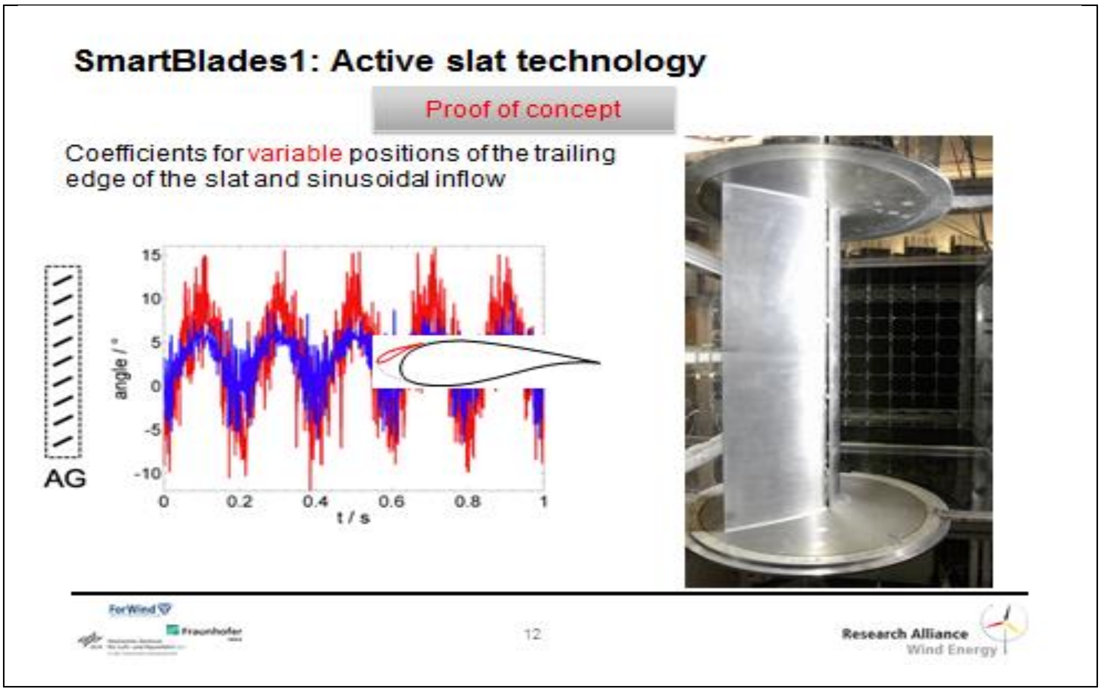
- Goal: investigation of aerodynamic forces for varying incoming angels of attack in the inflow



SmartBlades1: Active slat technology

Proof of concept

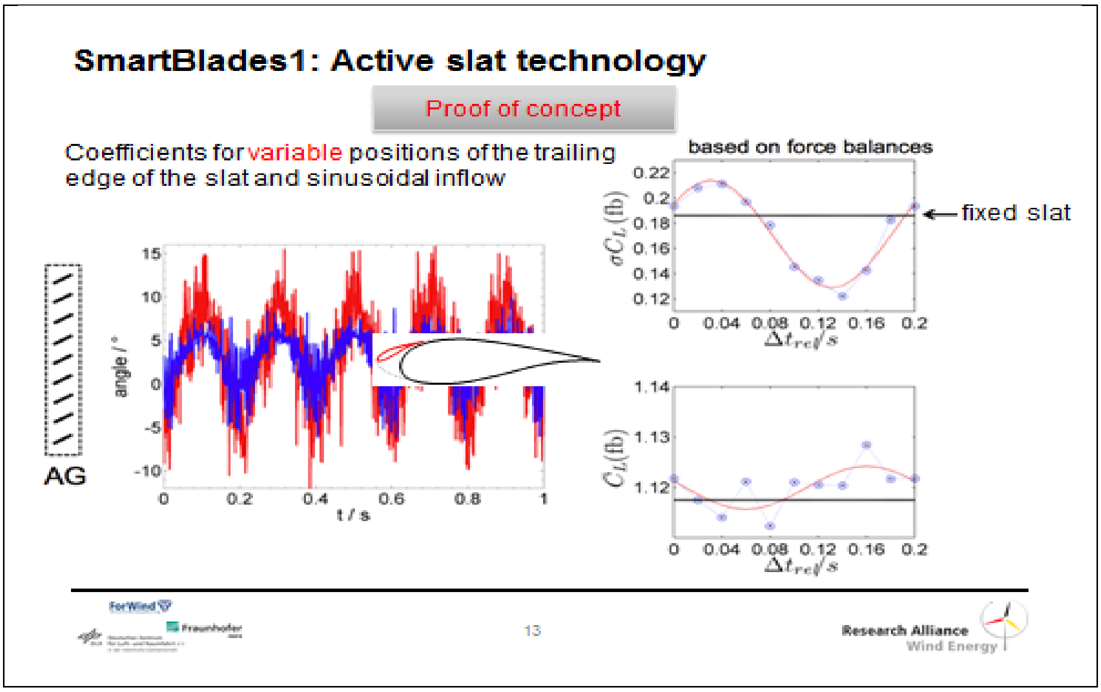
Mean coefficients for fixed positions of the trailing edge of the slat and sinusoidal inflow



SmartBlades1: Active slat technology

Proof of concept

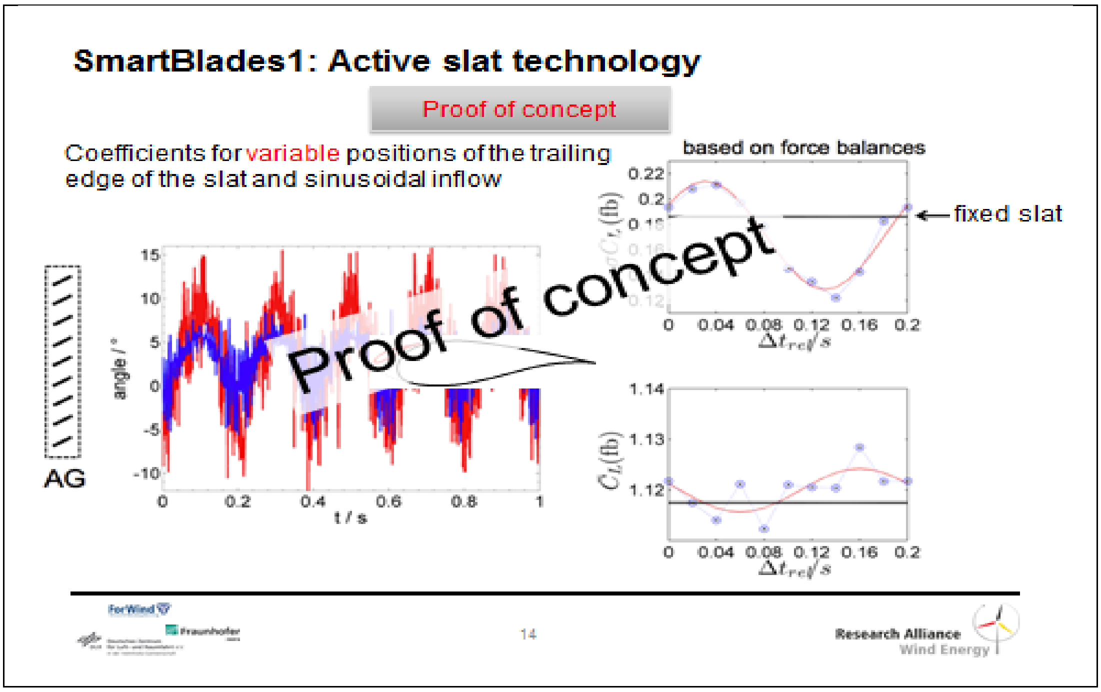
Coefficients for variable positions of the trailing edge of the slat and sinusoidal inflow



SmartBlades1: Active slat technology

Proof of concept

Coefficients for variable positions of the trailing edge of the slat and sinusoidal inflow

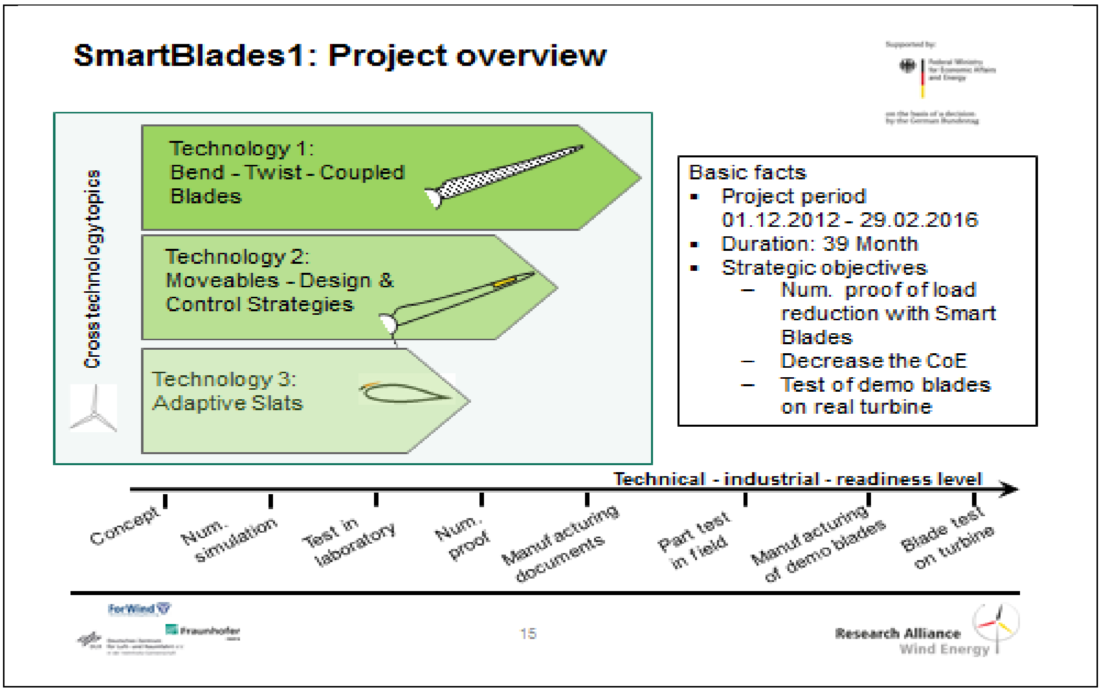


SmartBlades1: Active slat technology

Proof of concept

Coefficients for variable positions of the trailing edge of the slat and sinusoidal inflow

based on force balances



SmartBlades1: Project overview

Technology 1: Bend - Twist - Coupled Blades

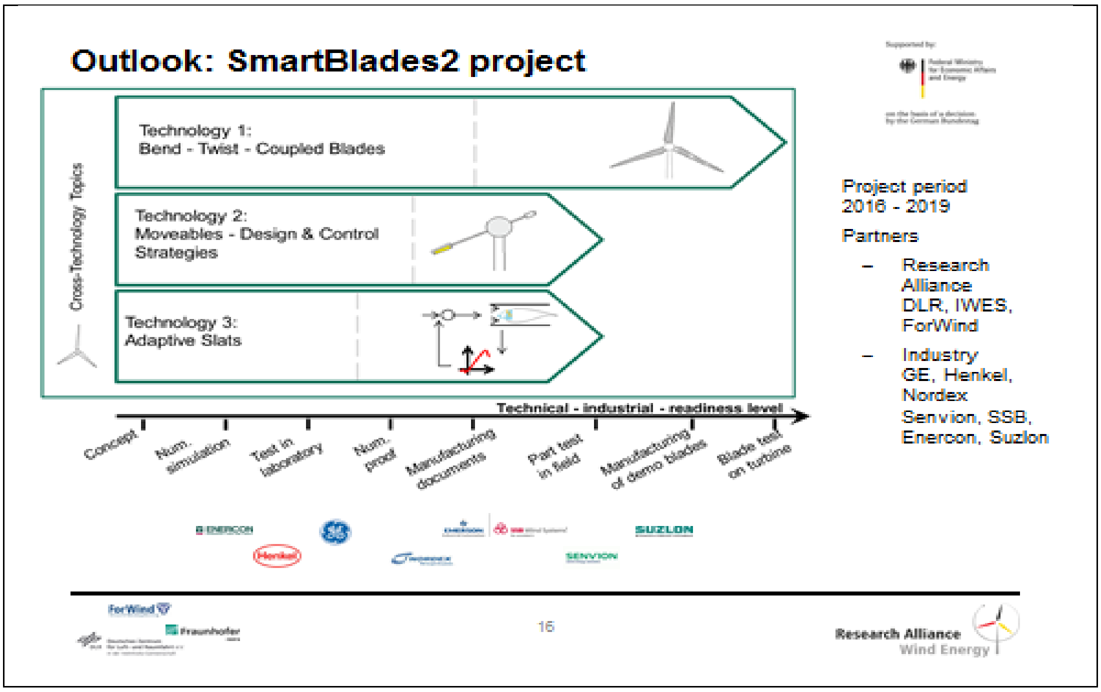
Technology 2: Moveables - Design & Control Strategies

Technology 3: Adaptive Slats

Basic facts

- Project period 01.12.2012 - 29.02.2016
- Duration: 39 Month
- Strategic objectives
  - Num. proof of load reduction with Smart Blades
  - Decrease the CoE
  - Test of demo blades on real turbine

Technical - industrial - readiness level



Outlook: SmartBlades2 project

Technology 1:
Bend - Twist - Coupled Blades

Technology 2:
Moveables - Design & Control Strategies

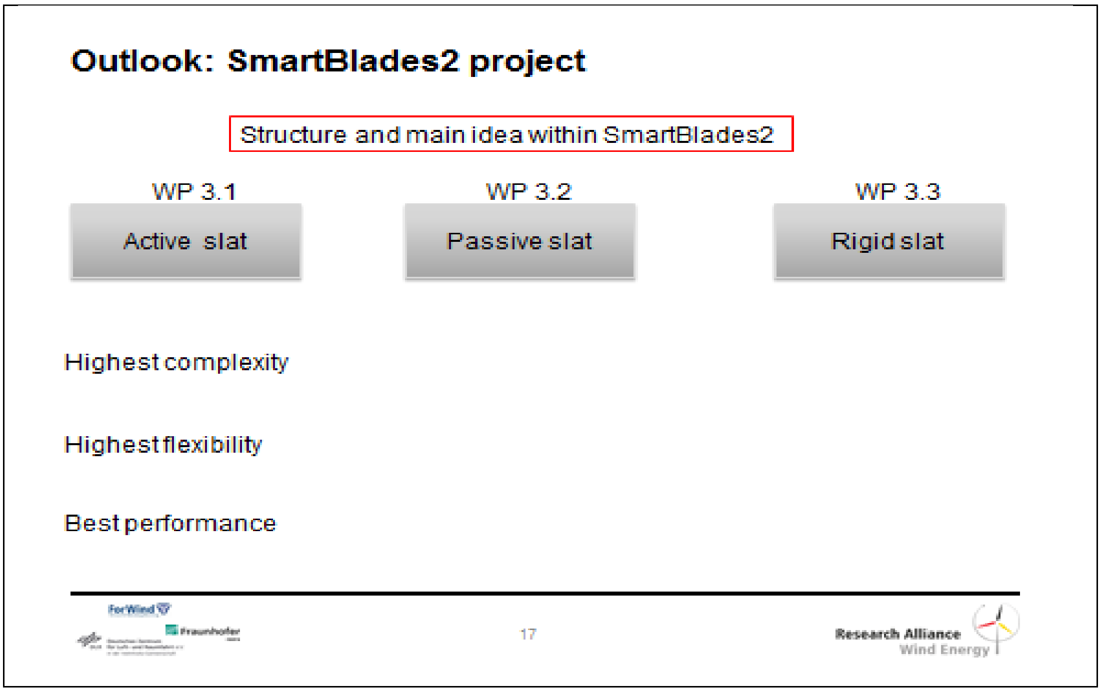
Technology 3:
Adaptive Slats

Technical - industrial - readiness level

Project period
2016 - 2019

Partners

- Research Alliance
  DLR, IWES, ForWind
- Industry
  GE, Henkel, Nordex
  Senvion, SSB, Enercon, Suzlon



Outlook: SmartBlades2 project

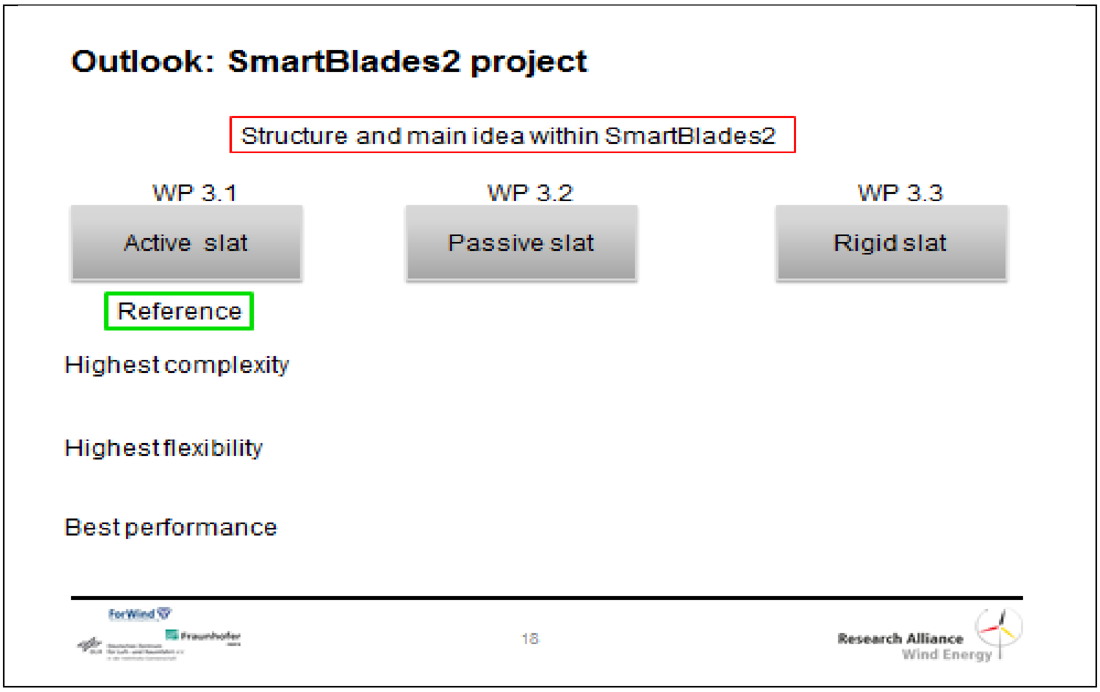
Structure and main idea within SmartBlades2

WP 3.1	WP 3.2	WP 3.3
Active slat	Passive slat	Rigid slat

Highest complexity

Highest flexibility

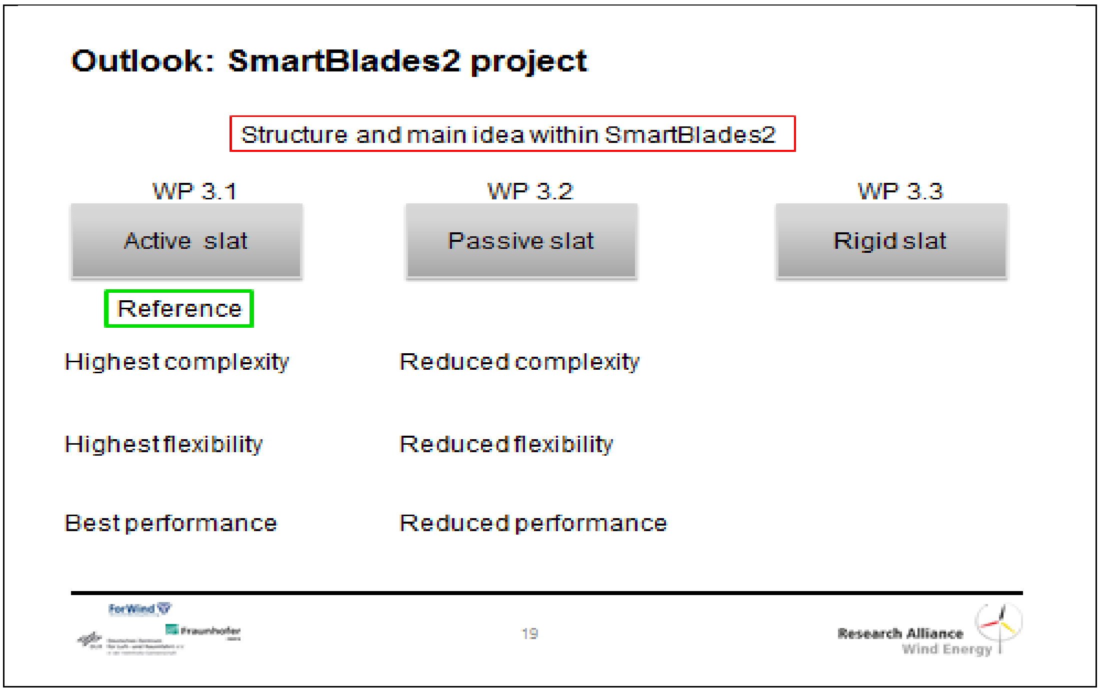
Best performance



Outlook: SmartBlades2 project

Structure and main idea within SmartBlades2

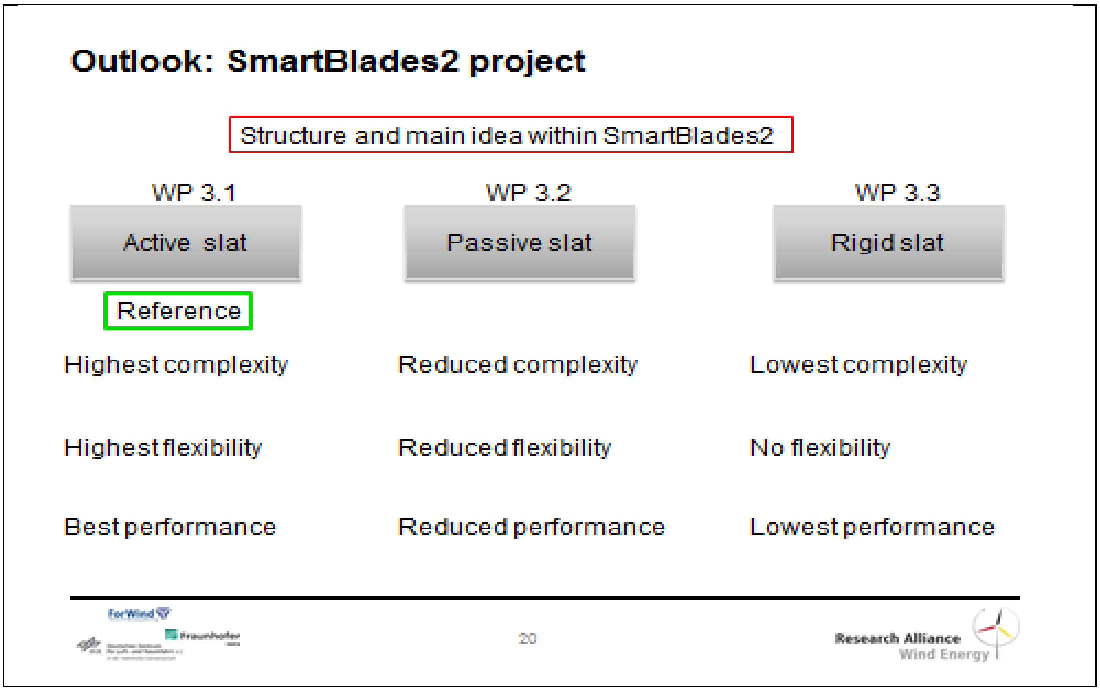
WP 3.1	WP 3.2	WP 3.3
Active slat	Passive slat	Rigid slat
Reference		
Highest complexity		
Highest flexibility		
Best performance		



Outlook: SmartBlades2 project

Structure and main idea within SmartBlades2

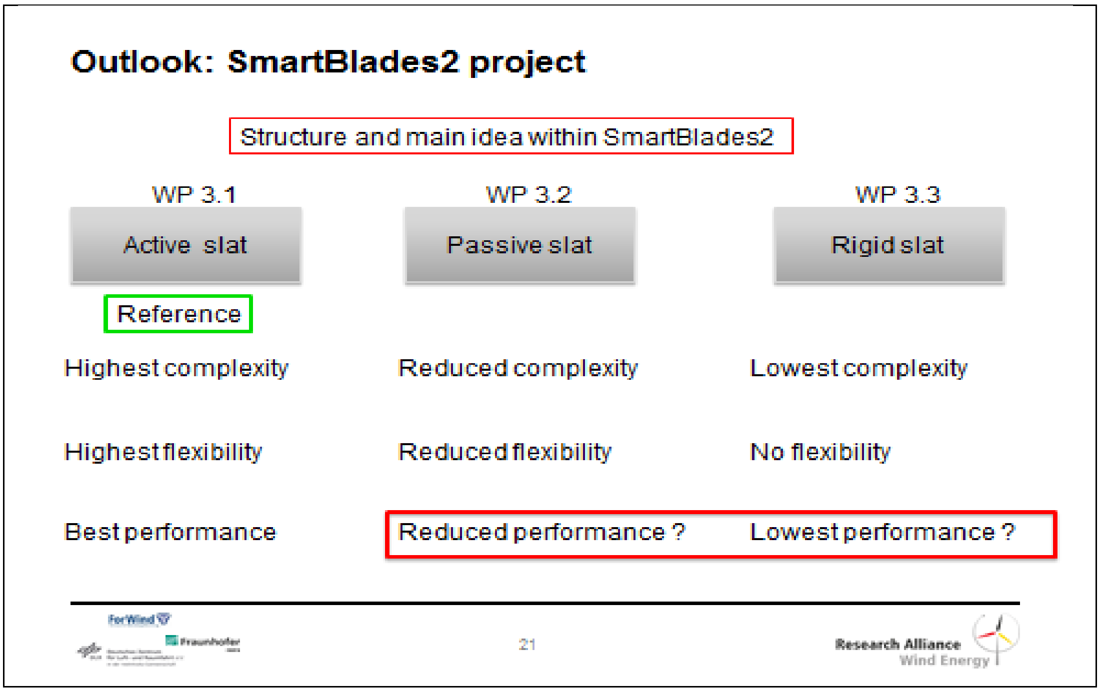
WP 3.1	WP 3.2	WP 3.3
Active slat	Passive slat	Rigid slat
Reference		
Highest complexity	Reduced complexity	
Highest flexibility	Reduced flexibility	
Best performance	Reduced performance	



Outlook: SmartBlades2 project

Structure and main idea within SmartBlades2

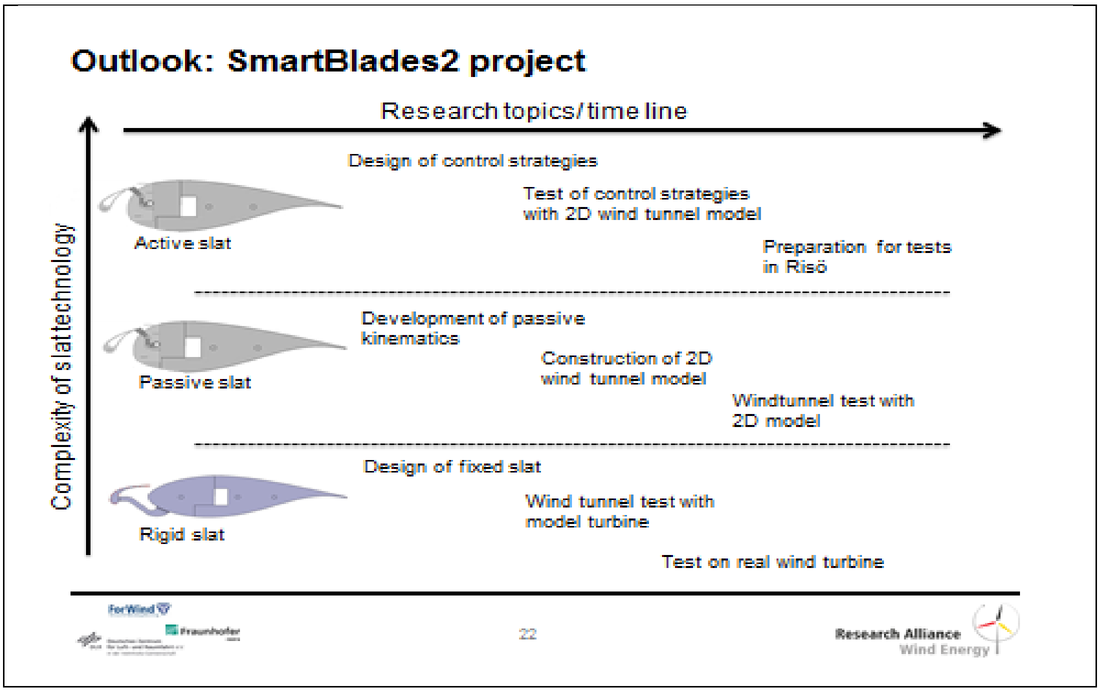
WP 3.1	WP 3.2	WP 3.3
Active slat	Passive slat	Rigid slat
Reference		
Highest complexity	Reduced complexity	Lowest complexity
Highest flexibility	Reduced flexibility	No flexibility
Best performance	Reduced performance	Lowest performance



Outlook: SmartBlades2 project

Structure and main idea within SmartBlades2

WP 3.1	WP 3.2	WP 3.3
Active slat	Passive slat	Rigid slat
Reference		
Highest complexity	Reduced complexity	Lowest complexity
Highest flexibility	Reduced flexibility	No flexibility
Best performance	Reduced performance ?	Lowest performance ?



Outlook: SmartBlades2 project

Design of control strategies

Test of control strategies with 2D wind tunnel model

Preparation for tests in Risö

Development of passive kinematics

Construction of 2D wind tunnel model

Windtunnel test with 2D model

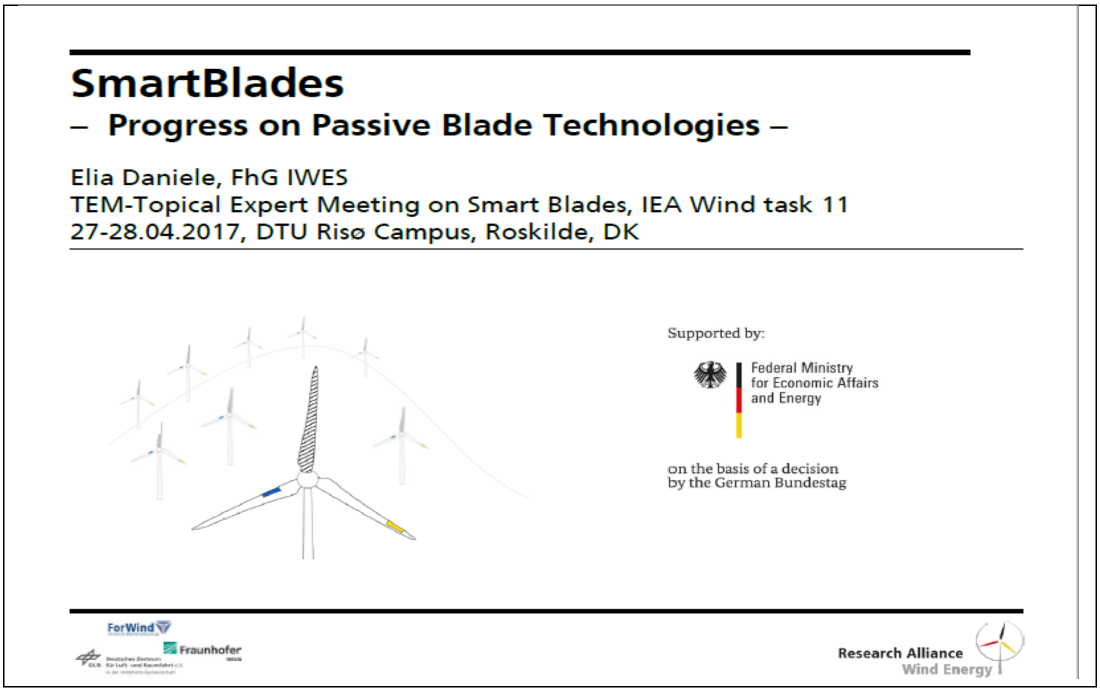
Design of fixed slat

Wind tunnel test with model turbine

Test on real wind turbine

Thank you for your attention!

Contact: michael.hoelling@uni-oldenburg.de



SmartBlades
– Progress on Passive Blade Technologies –

Elia Daniele, FhG IWES
TEM-Topical Expert Meeting on Smart Blades, IEA Wind task 11
27-28.04.2017, DTU Risø Campus, Roskilde, DK

Supported by:

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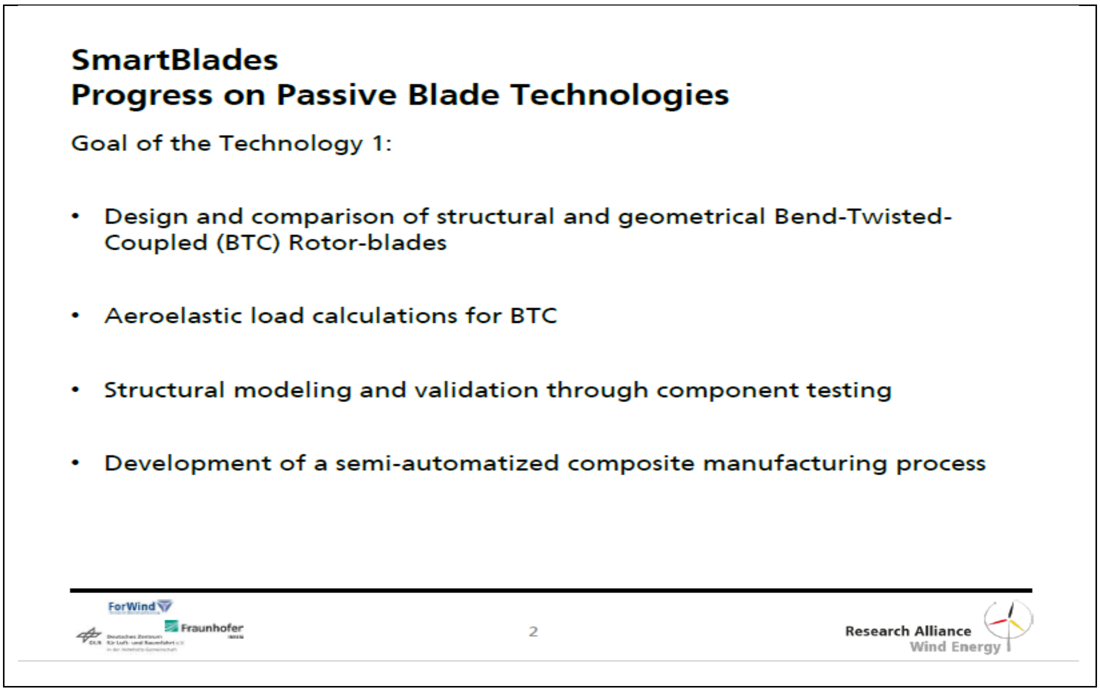
ForWind

Fraunhofer

Research Alliance
Wind Energy



SmartBlades
Progress on Passive Blade Technologies

Goal of the Technology 1:

- Design and comparison of structural and geometrical Bend-Twisted-Coupled (BTC) Rotor-blades
- Aeroelastic load calculations for BTC
- Structural modeling and validation through component testing
- Development of a semi-automatized composite manufacturing process

ForWind

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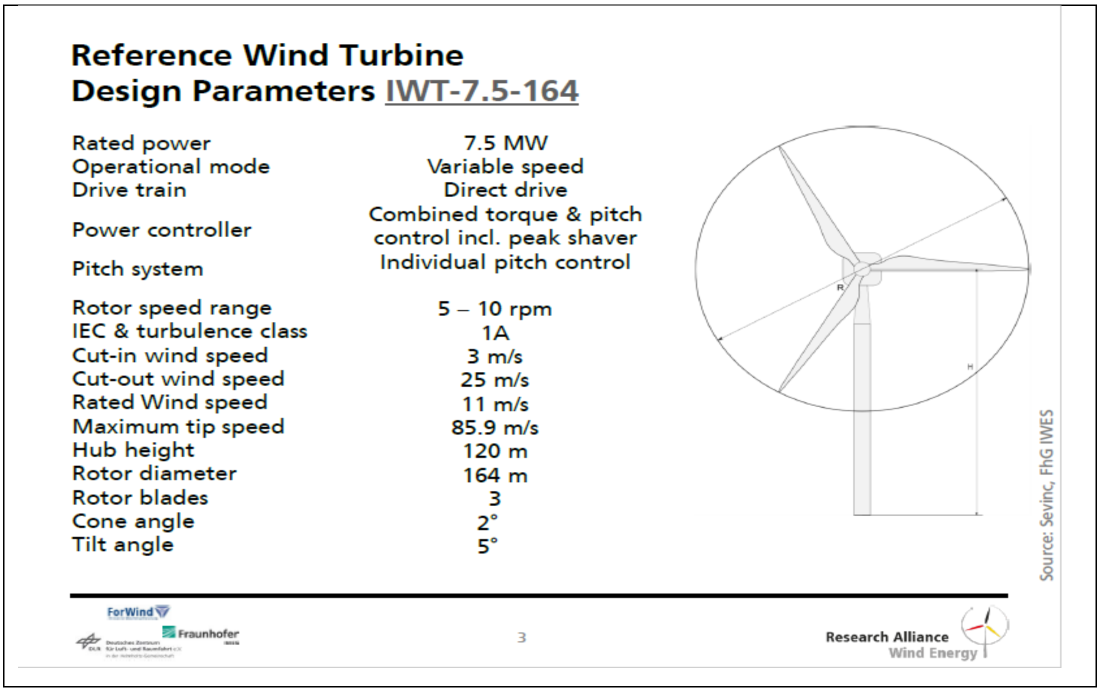
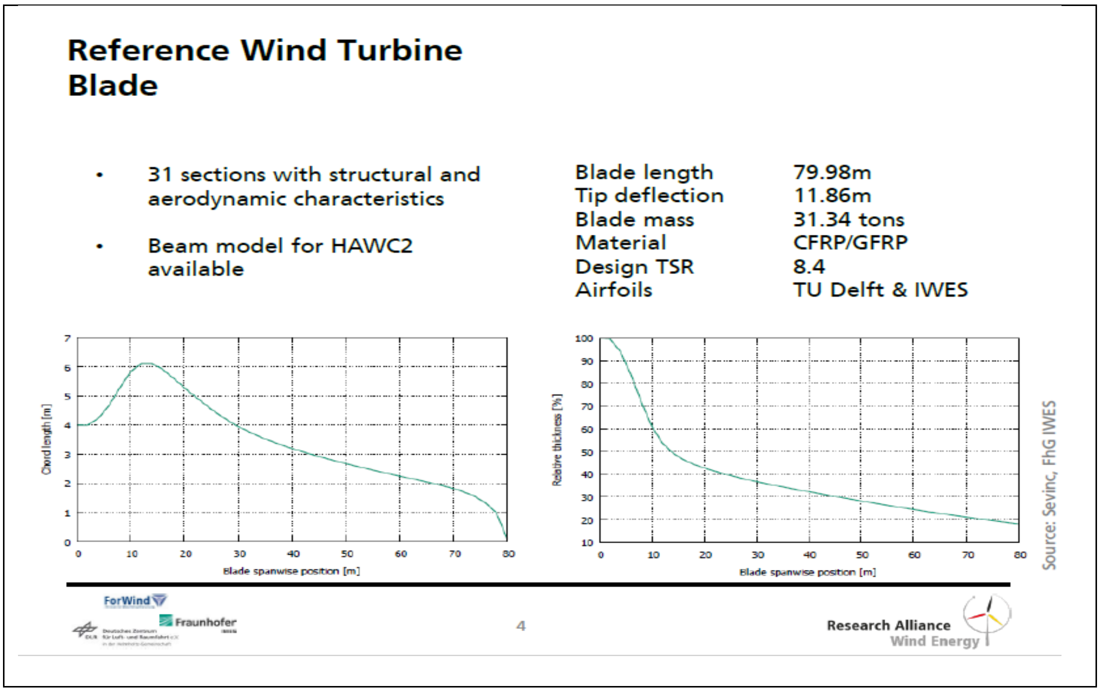
Wind Energy



Reference Wind Turbine
Design Parameters IWT-7.5-164

Rated power	7.5 MW
Operational mode	Variable speed
Drive train	Direct drive
Power controller	Combined torque & pitch control incl. peak shaver
Pitch system	Individual pitch control
Rotor speed range	5 – 10 rpm
IEC & turbulence class	1A
Cut-in wind speed	3 m/s
Cut-out wind speed	25 m/s
Rated Wind speed	11 m/s
Maximum tip speed	85.9 m/s
Hub height	120 m
Rotor diameter	164 m
Rotor blades	3
Cone angle	2°
Tilt angle	5°

Source: Sevinc, FhG IWES

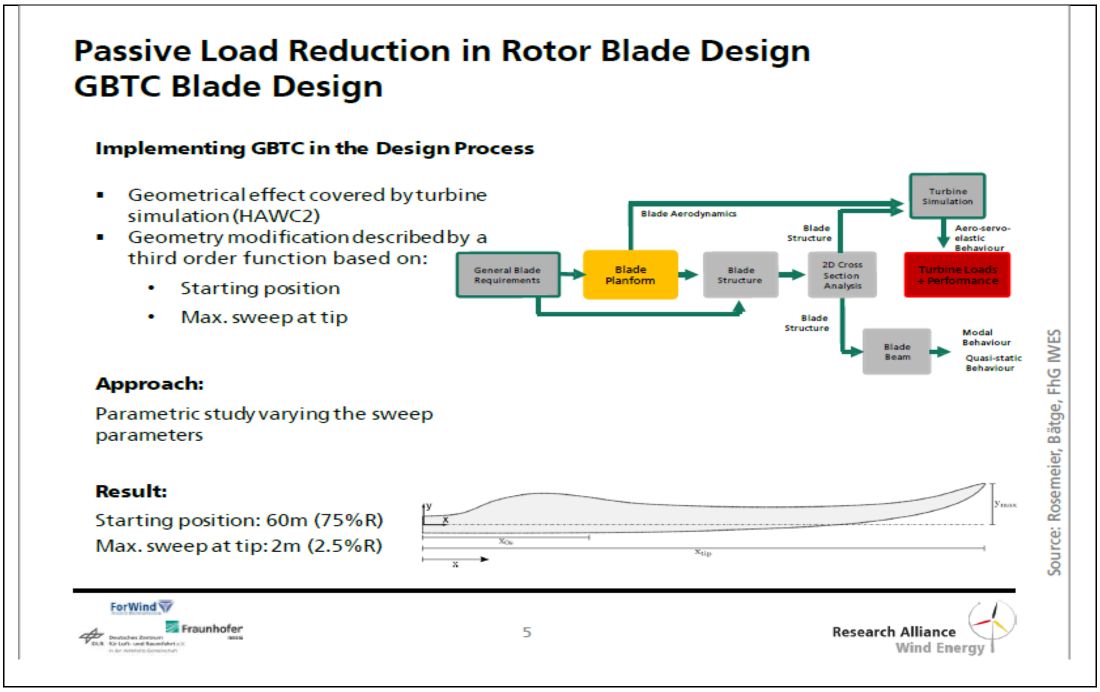


Reference Wind Turbine
Blade

- 31 sections with structural and aerodynamic characteristics
- Beam model for HAWC2 available

Blade length	79.98m
Tip deflection	11.86m
Blade mass	31.34 tons
Material	CFRP/GFRP
Design TSR	8.4
Airfoils	TU Delft & IWES

Source: Sevinc, FhG IWES



Passive Load Reduction in Rotor Blade Design
GBTC Blade Design

Implementing GBTC in the Design Process

- Geometrical effect covered by turbine simulation (HAWC2)
- Geometry modification described by a third order function based on:
  - Starting position
  - Max. sweep at tip

Approach:

Parametric study varying the sweep parameters

Result:

Starting position: 60m (75%R)
Max. sweep at tip: 2m (2.5%R)

Source: Rosemeier, Bätge, FhG IWES

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DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.

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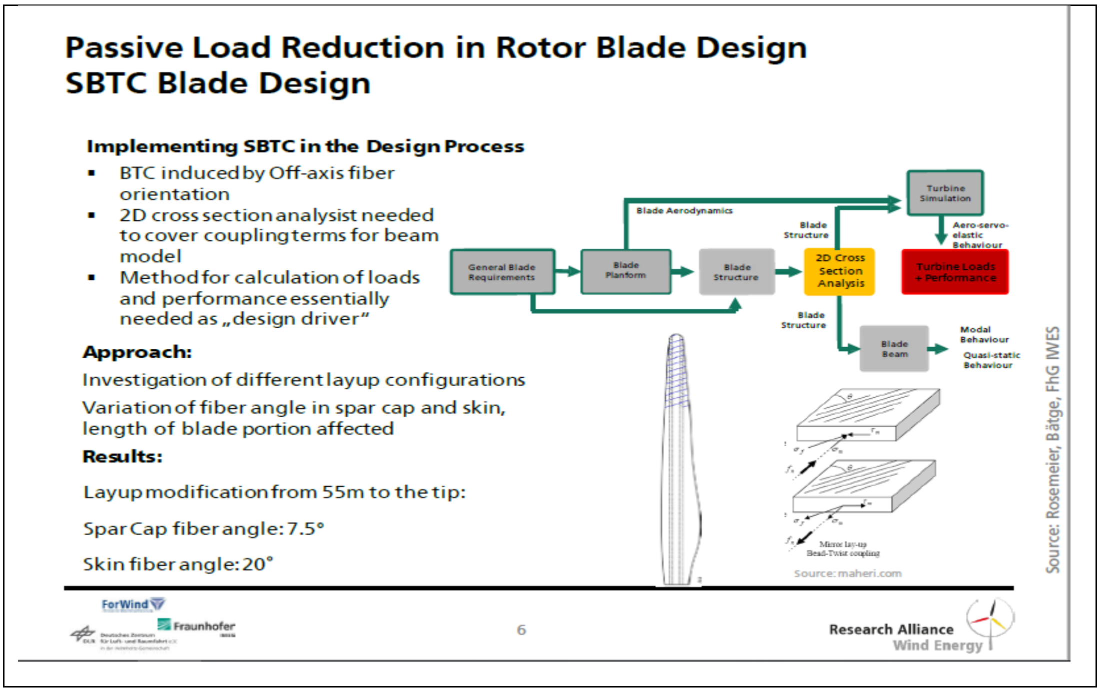
Research Alliance Wind Energy



Passive Load Reduction in Rotor Blade Design
SBTC Blade Design

Implementing SBTC in the Design Process

- BTC induced by Off-axis fiber orientation
- 2D cross section analysist needed to cover coupling terms for beam model
- Method for calculation of loads and performance essentially needed as „design driver"

Approach:

Investigation of different layup configurations

Variation of fiber angle in spar cap and skin, length of blade portion affected

Results:

Layup modification from 55m to the tip:

Spar Cap fiber angle: 7.5°

Skin fiber angle: 20°

Source: maheri.com

Source: Rosemeier, Bätge, FhG IWES

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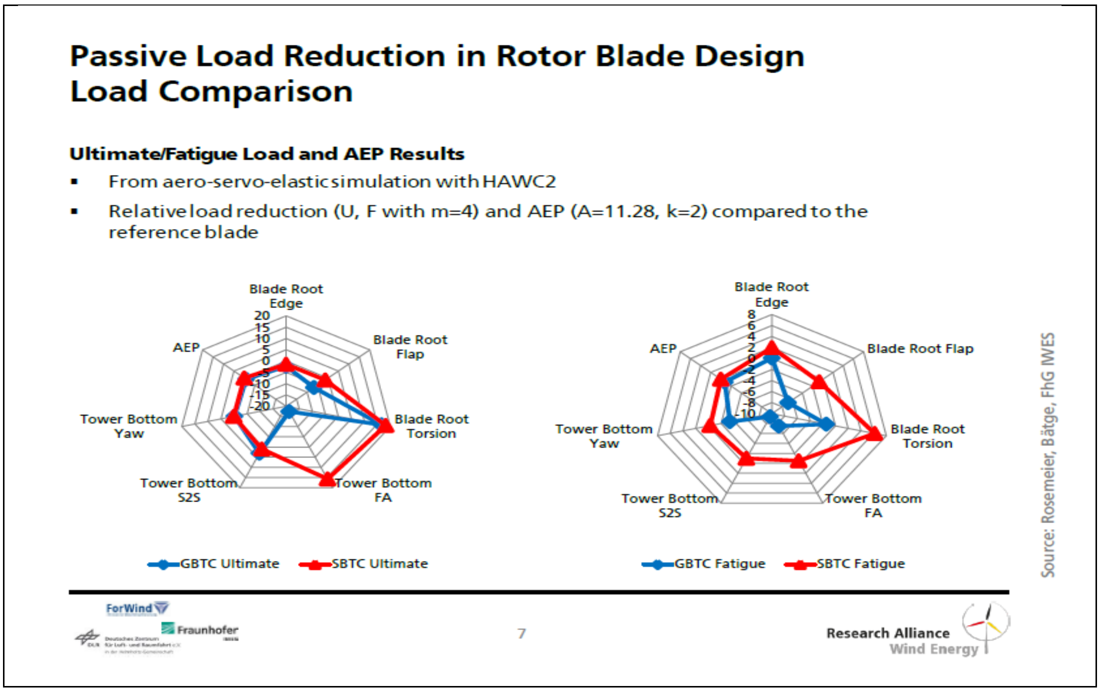
Research Alliance Wind Energy

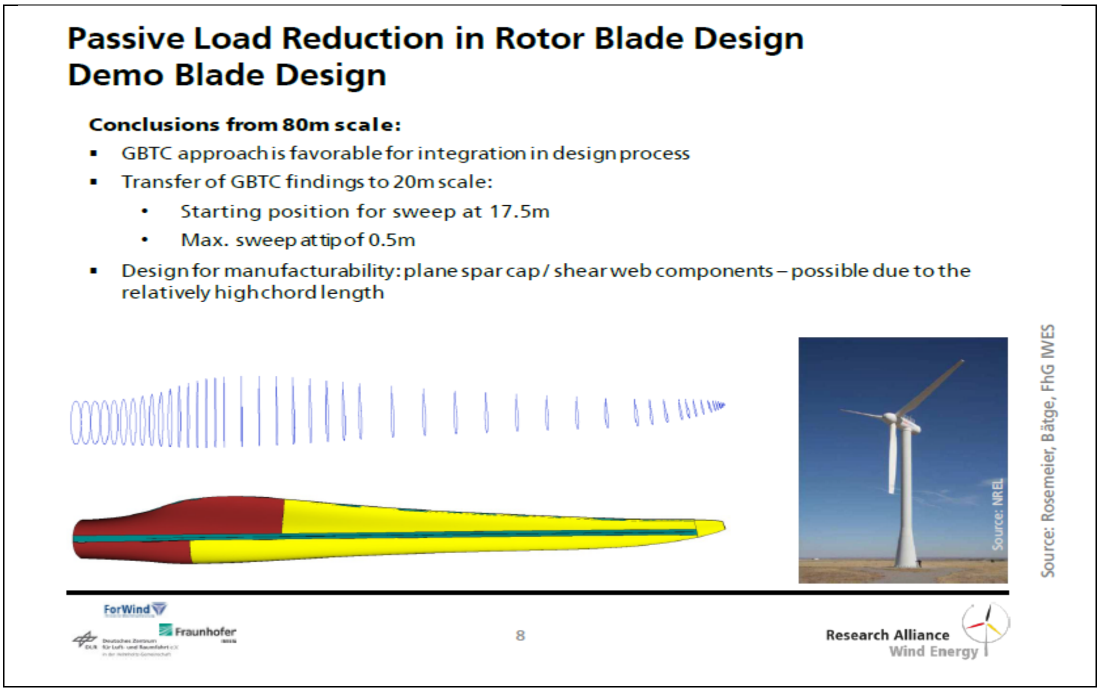


Passive Load Reduction in Rotor Blade Design
Load Comparison

Ultimate/Fatigue Load and AEP Results

- From aero-servo-elastic simulation with HAWC2
- Relative load reduction (U, F with m=4) and AEP (A=11.28, k=2) compared to the reference blade

Source: Rosemeier, Bätge, FhG IWES



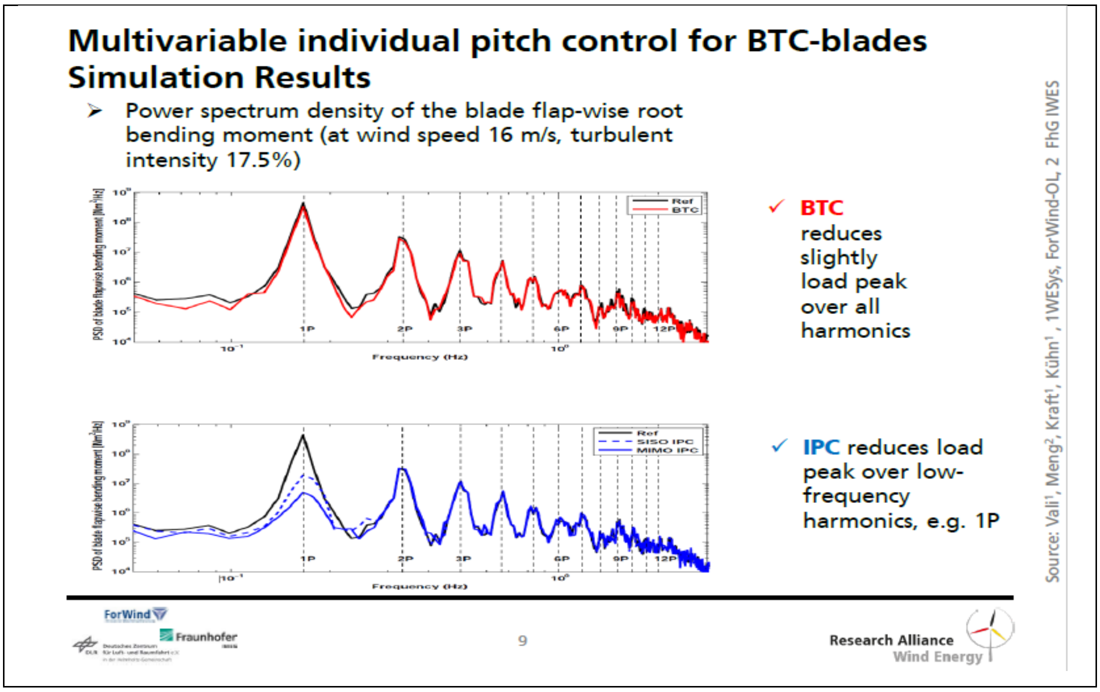
Passive Load Reduction in Rotor Blade Design
Demo Blade Design

Conclusions from 80m scale:

- GBTC approach is favorable for integration in design process
- Transfer of GBTC findings to 20m scale:
  - Starting position for sweep at 17.5m
  - Max. sweep at tip of 0.5m
- Design for manufacturability: plane spar cap / shear web components – possible due to the relatively high chord length

Source: NREL

Source: Rosemeier, Bätge, FhG IWES



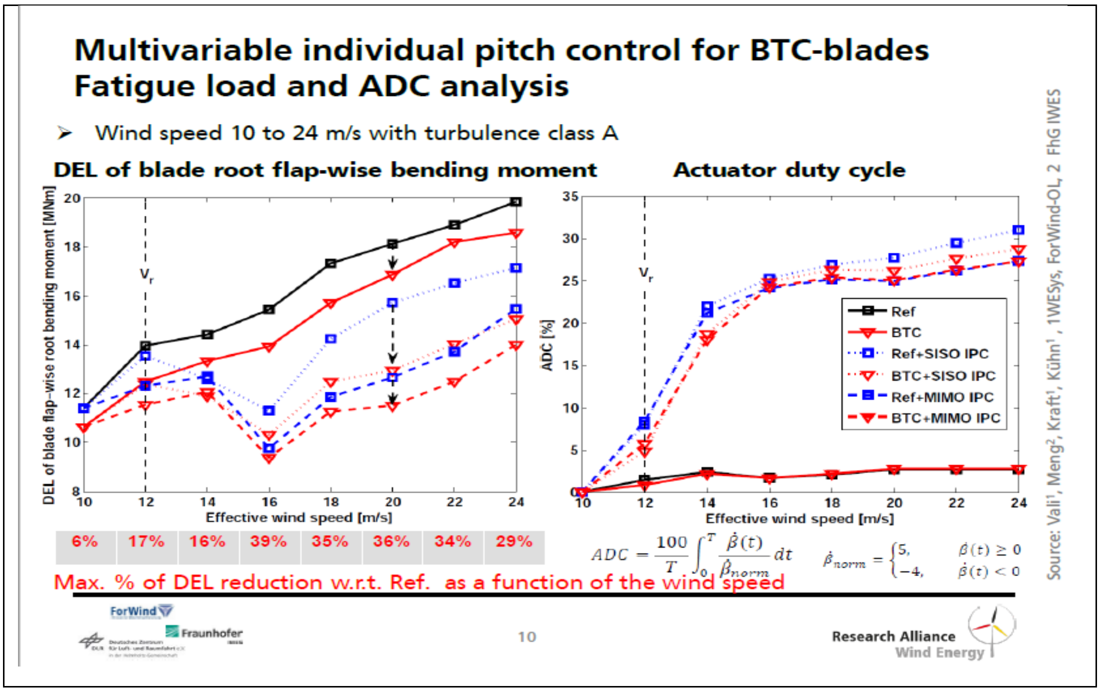
Multivariable individual pitch control for BTC-blades
Simulation Results

- ➤ Power spectrum density of the blade flap-wise root bending moment (at wind speed 16 m/s, turbulent intensity 17.5%)

✓ **BTC** reduces slightly load peak over all harmonics

✓ **IPC** reduces load peak over low-frequency harmonics, e.g. 1P

Source: Vali^1, Meng^2, Kraft^1, Kühn^1, 1WESys, ForWind-OL, 2 FhG IWES



Multivariable individual pitch control for BTC-blades
Fatigue load and ADC analysis

- ➤ Wind speed 10 to 24 m/s with turbulence class A

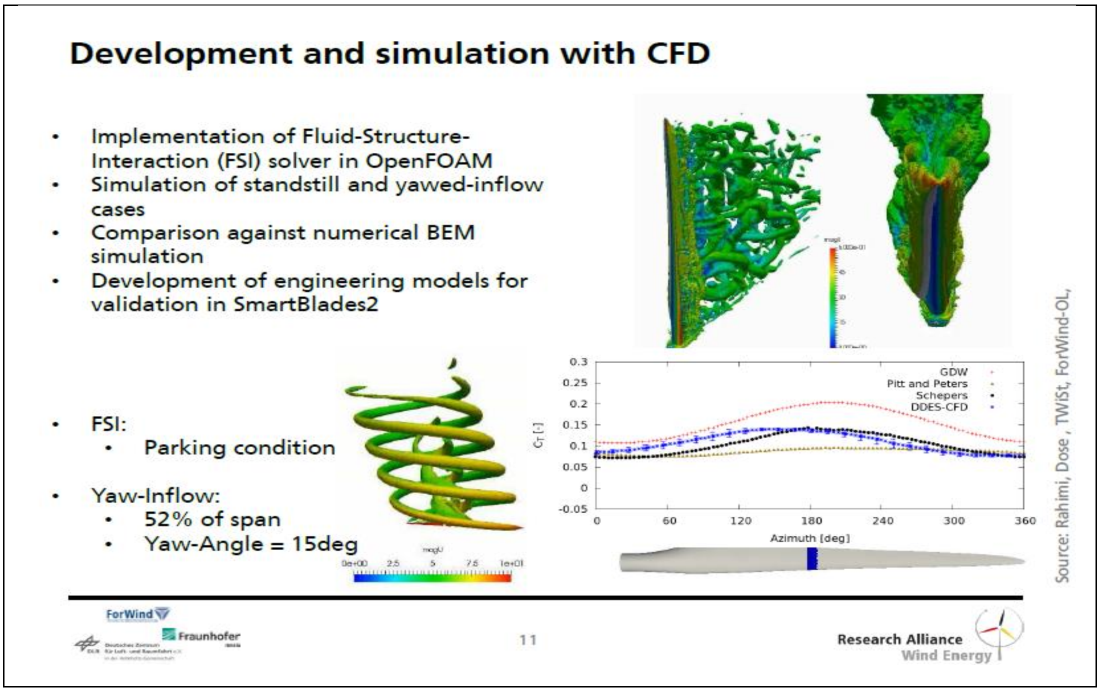
DEL of blade root flap-wise bending moment **Actuator duty cycle**

6%	17%	16%	39%	35%	36%	34%	29%

$$ADC = \frac{100}{T}\int_0^T \frac{\dot{\beta}(t)}{\dot{\beta}_{norm}}\,dt \qquad \dot{\beta}_{norm} = \begin{cases} 5, & \dot{\beta}(t) \geq 0 \\ -4, & \dot{\beta}(t) < 0 \end{cases}$$

Max. % of DEL reduction w.r.t. Ref. as a function of the wind speed

Source: Vali^1, Meng^2, Kraft^1, Kühn^1, 1WESys, ForWind-OL, 2 FhG IWES

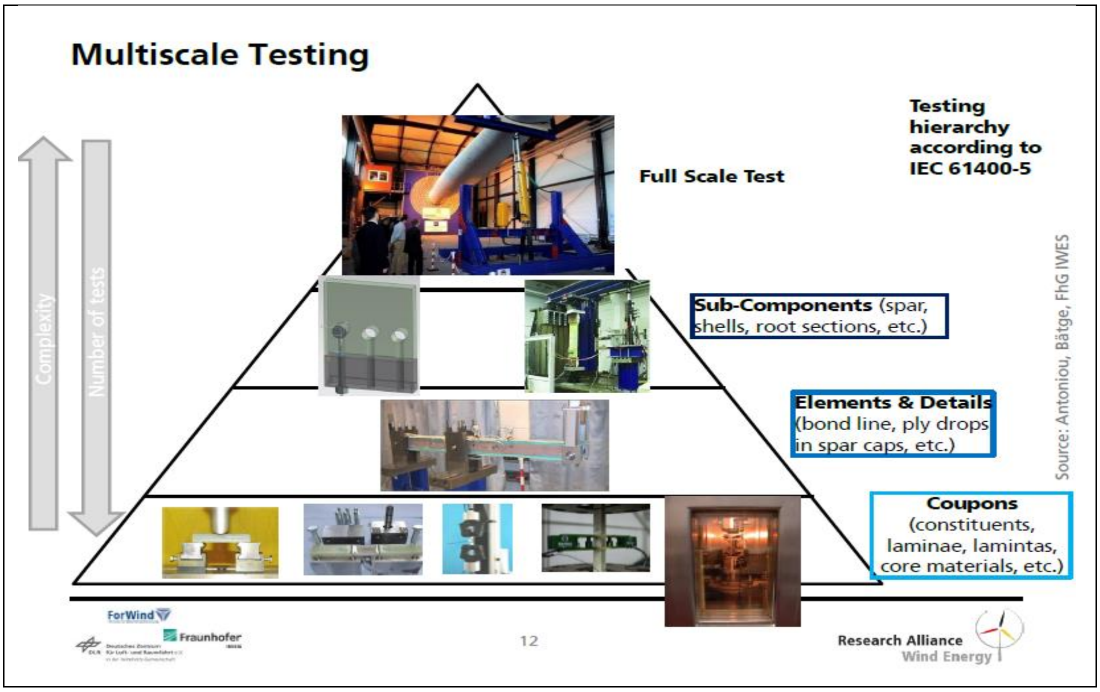


Development and simulation with CFD

- Implementation of Fluid-Structure-Interaction (FSI) solver in OpenFOAM
- Simulation of standstill and yawed-inflow cases
- Comparison against numerical BEM simulation
- Development of engineering models for validation in SmartBlades2

- FSI:
  - Parking condition
- Yaw-Inflow:
  - 52% of span
  - Yaw-Angle = 15deg

Source: Rahimi, Dose , TWISt, ForWind-OL,



Multiscale Testing

Testing hierarchy according to IEC 61400-5

Full Scale Test

Sub-Components (spar, shells, root sections, etc.)

Elements & Details (bond line, ply drops in spar caps, etc.)

Coupons (constituents, laminae, lamintas, core materials, etc.)

Source: Antoniou, Bätge, FhG IWES

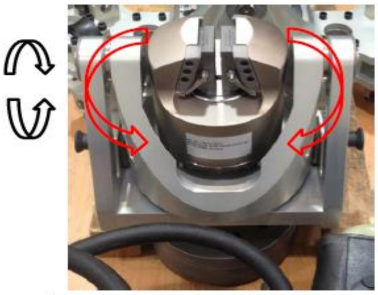
Multiscale Testing
Coupons Testing

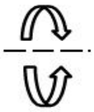
Design of Experiment

- State of the art grips fix the specimen
- High stresses on the clamping area for off axis specimens
- Ideal free rotation about the coupon axis and in-plane

Material Tests:

- Static tests with UD20° unsymmetric laminates (20° /-20° /20° /-20°)T
- Allowed induced torsional shear deformation up to 23° rotational angle
- Allowed shear load up to 15° in-plane rotation (safety factor equal to 2)





Source: Antoniou, Bätge, FhG IWES

Multiscale Testing
Elements and Details Testing: Bond line

Typical Bond Line Loadings

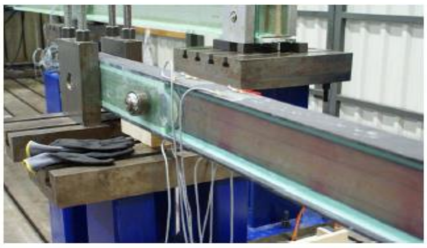
- Axial stresses along the blade length (Axis 1)
- In plane Shear (Plane 1-2)
- BTC: additional shear due to twist (about axis 1)

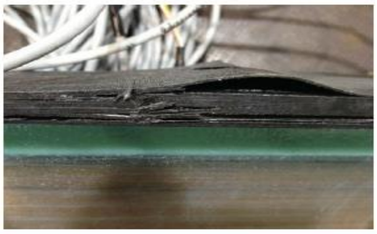
Bend Twist Coupled Beam

- Beam design was developed
- 0° /20° plies on the spar caps to facilitate BTC

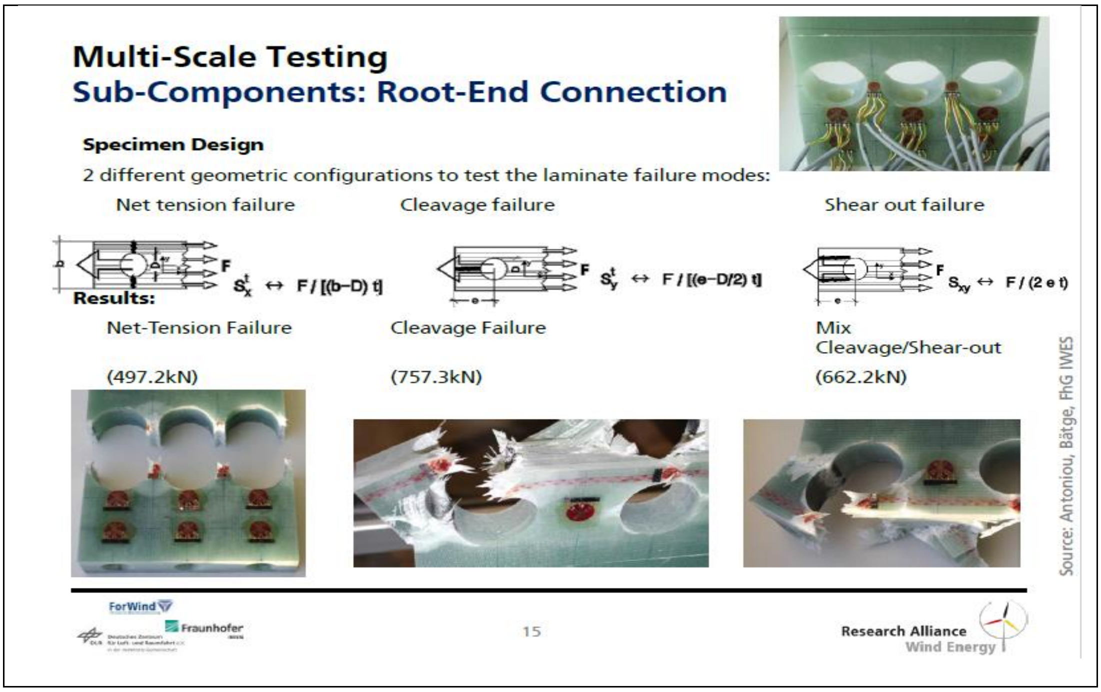
Results:

- Torsion of 3,8°
- The beam failed at 43.77kN in the compression side (spar cap laminate)





Source: Antoniou, Bätge, FhG IWES



Multi-Scale Testing
Sub-Components: Root-End Connection

Specimen Design

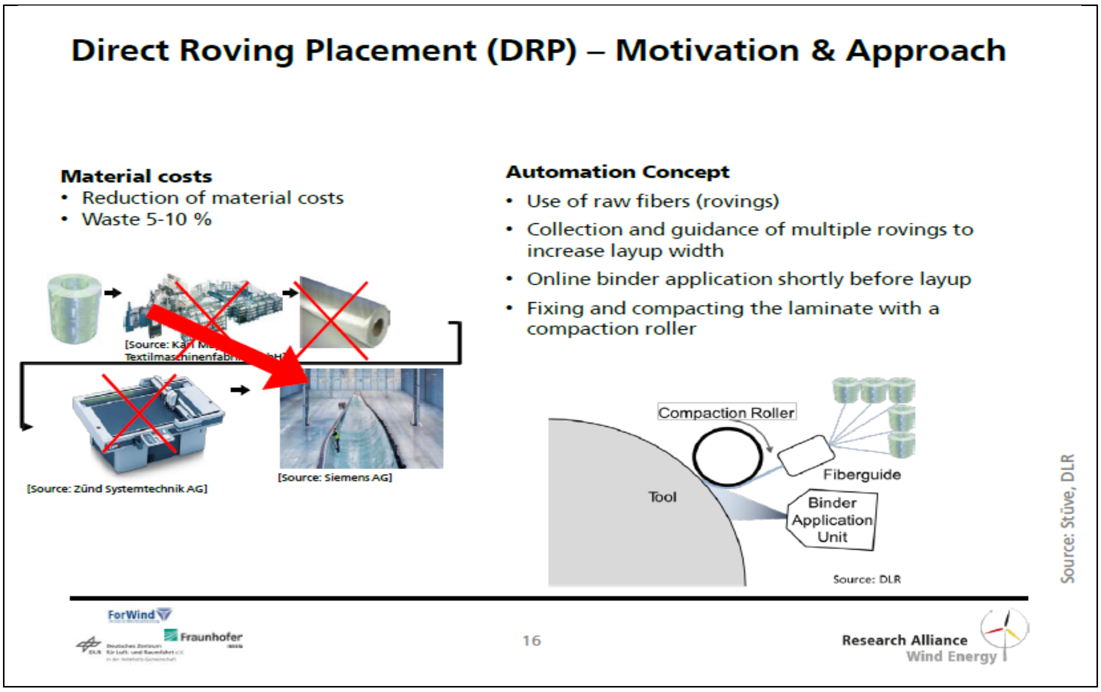
2 different geometric configurations to test the laminate failure modes:

Net tension failure	Cleavage failure	Shear out failure
$S_x^t \leftrightarrow F / [(b-D)\,t]$	$S_y^t \leftrightarrow F / [(e-D/2)\,t]$	$S_{xy} \leftrightarrow F / (2\,e\,t)$

Results:

Net-Tension Failure	Cleavage Failure	Mix Cleavage/Shear-out
(497.2kN)	(757.3kN)	(662.2kN)

Source: Antoniou, Bätge, FhG IWES



Direct Roving Placement (DRP) – Motivation & Approach

Material costs
- Reduction of material costs
- Waste 5-10 %

[Source: Ka
Textilmaschinenfabr

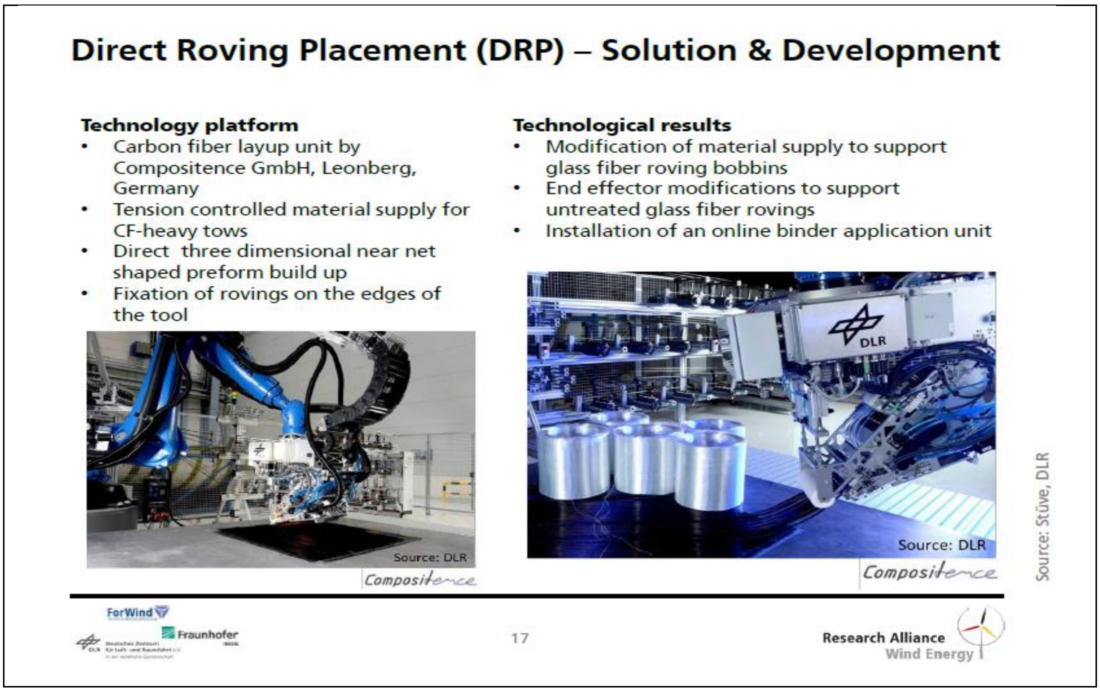
[Source: Zünd Systemtechnik AG]

[Source: Siemens AG]

Automation Concept
- Use of raw fibers (rovings)
- Collection and guidance of multiple rovings to increase layup width
- Online binder application shortly before layup
- Fixing and compacting the laminate with a compaction roller

Source: DLR

Source: Stüve, DLR



Direct Roving Placement (DRP) – Solution & Development

Technology platform
- Carbon fiber layup unit by Compositence GmbH, Leonberg, Germany
- Tension controlled material supply for CF-heavy tows
- Direct three dimensional near net shaped preform build up
- Fixation of rovings on the edges of the tool

Source: DLR

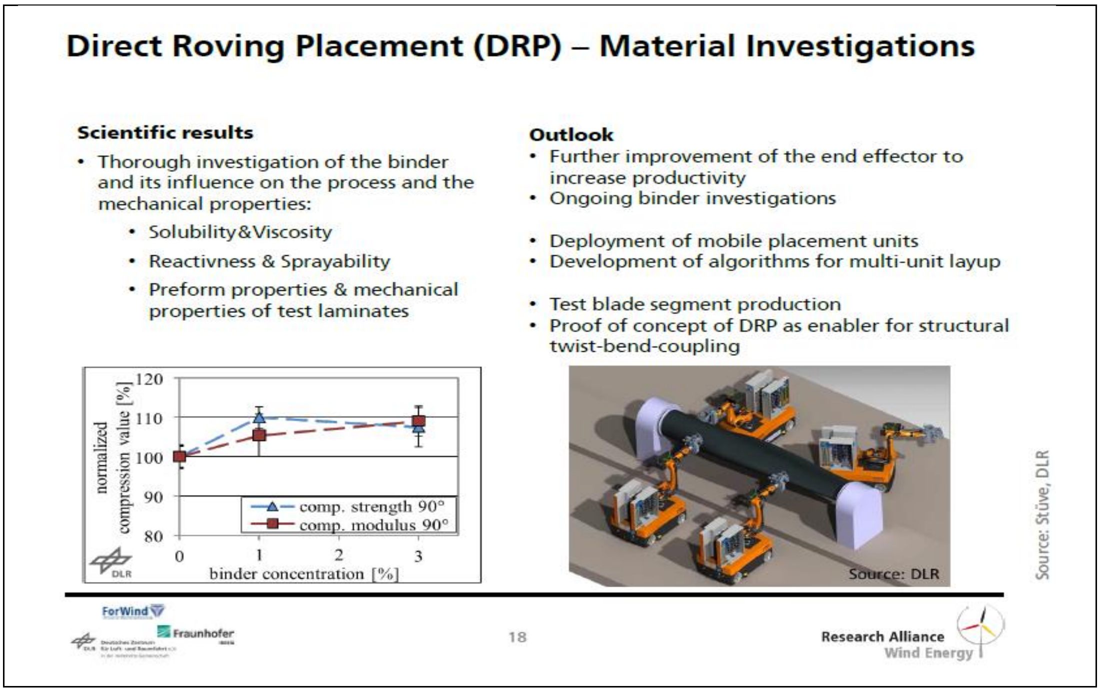
Compositence

Technological results
- Modification of material supply to support glass fiber roving bobbins
- End effector modifications to support untreated glass fiber rovings
- Installation of an online binder application unit

Source: DLR

Compositence

Source: Stüve, DLR



Direct Roving Placement (DRP) – Material Investigations

Scientific results
- Thorough investigation of the binder and its influence on the process and the mechanical properties:
    - Solubility&Viscosity
    - Reactivness & Sprayability
    - Preform properties & mechanical properties of test laminates

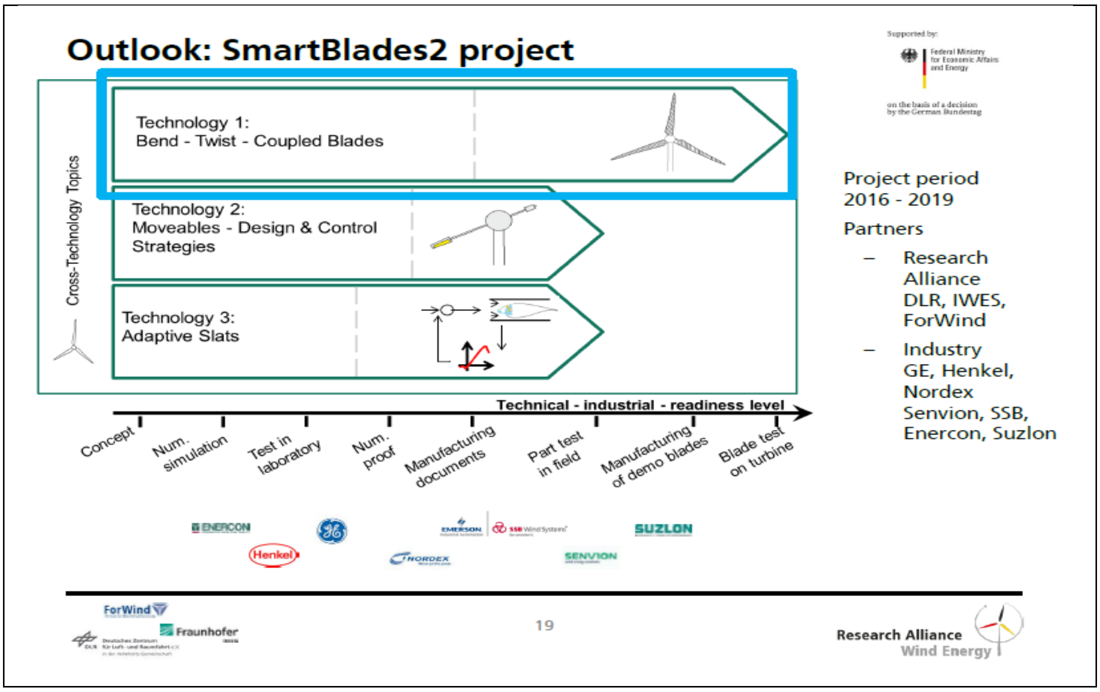
Outlook
- Further improvement of the end effector to increase productivity
- Ongoing binder investigations

- Deployment of mobile placement units
- Development of algorithms for multi-unit layup

- Test blade segment production
- Proof of concept of DRP as enabler for structural twist-bend-coupling

Source: DLR

Source: Stüve, DLR



Outlook: SmartBlades2 project

Supported by:
Federal Ministry
for Economic Affairs
and Energy
on the basis of a decision
by the German Bundestag

Cross-Technology Topics

Technology 1:
Bend - Twist - Coupled Blades

Technology 2:
Moveables - Design & Control Strategies

Technology 3:
Adaptive Slats

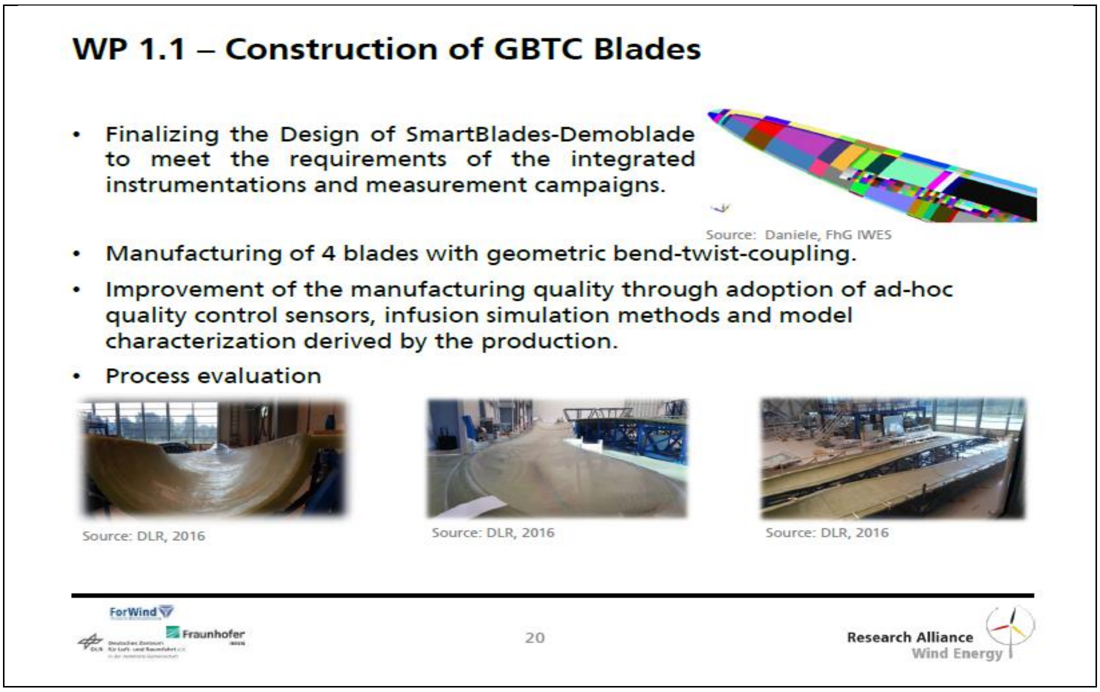
Technical - industrial - readiness level

Concept
Num. simulation
Test in laboratory
Num. proof
Manufacturing documents
Part test in field
Manufacturing of demo blades
Blade test on turbine

Project period
2016 - 2019

Partners

- Research Alliance DLR, IWES, ForWind
- Industry GE, Henkel, Nordex Senvion, SSB, Enercon, Suzlon



WP 1.1 – Construction of GBTC Blades

- Finalizing the Design of SmartBlades-Demoblade to meet the requirements of the integrated instrumentations and measurement campaigns.

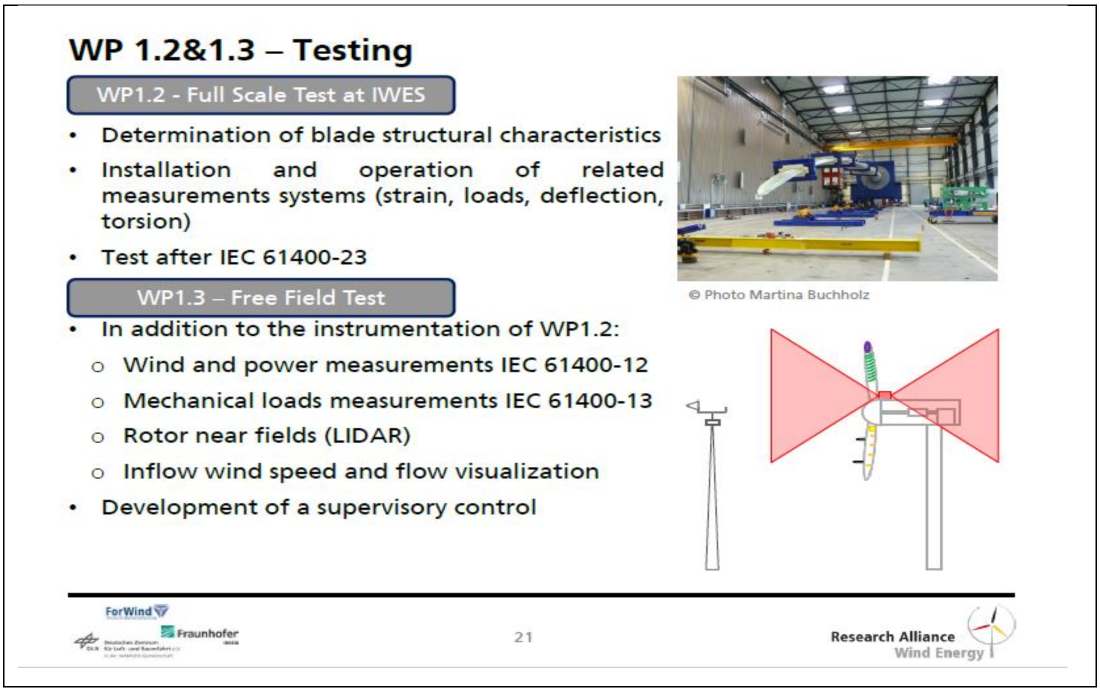
Source: Daniele, FhG IWES

- Manufacturing of 4 blades with geometric bend-twist-coupling.
- Improvement of the manufacturing quality through adoption of ad-hoc quality control sensors, infusion simulation methods and model characterization derived by the production.
- Process evaluation

Source: DLR, 2016

Source: DLR, 2016

Source: DLR, 2016



WP 1.2&1.3 – Testing

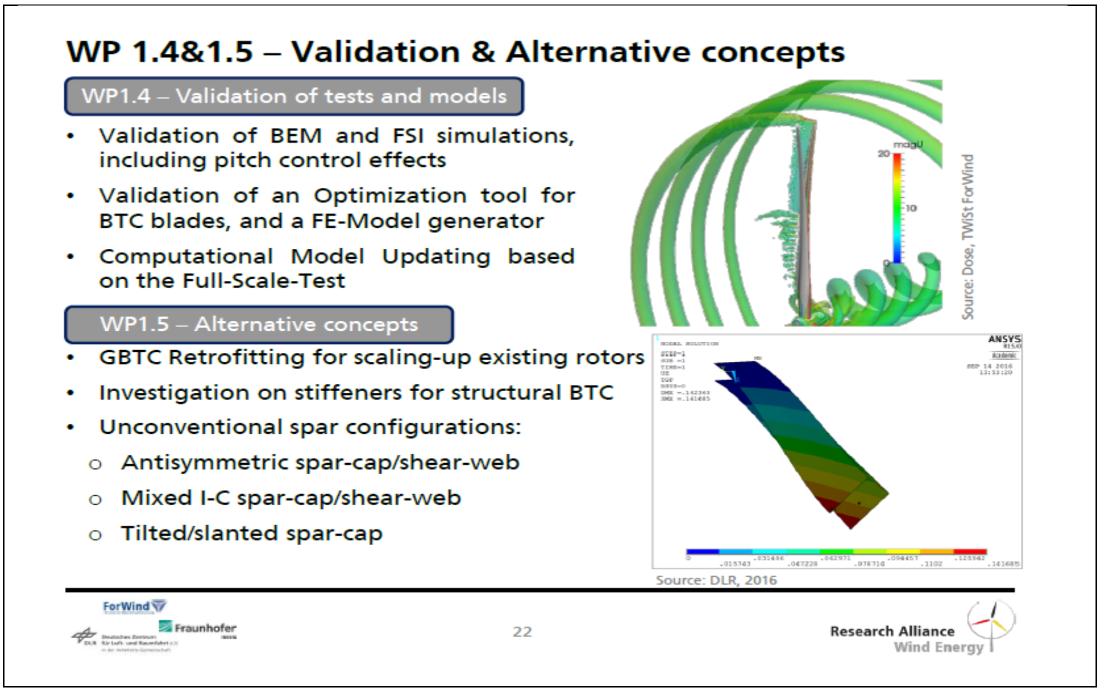
WP1.2 - Full Scale Test at IWES

- Determination of blade structural characteristics
- Installation and operation of related measurements systems (strain, loads, deflection, torsion)
- Test after IEC 61400-23

© Photo Martina Buchholz

WP1.3 – Free Field Test

- In addition to the instrumentation of WP1.2:
  - Wind and power measurements IEC 61400-12
  - Mechanical loads measurements IEC 61400-13
  - Rotor near fields (LIDAR)
  - Inflow wind speed and flow visualization
- Development of a supervisory control



WP 1.4&1.5 – Validation & Alternative concepts

WP1.4 – Validation of tests and models

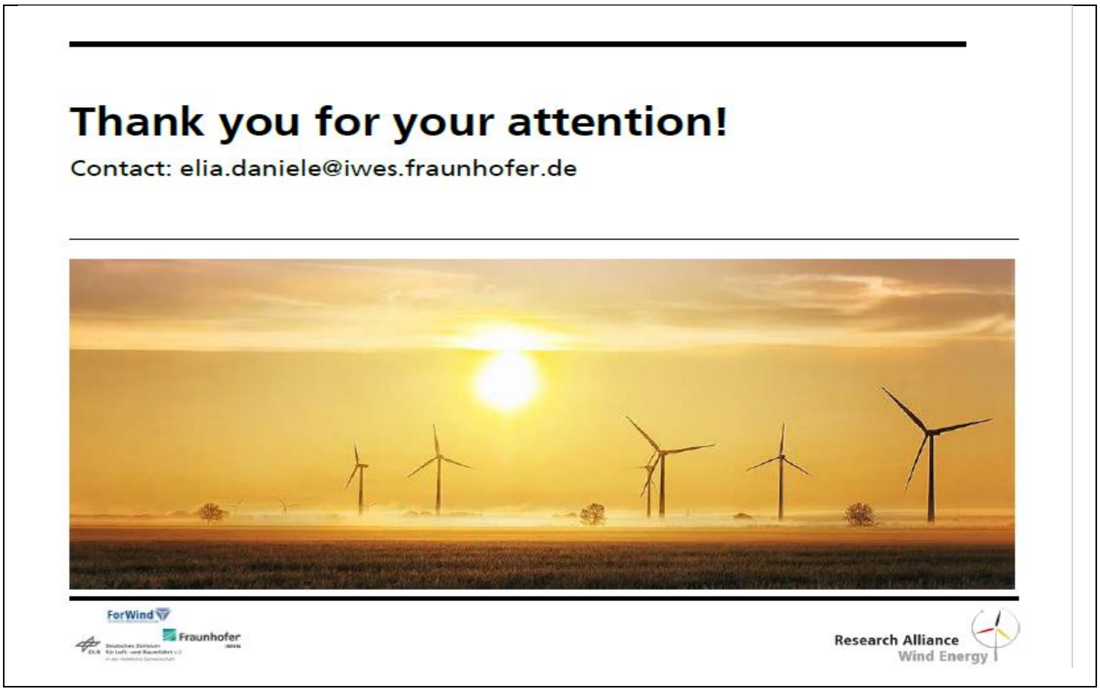
- Validation of BEM and FSI simulations, including pitch control effects
- Validation of an Optimization tool for BTC blades, and a FE-Model generator
- Computational Model Updating based on the Full-Scale-Test

Source: Dose, TWiSt ForWind

WP1.5 – Alternative concepts

- GBTC Retrofitting for scaling-up existing rotors
- Investigation on stiffeners for structural BTC
- Unconventional spar configurations:
  - Antisymmetric spar-cap/shear-web
  - Mixed I-C spar-cap/shear-web
  - Tilted/slanted spar-cap

Source: DLR, 2016



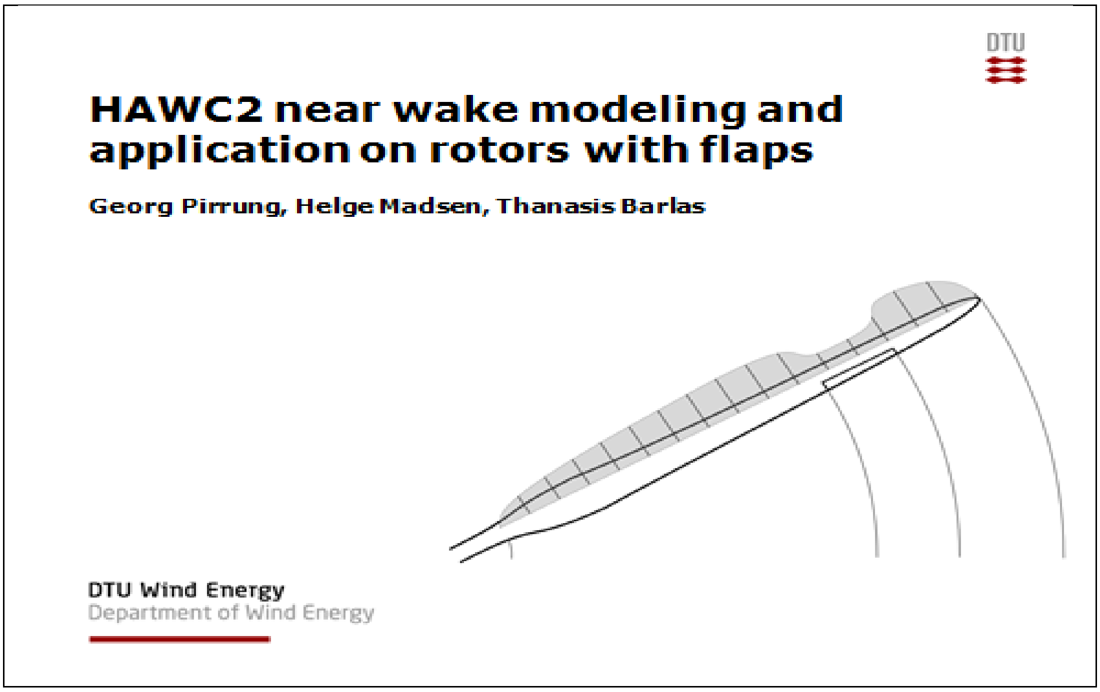
Thank you for your attention!

Contact: elia.daniele@iwes.fraunhofer.de

ForWind

Fraunhofer

Research Alliance
Wind Energy



DTU

HAWC2 near wake modeling and application on rotors with flaps

Georg Pirrung, Helge Madsen, Thanasis Barlas

DTU Wind Energy
Department of Wind Energy

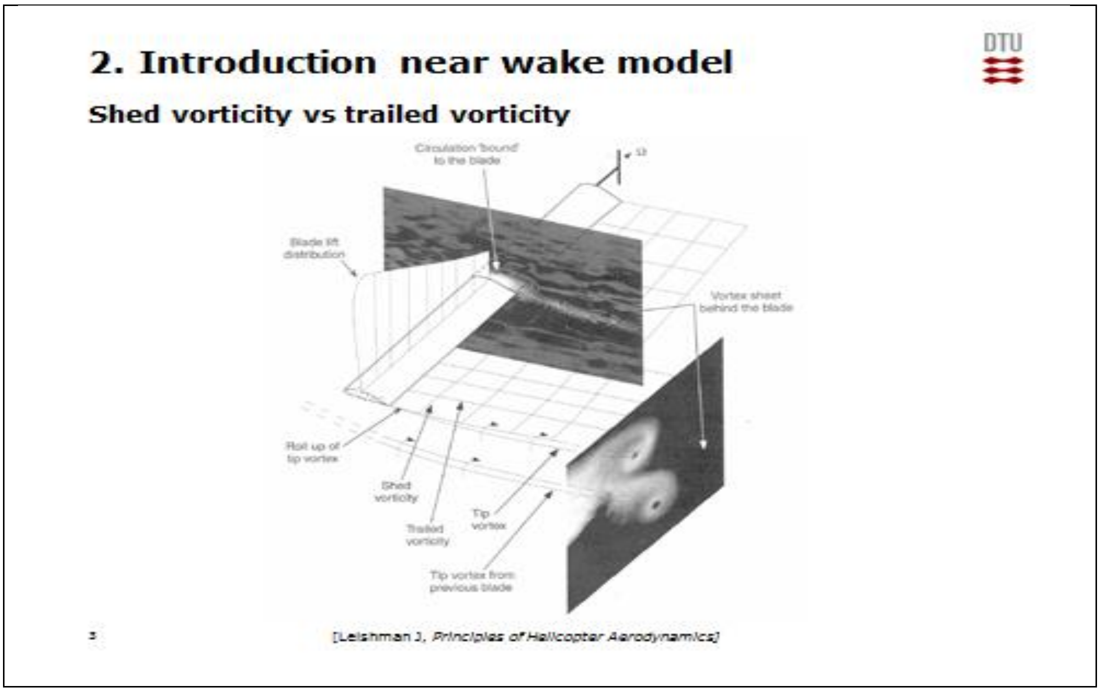
1. Motivation

Near wake model

- Fast trailed vorticity model to be used as BEM extension
  - Introduces coupling between the annular sections
  - Induction model in standstill conditions
  - Aeroelastic computations in the order of real time

Trailing edge flaps

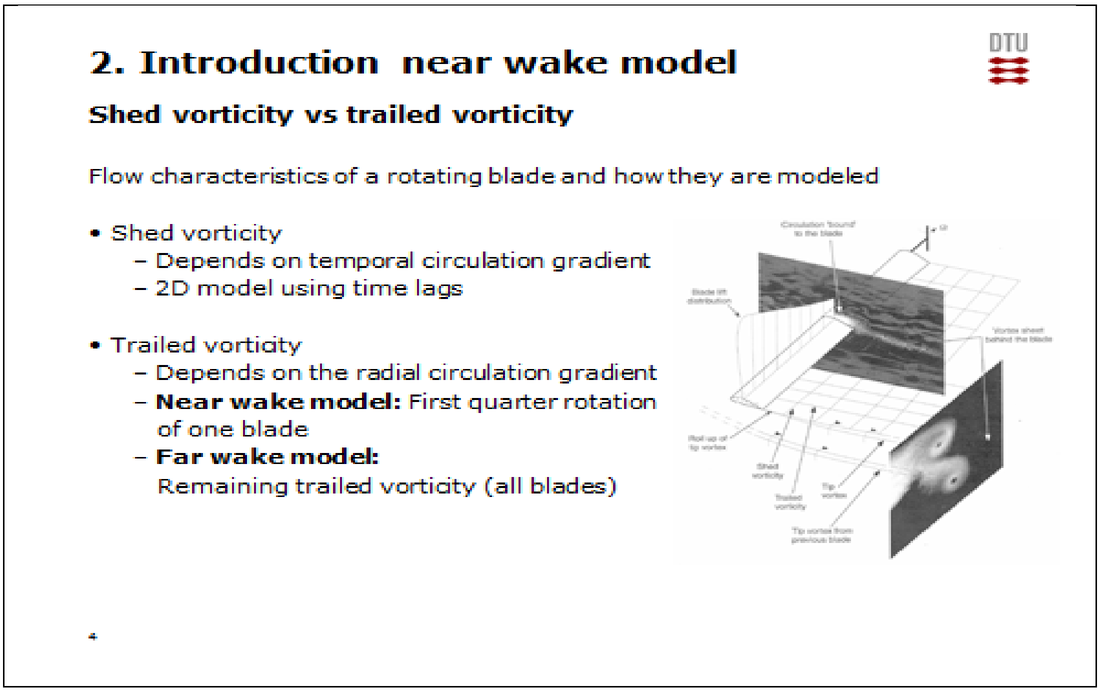
- Trailing edge flaps introduce a step in the load distribution along the blade
  - Trailed vortices at the edges of the flaps
  - Load distribution can’t be predicted with BEM model



2. Introduction near wake model

Shed vorticity vs trailed vorticity

[Leishman J, *Principles of Helicopter Aerodynamics*]

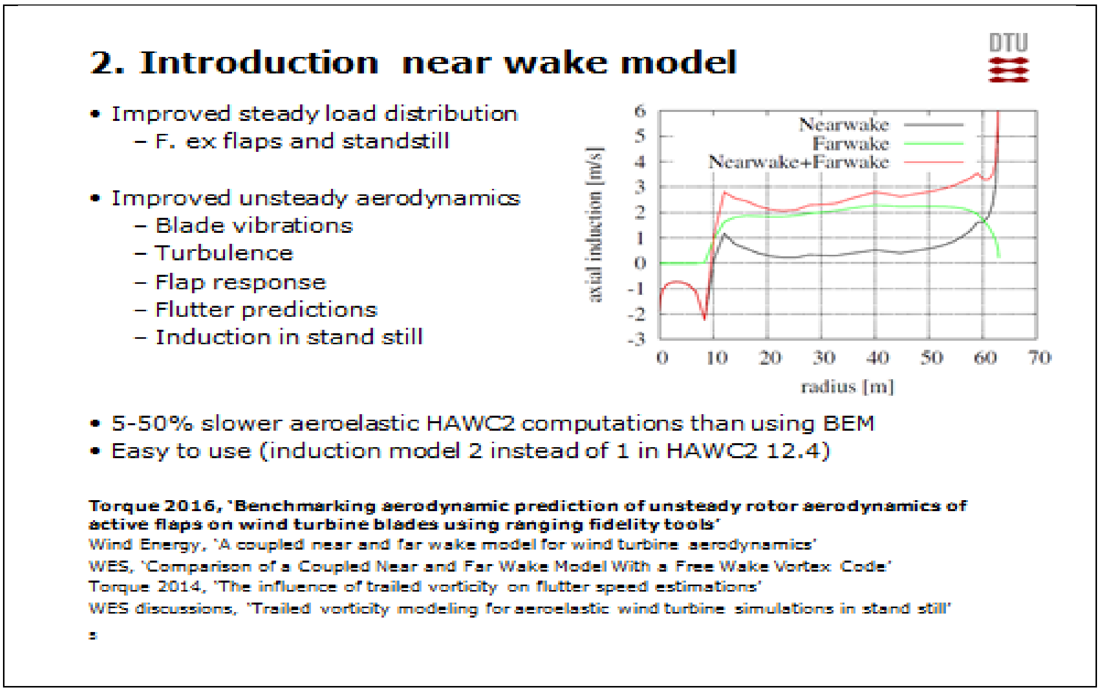


2. Introduction near wake model

Shed vorticity vs trailed vorticity

Flow characteristics of a rotating blade and how they are modeled

- Shed vorticity
  - Depends on temporal circulation gradient
  - 2D model using time lags
- Trailed vorticity
  - Depends on the radial circulation gradient
  - **Near wake model:** First quarter rotation of one blade
  - **Far wake model:** Remaining trailed vorticity (all blades)



2. Introduction near wake model

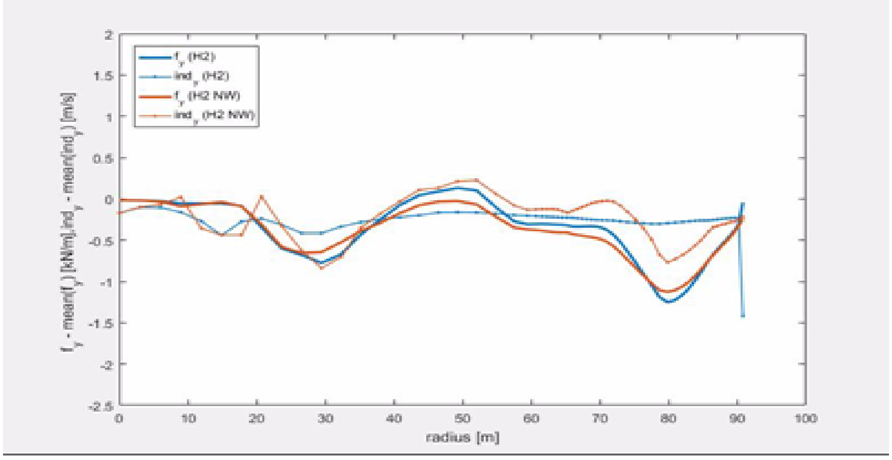
- Improved steady load distribution
  - F. ex flaps and standstill
- Improved unsteady aerodynamics
  - Blade vibrations
  - Turbulence
  - Flap response
  - Flutter predictions
  - Induction in stand still

- 5-50% slower aeroelastic HAWC2 computations than using BEM
- Easy to use (induction model 2 instead of 1 in HAWC2 12.4)

Torque 2016, 'Benchmarking aerodynamic prediction of unsteady rotor aerodynamics of active flaps on wind turbine blades using ranging fidelity tools'
Wind Energy, 'A coupled near and far wake model for wind turbine aerodynamics'
WES, 'Comparison of a Coupled Near and Far Wake Model With a Free Wake Vortex Code'
Torque 2014, 'The influence of trailed vorticity on flutter speed estimations'
WES discussions, 'Trailed vorticity modeling for aeroelastic wind turbine simulations in stand still'

3. Model behavior in turbulent inflow

- Turbulent inflow at 6 m/s, Turbulence intensity 0.269
- Deviations from mean forces and mean induction are shown



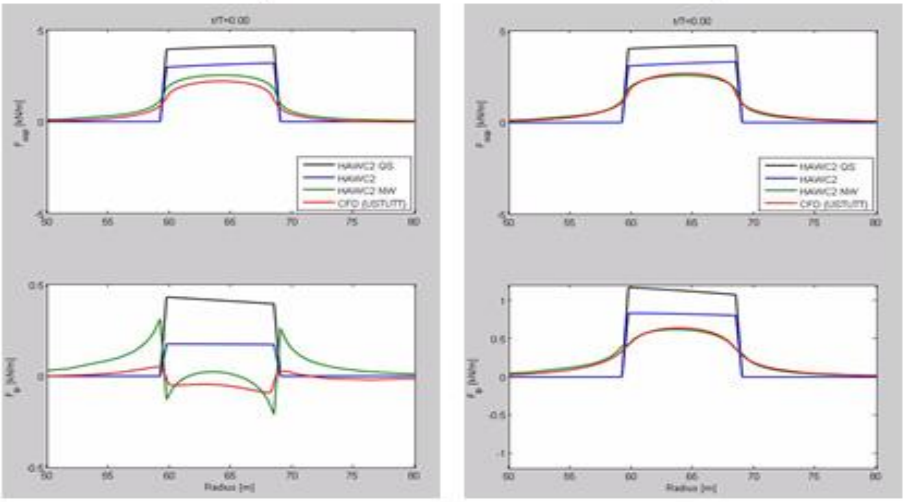
4 Results from flap comparison

- DTU 10 MW with trailing edge flaps from 70 to 80% blade span
- Flap angle oscillating between -10 and +10 deg at 6p frequency
- Stiff turbine operating at 11.4 and 19 m/s wind speed at constant rpm
- Comparison of spanwise thrust force and in-plane force distribution between
  - HAWC2 QS (no shed vorticity)
  - HAWC2 (shed vorticity)
  - HAWC2 NW (shed vorticity and trailed vorticity)
  - 3D CFD from the University of Stuttgart

4 Results from flap comparison

11.4 m/s

19 m/s



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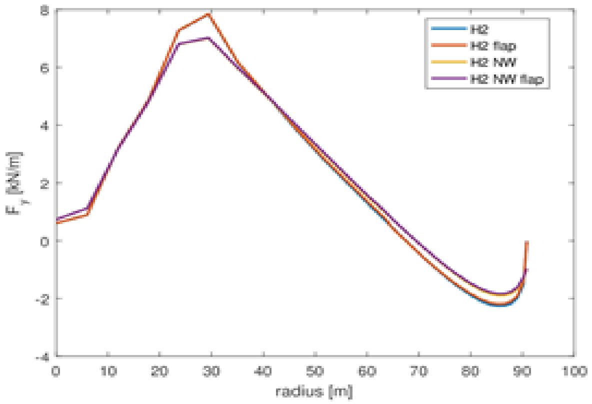
4. Load reduction at 24 m/s, TI 0.157

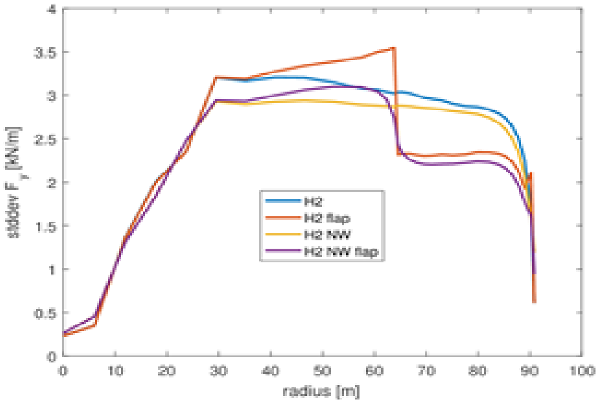
Mean value of F_y (normal to chord)



- Flap does not influence mean loading
- Less positive loading inboard less negative loading outboard in H2 NW
- Consistent with in-house CFD computations

4. Load reduction at 24 m/s, TI 0.157

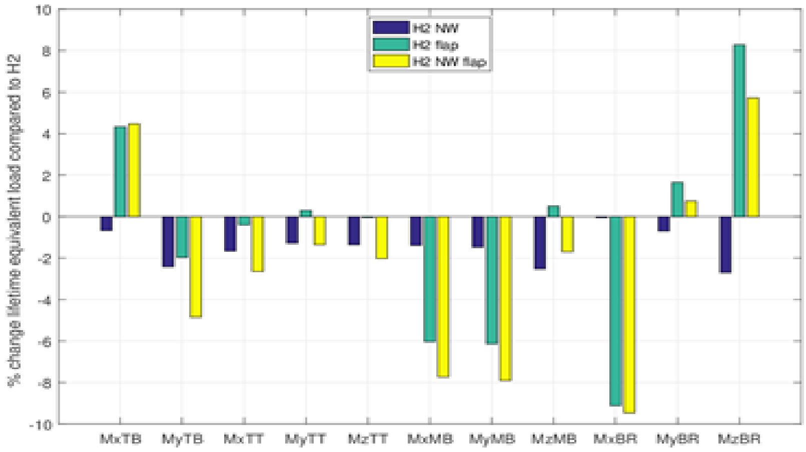
Standard deviation of F_y (normal to chord)



- Flap strongly decreases load variations on flap
- Additional torsion due to flap increases loading inboard
- Near wake model reduces effects on both sides of the inner flap border

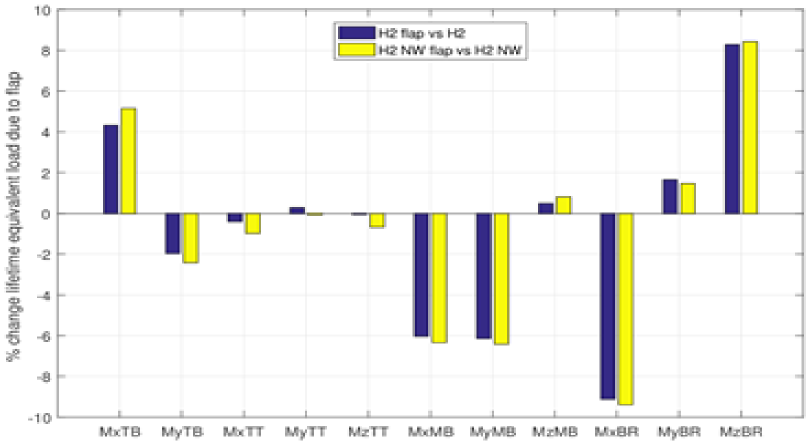
5. Fatigue load reduction

– Change in lifetime equivalent load relative to H2



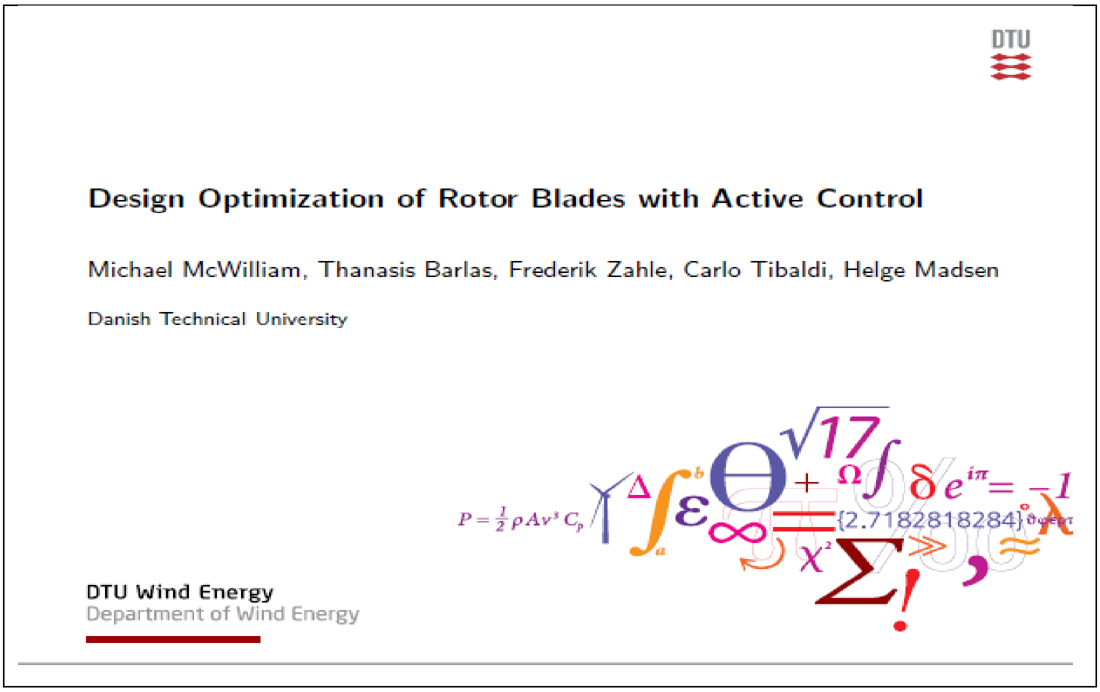
5. Fatigue load reduction

– Change in lifetime equivalent load due to flap in H2 and H2 NW



6 Conclusions

- HAWC2 can simulate dynamic flap motions including the aerodynamic 3D effects
- Much faster computation possible than with more complex aerodynamic models (for example CFD or free vortex codes)
- Overall effect of the near wake model on flap effectiveness for fatigue load reduction is small in a full load basis
- Model works in all normal operation cases for the DTU 10MW, but has limitations in stall (typical for vortex codes)

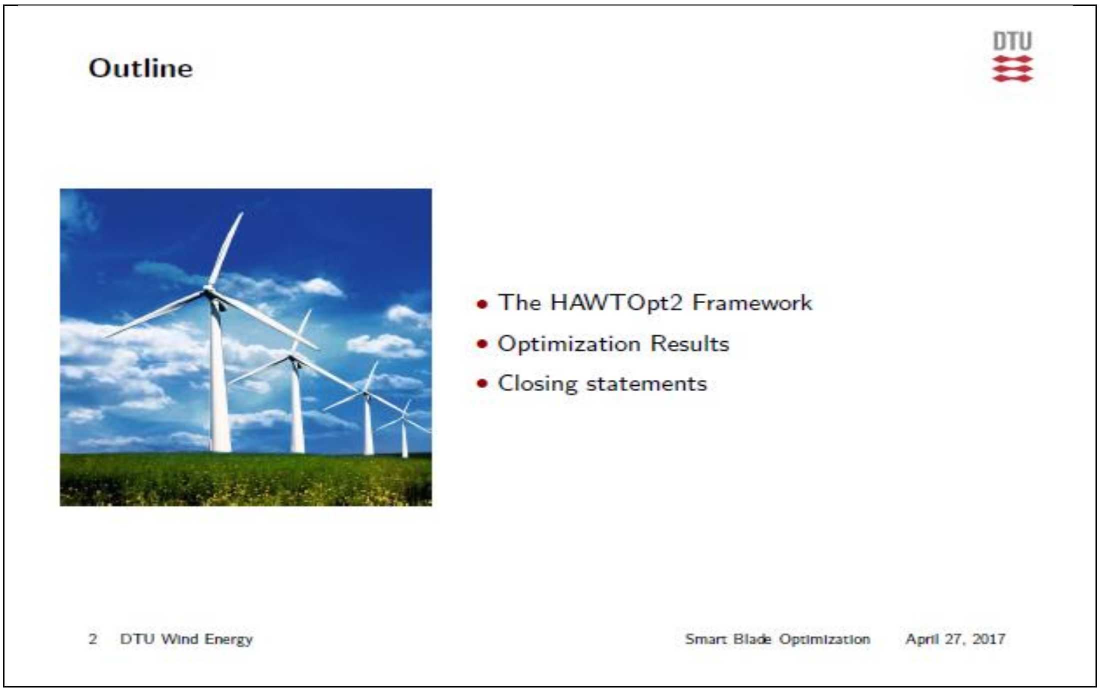


Design Optimization of Rotor Blades with Active Control

Michael McWilliam, Thanasis Barlas, Frederik Zahle, Carlo Tibaldi, Helge Madsen

Danish Technical University

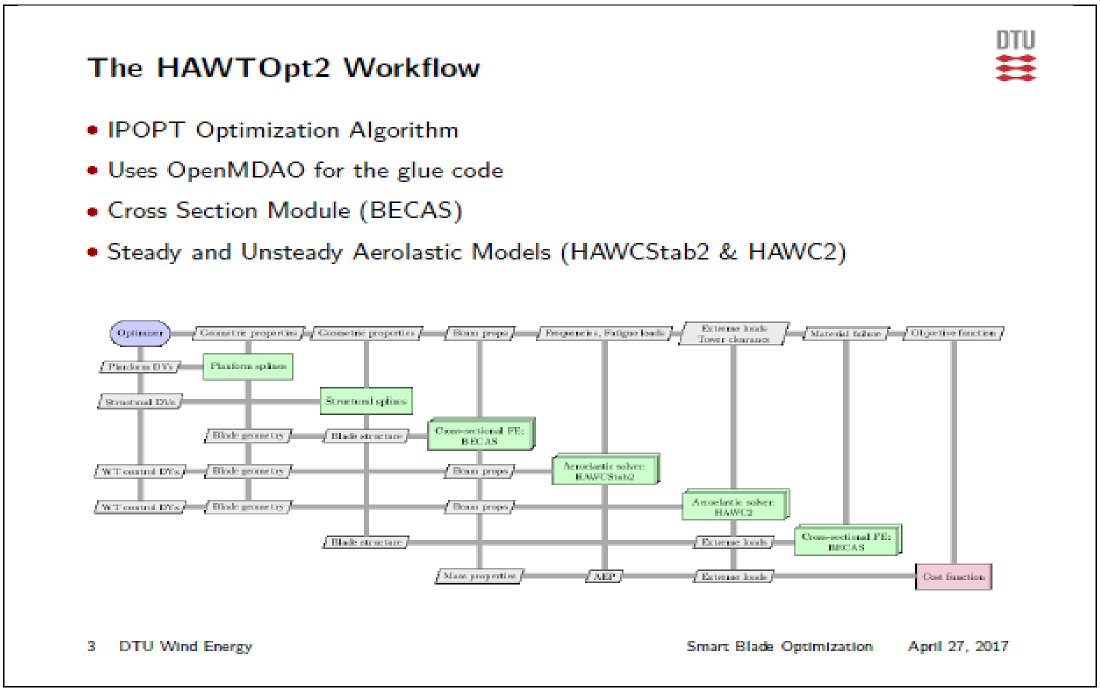
DTU Wind Energy
Department of Wind Energy



Outline

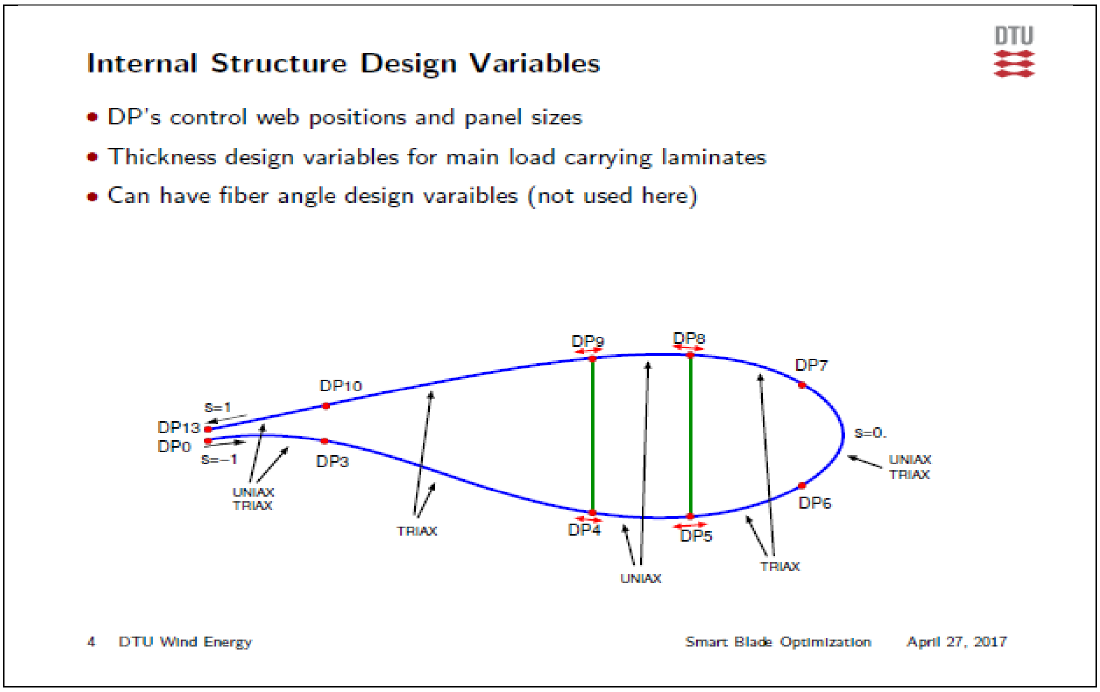
- The HAWTOpt2 Framework
- Optimization Results
- Closing statements

2 DTU Wind Energy Smart Blade Optimization April 27, 2017



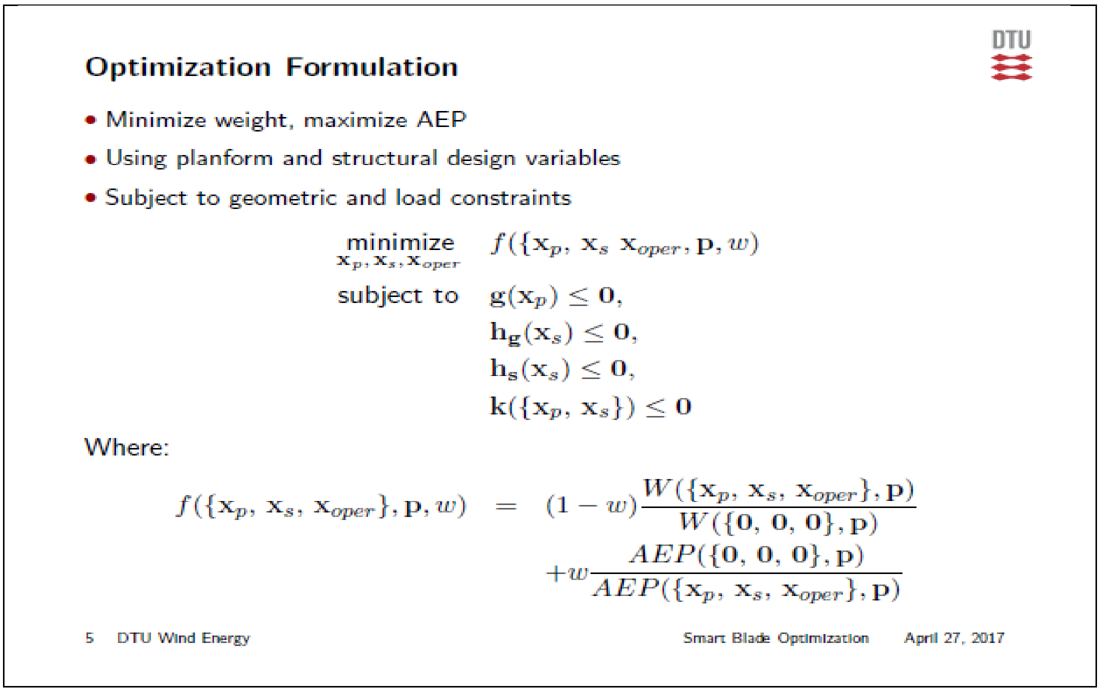
The HAWTOpt2 Workflow

- IPOPT Optimization Algorithm
- Uses OpenMDAO for the glue code
- Cross Section Module (BECAS)
- Steady and Unsteady Aerolastic Models (HAWCStab2 & HAWC2)



Internal Structure Design Variables

- DP's control web positions and panel sizes
- Thickness design variables for main load carrying laminates
- Can have fiber angle design varaibles (not used here)



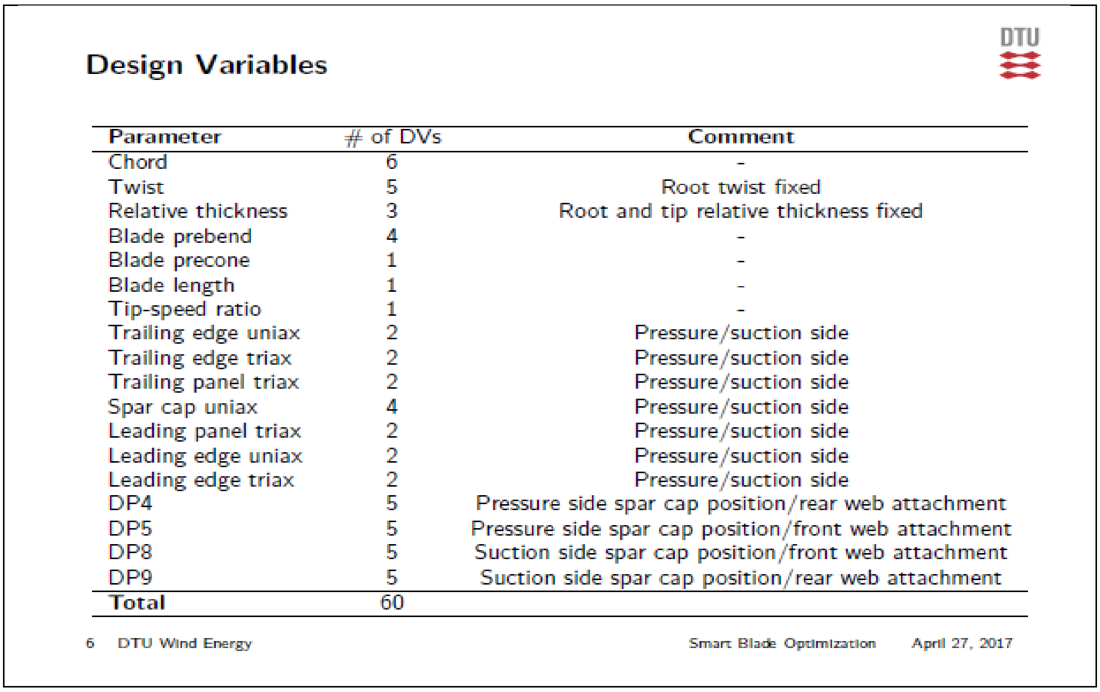
Optimization Formulation

- Minimize weight, maximize AEP
- Using planform and structural design variables
- Subject to geometric and load constraints

$$\begin{aligned} \underset{\mathbf{x}_p,\,\mathbf{x}_s,\,\mathbf{x}_{oper}}{\text{minimize}} \quad & f(\{\mathbf{x}_p,\ \mathbf{x}_s\ \mathbf{x}_{oper}, \mathbf{p}, w) \\ \text{subject to} \quad & \mathbf{g}(\mathbf{x}_p) \leq \mathbf{0}, \\ & \mathbf{h_g}(\mathbf{x}_s) \leq \mathbf{0}, \\ & \mathbf{h_s}(\mathbf{x}_s) \leq \mathbf{0}, \\ & \mathbf{k}(\{\mathbf{x}_p,\ \mathbf{x}_s\}) \leq \mathbf{0} \end{aligned}$$

Where:

$$\begin{aligned} f(\{\mathbf{x}_p,\ \mathbf{x}_s,\ \mathbf{x}_{oper}\}, \mathbf{p}, w) \quad = \quad & (1-w)\frac{W(\{\mathbf{x}_p,\ \mathbf{x}_s,\ \mathbf{x}_{oper}\}, \mathbf{p})}{W(\{\mathbf{0},\ \mathbf{0},\ \mathbf{0}\}, \mathbf{p})} \\ & +w\frac{AEP(\{\mathbf{0},\ \mathbf{0},\ \mathbf{0}\}, \mathbf{p})}{AEP(\{\mathbf{x}_p,\ \mathbf{x}_s,\ \mathbf{x}_{oper}\}, \mathbf{p})} \end{aligned}$$



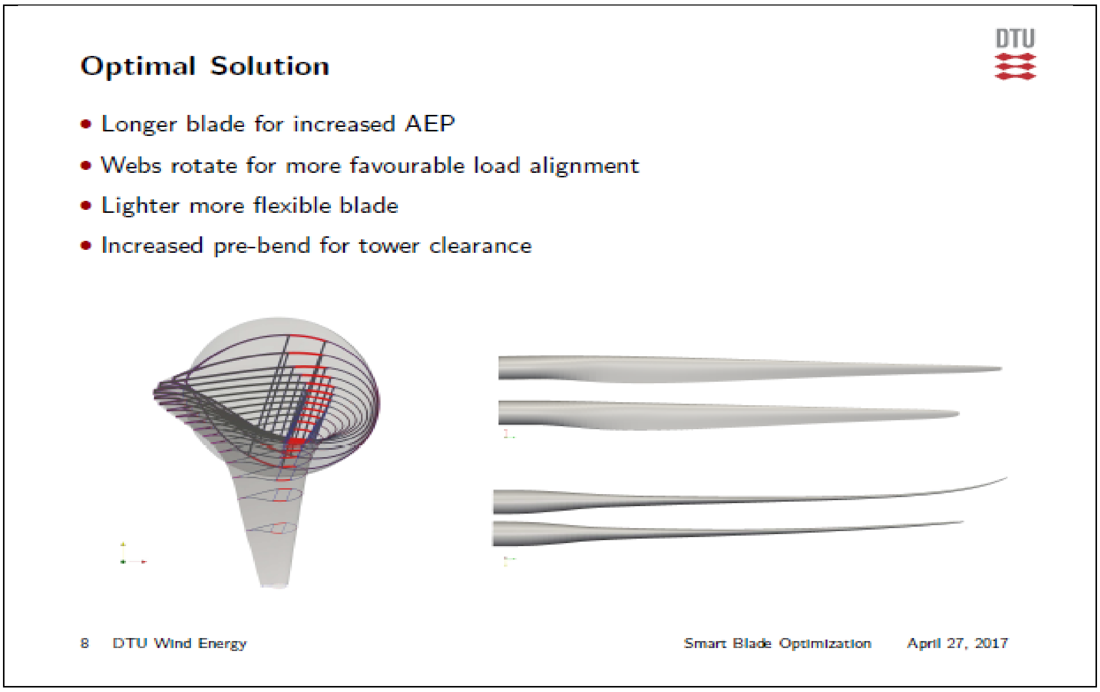
Design Variables

Parameter	# of DVs	Comment
Chord	6	-
Twist	5	Root twist fixed
Relative thickness	3	Root and tip relative thickness fixed
Blade prebend	4	-
Blade precone	1	-
Blade length	1	-
Tip-speed ratio	1	-
Trailing edge uniax	2	Pressure/suction side
Trailing edge triax	2	Pressure/suction side
Trailing panel triax	2	Pressure/suction side
Spar cap uniax	4	Pressure/suction side
Leading panel triax	2	Pressure/suction side
Leading edge uniax	2	Pressure/suction side
Leading edge triax	2	Pressure/suction side
DP4	5	Pressure side spar cap position/rear web attachment
DP5	5	Pressure side spar cap position/front web attachment
DP8	5	Suction side spar cap position/front web attachment
DP9	5	Suction side spar cap position/rear web attachment
Total	60	

Constraints

Constraint	Value	Comment
max(chord)	< 6.2 m	Maximum chord limited for transport.
max(prebend)	< 6.2 m	Maximum prebend limited for transport.
max(rotor cone angle)	> -5 deg	-
min(relative thickness)	> 0.24	Same airfoil series as used on the DTU 10MW RWT.
min(material thickness)	> 0.0	Ensure FFD splines do not produce negative thickness.
$t/w_{sparcap}$	> 0.08	Basic constraint to avoid spar cap buckling.
min(tip tower distance)	$>$ ref value	DLC1.3 operational tip deflection cannot exceed that of the DTU 10MW RWT.
Blade root flapwise moments (MxBR)	$<$ ref value	DLB loads cannot exceed starting point.
Blade root edgewise moments (MyBR)	$<$ ref value	DLB loads cannot exceed starting point.
Tower bottom fore-aft moments (MxTB)	$<$ ref value	DLB loads cannot exceed that starting point.
Rotor torque	$<$ ref value	Ensure that the rotational speed is high enough below rated to not exceed generator maximum torque.
Blade mass	$<$ 1.01 * ref value	Limit increase in blade mass to maintain equivalent production costs.
Blade mass moment	$<$ 1.01 * ref value	Limit increase in blade mass moment to minimise edgewise fatigue.
Lift coefficient @ $r/R = [0.5 - 1.]$	< 1.35	Limit operational lift coefficient to avoid stall for turbulent inflow conditions.
Ultimate strain criteria	< 1.0	Aggregated material failure in each section for 12 load cases.

7 DTU Wind Energy Smart Blade Optimization April 27, 2017



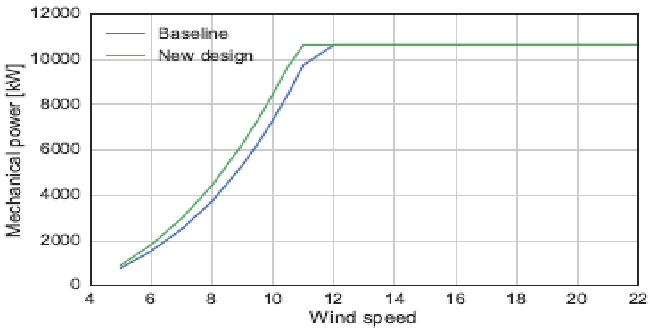
Optimal Solution

- Longer blade for increased AEP
- Webs rotate for more favourable load alignment
- Lighter more flexible blade
- Increased pre-bend for tower clearance

8 DTU Wind Energy Smart Blade Optimization April 27, 2017

Optimal Performance

- Increased production below rated
- Increases AEP

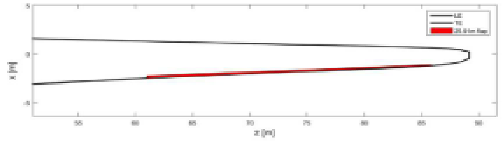


Optimization for Fatigue Control

- Used only steady state models in the optimization
- Flaps placed on the outer quarter of the blade

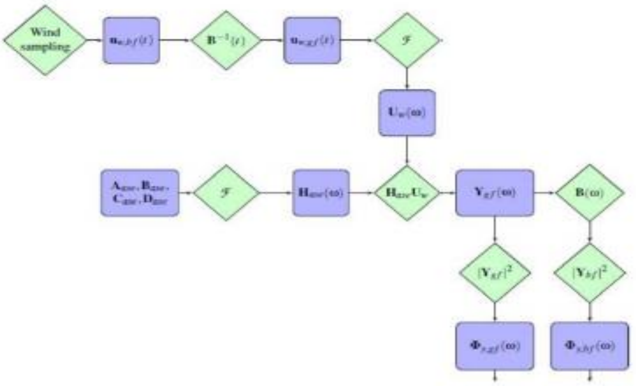
DTU 10MW Reference Wind Turbine	
Rated power	10 MW
Rotor diameter	178.3 m
Rated rotor speed	9.6 rpm
Rated wind speed	11.4 m/s
Cut-in, cut-out wind speed	4 m/s, 25 m/s
Gearbox Ratio	50.0
Pitch Rate Limit	10°/s

Flap configuration	
Chordwise extension	10%
Deflection angle limits	±10°
Spanwise length	25.9m (30% blade length)
Spanwise location	59.59m-85.50m (from blade root)
Airfoil	FFA-W3-241
Max ΔC_l	0.4
Deflection rate limit	100°/s
Actuator time constant	100ms



Fatugue Frequency Domain Model

- Aerodynamic loads converted to a power spectrum
- Load power spectrum solved in the frequency domain with linear model
- Semi-emperical model for Damage Equivalent Loads (DEL)



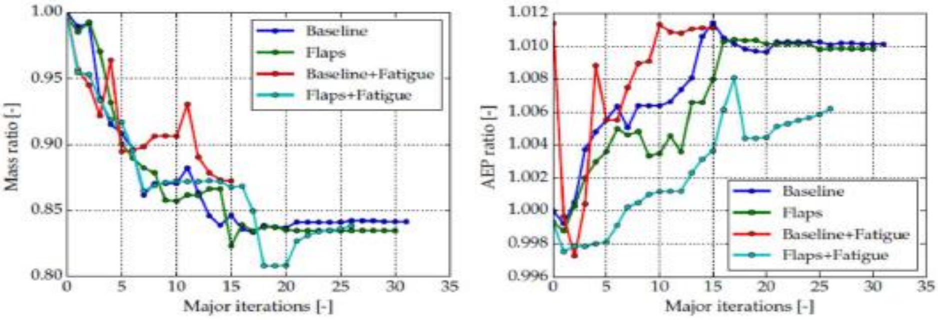
Optimization Case Studies

- Comparison between a blade with or without flaps
- Seperated the effect of flat-back geometry and active control
- Used optimization to determine the best performance

DTU 10MW Reference Wind Turbine (RWT) models	
Case 1	Baseline DTU 10MW RWT
Case 2	Baseline DTU 10MW RWT with flap geometry
Case 3	Optimized baseline
Case 4	Optimized design with flap geometry
Case 5	Optimized baseline + fatigue constraint
Case 6	Optimized design with flap geometry + fatigue constraint

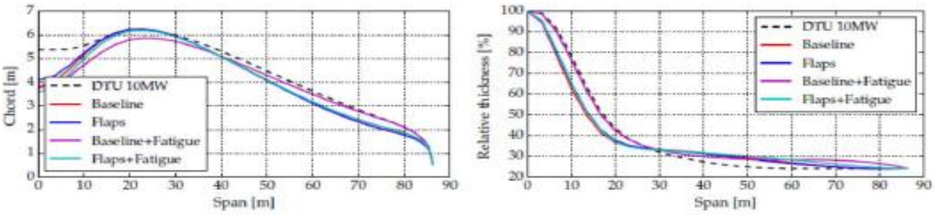
Optimization Progress

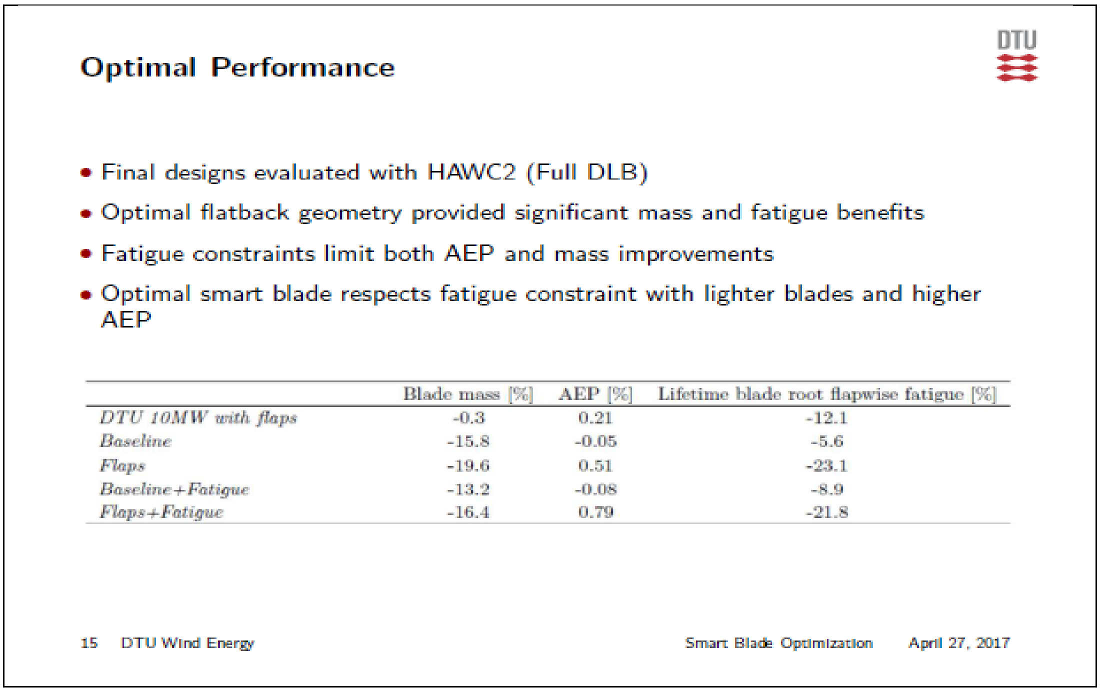
- Reduced mass in all cases
- Increased AEP in all cases



Optimal Design

- Unloads the blade towards the tip, increases loading near the root
- Thickness increases outboard and decreases inboard

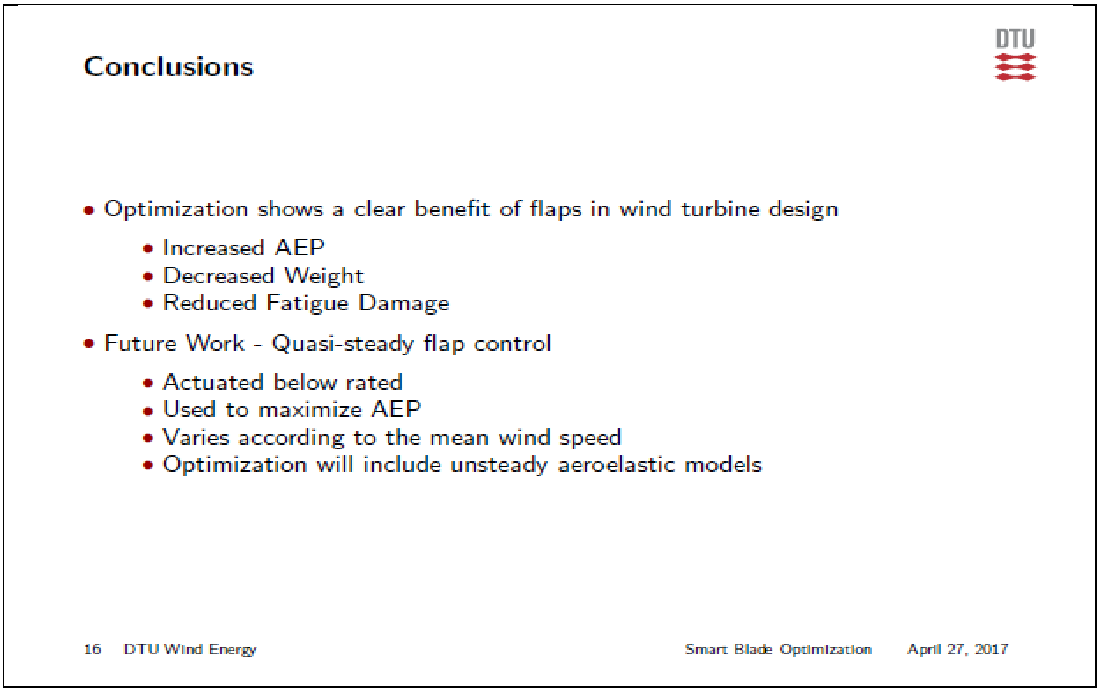




Optimal Performance

- Final designs evaluated with HAWC2 (Full DLB)
- Optimal flatback geometry provided significant mass and fatigue benefits
- Fatigue constraints limit both AEP and mass improvements
- Optimal smart blade respects fatigue constraint with lighter blades and higher AEP

	Blade mass [%]	AEP [%]	Lifetime blade root flapwise fatigue [%]
DTU 10MW with flaps	-0.3	0.21	-12.1
Baseline	-15.8	-0.05	-5.6
Flaps	-19.6	0.51	-23.1
Baseline+Fatigue	-13.2	-0.08	-8.9
Flaps+Fatigue	-16.4	0.79	-21.8



Conclusions

- Optimization shows a clear benefit of flaps in wind turbine design
    - Increased AEP
    - Decreased Weight
    - Reduced Fatigue Damage
- Future Work - Quasi-steady flap control
    - Actuated below rated
    - Used to maximize AEP
    - Varies according to the mean wind speed
    - Optimization will include unsteady aeroelastic models

Thank-you for your interest

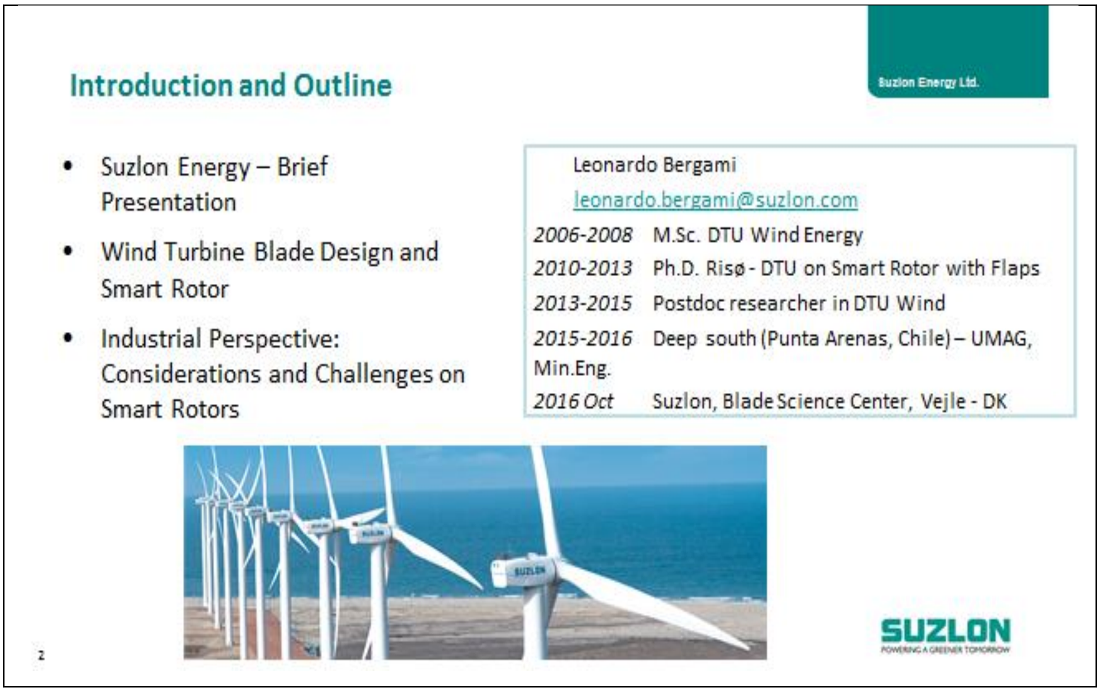
Comments or Questions?

Rotor Design in Suzlon

IEA Wind Task 11
Topical Expert Meeting on Smart Blades
27-28th April 2017
DTU – Risø Campus, Denmark

Leonardo Bergami
leonardo.bergami@suzlon.com

Suzlon wind farm in Utah, USA



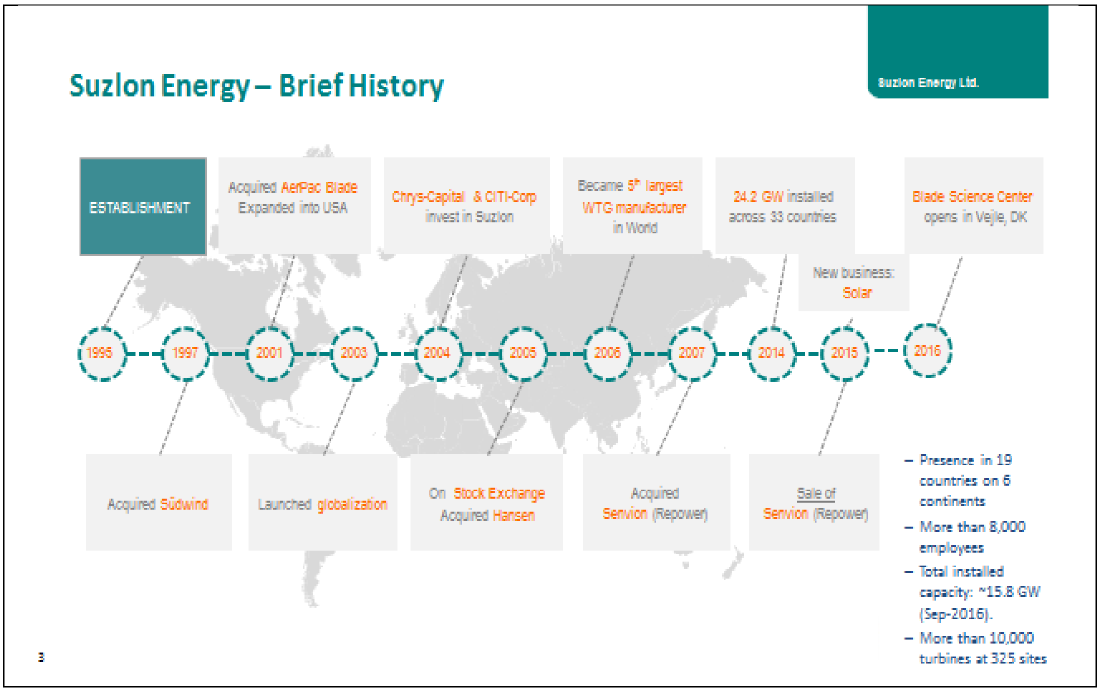
Introduction and Outline

- Suzlon Energy – Brief Presentation
- Wind Turbine Blade Design and Smart Rotor
- Industrial Perspective: Considerations and Challenges on Smart Rotors

Leonardo Bergami

leonardo.bergami@suzlon.com

2006-2008	M.Sc. DTU Wind Energy
2010-2013	Ph.D. Risø - DTU on Smart Rotor with Flaps
2013-2015	Postdoc researcher in DTU Wind
2015-2016	Deep south (Punta Arenas, Chile) – UMAG, Min.Eng.
2016 Oct	Suzlon, Blade Science Center, Vejle - DK



Suzlon Energy – Brief History

1995 – ESTABLISHMENT

1997 – Acquired Südwind

2001 – Acquired AerPac Blade Expanded into USA

2003 – Launched globalization

2004 – Chrys-Capital & CITI-Corp invest in Suzlon

2005 – On Stock Exchange Acquired Hansen

2006 – Became 5th largest WTG manufacturer in World

2007 – Acquired Senvion (Repower)

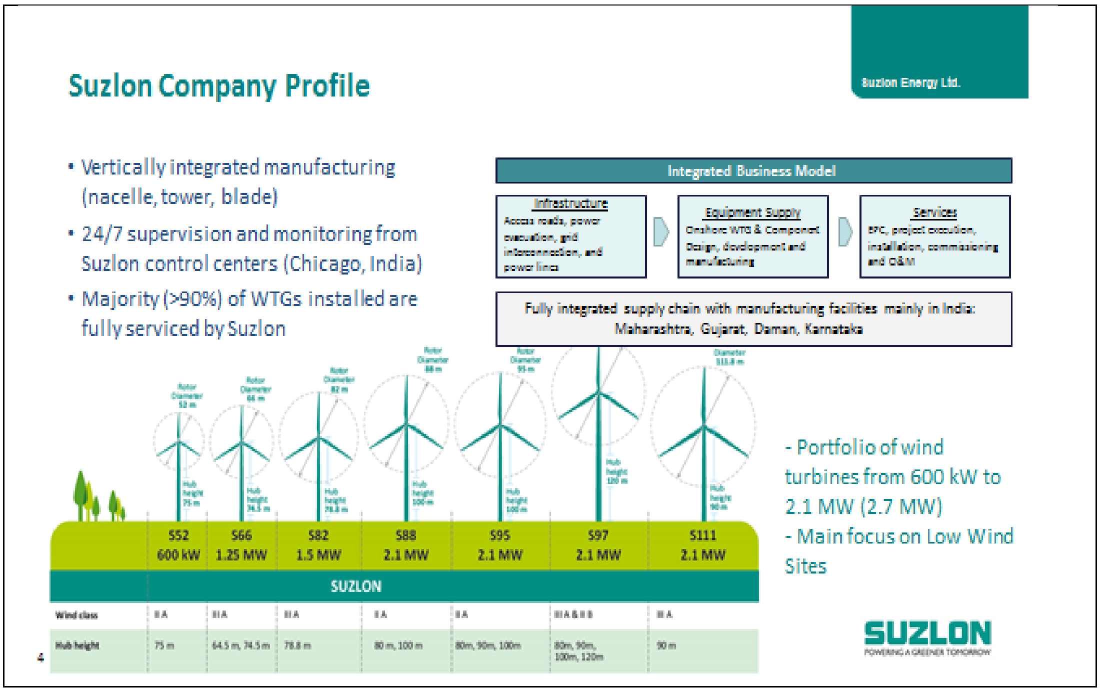
2014 – 24.2 GW installed across 33 countries

2015 – New business: Solar

2015 – Sale of Senvion (Repower)

2016 – Blade Science Center opens in Vejle, DK

- Presence in 19 countries on 6 continents
- More than 8,000 employees
- Total installed capacity: ~15.8 GW (Sep-2016).
- More than 10,000 turbines at 325 sites



Suzlon Energy Ltd.

Suzlon Company Profile

- Vertically integrated manufacturing (nacelle, tower, blade)
- 24/7 supervision and monitoring from Suzlon control centers (Chicago, India)
- Majority (>90%) of WTGs installed are fully serviced by Suzlon

Integrated Business Model

Infrastructure
Access roads, power evacuation, grid interconnection, and power lines

Equipment Supply
Onshore WTG & Component Design, development and manufacturing

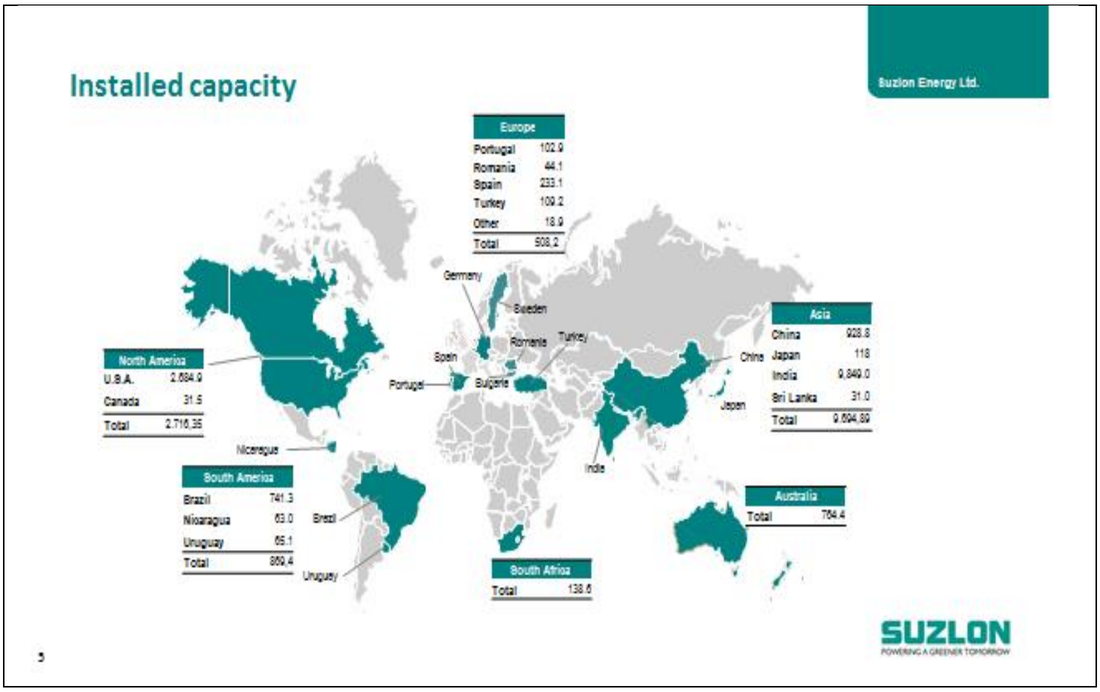
Services
EPC, project execution, installation, commissioning and O&M

Fully integrated supply chain with manufacturing facilities mainly in India:
Maharashtra, Gujarat, Daman, Karnataka

	S52 600 kW	S66 1.25 MW	S82 1.5 MW	S88 2.1 MW	S95 2.1 MW	S97 2.1 MW	S111 2.1 MW
Wind class	II A	III A	III A	II A	II A	III A & III B	III A
Hub height	75 m	64.5 m, 74.5 m	78.8 m	80 m, 100 m	80m, 90m, 100m	80m, 90m, 100m, 120m	90 m

- Portfolio of wind turbines from 600 kW to 2.1 MW (2.7 MW)
- Main focus on Low Wind Sites

SUZLON POWERING A GREENER TOMORROW



Suzlon Energy Ltd.

Installed capacity

Europe	
Portugal	102.9
Romania	44.1
Spain	233.1
Turkey	109.2
Other	18.9
Total	508.2

North America	
U.S.A.	2.684.9
Canada	31.5
Total	2.716,35

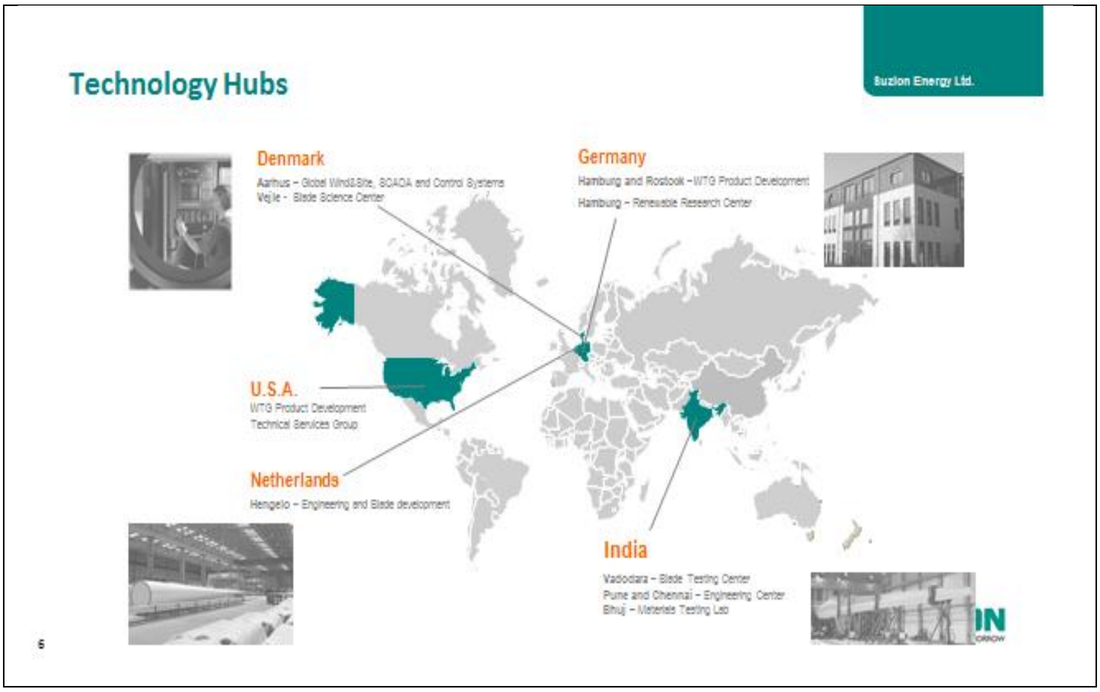
South America	
Brazil	741.3
Nicaragua	63.0
Uruguay	65.1
Total	869,4

South Africa	
Total	138.6

Asia	
China	928.8
Japan	118
India	9,849.0
Sri Lanka	31.0
Total	9.694,89

Australia	
Total	764.4

SUZLON POWERING A GREENER TOMORROW



Technology Hubs

Denmark
Aarhus – Global Wind&Site, SCADA and Control Systems
Vejle – Blade Science Center

Germany
Hamburg and Rostock – WTG Product Development
Hamburg – Renewable Research Center

U.S.A.
WTG Product Development
Technical Services Group

Netherlands
Hengelo – Engineering and Blade development

India
Vadodara – Blade Testing Center
Pune and Chennai – Engineering Center
Bhuj – Materials Testing Lab

Production and Test Facilities

Blade Science Center in Vejle

In March 2016 opens the Blade Science Center in Vejle. 15 employees.

Supporting Suzlon's Vision as Technology Center for Wind Turbine Blade Design

- To be a Technology leader in the wind sector.
  - *BSC will test existing technologies for future and existing platforms*
  - *BSC will invent new technologies for future and existing platforms*
  - *BSC will show case that Suzlon is on the forefront of technology development*
- To be in the top three wind companies in the key markets of the world.
  - *BSC will focus on technology solutions for low wind markets*
- To be a global leader in providing profitable, wind power solutions.
  - *BSC will develop technology which brings down LCOE*
- To be the 'Company of Choice' for stakeholders
  - *BSC will develop and prove reliable solutions*

Wind Turbine Blade Design

Suzlon Energy Ltd.

Main Driver:

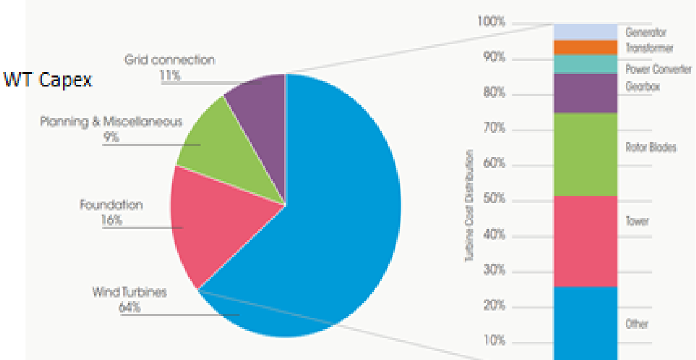
→ **Lower LCOE**

$$\mathrm{LCOE} = \left.\frac{Capex + Opex}{Energy}\right]_{Life\ Time}$$

CAPEX Breakdown (onshore):

→ Blades account for app. 20 % WT Capex

(13 % WF CAPEX)

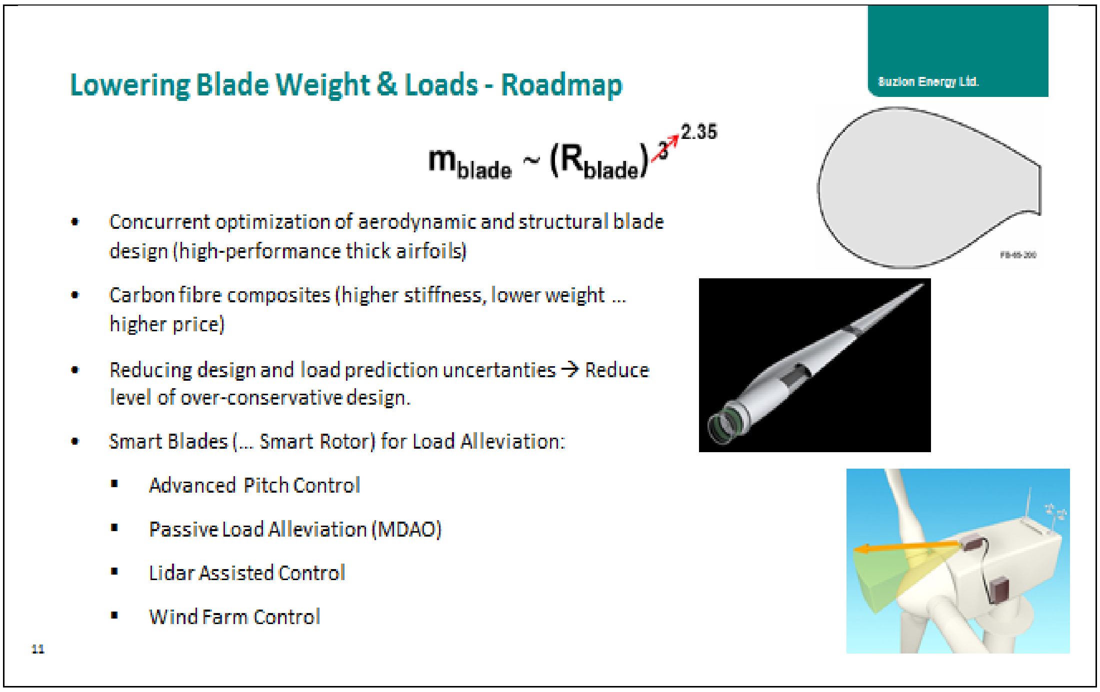


Source: International Renewable Energy Agency (2012)
Cost Analysis, Wind Power

Rotor impact on LCOE

- Increasing power output of wind turbine
  - 100% attributed to energy yield
- Lowering the cost of the blade
  - Directly impacts about 20% of the turbine cost
- Lowering the blade weight & Loads
  - Indirectly impacts cost of other components (drivetrain, tower, etc.)

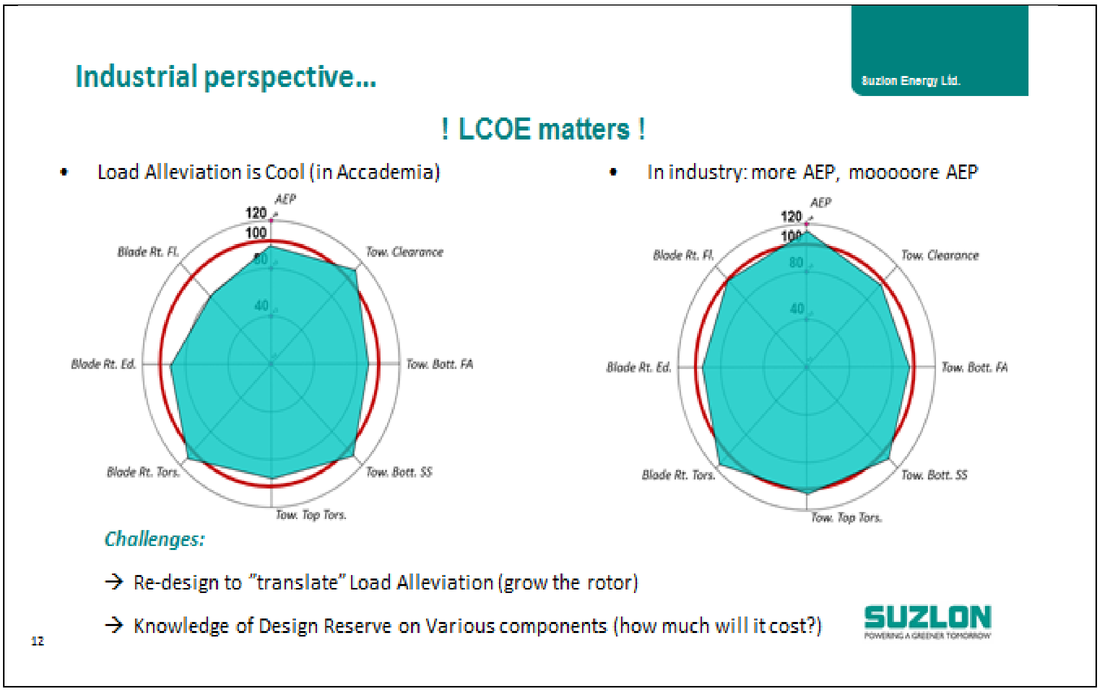
SUZLON
POWERING A GREENER TOMORROW



Lowering Blade Weight & Loads - Roadmap

$$m_{blade} \sim (R_{blade})^{\cancel{3} \nearrow 2.35}$$

- Concurrent optimization of aerodynamic and structural blade design (high-performance thick airfoils)
- Carbon fibre composites (higher stiffness, lower weight … higher price)
- Reducing design and load prediction uncertainties → Reduce level of over-conservative design.
- Smart Blades (… Smart Rotor) for Load Alleviation:
  - Advanced Pitch Control
  - Passive Load Alleviation (MDAO)
  - Lidar Assisted Control
  - Wind Farm Control



Industrial perspective…

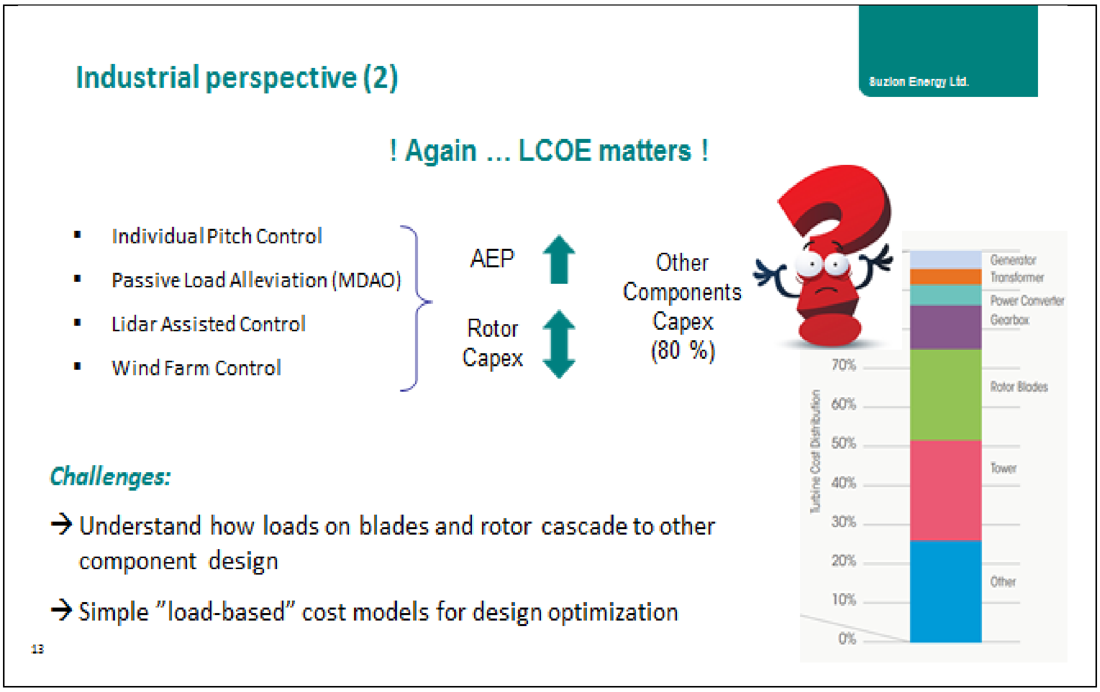
! LCOE matters !

- Load Alleviation is Cool (in Accademia)
- In industry: more AEP, mooooore AEP

Challenges:

→ Re-design to "translate" Load Alleviation (grow the rotor)

→ Knowledge of Design Reserve on Various components (how much will it cost?)



Industrial perspective (2)

! Again … LCOE matters !

- Individual Pitch Control
- Passive Load Alleviation (MDAO)
- Lidar Assisted Control
- Wind Farm Control

AEP ↑

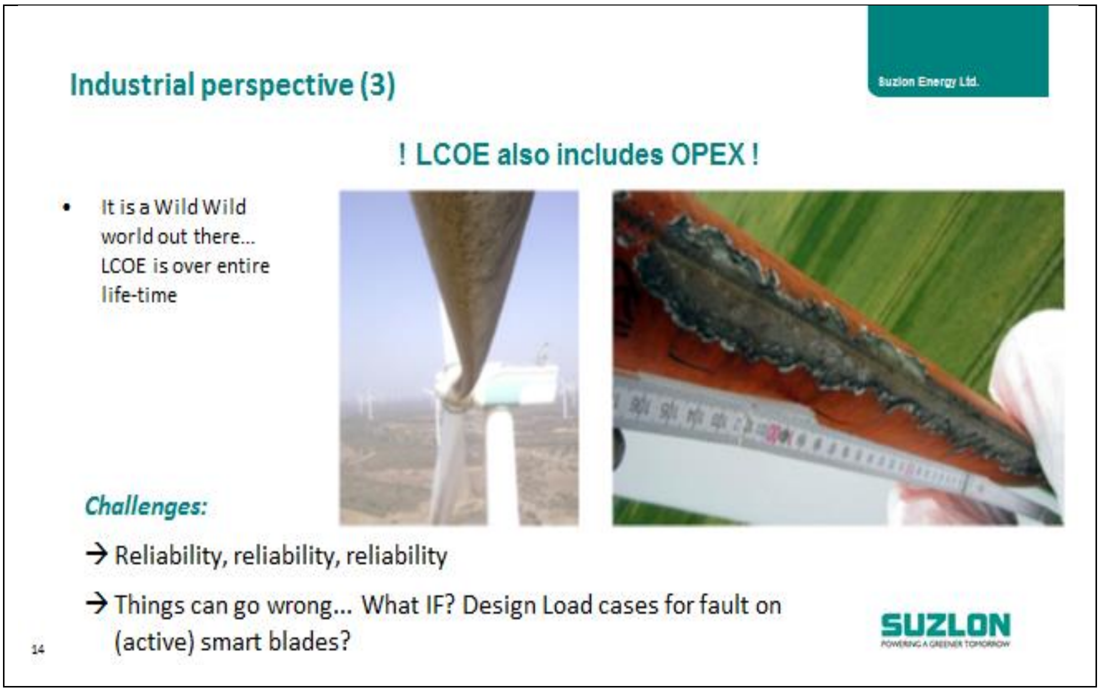
Rotor Capex ↕

Other Components Capex (80 %)

Challenges:

→ Understand how loads on blades and rotor cascade to other component design

→ Simple "load-based" cost models for design optimization



Industrial perspective (3)

! LCOE also includes OPEX !

- It is a Wild Wild world out there… LCOE is over entire life-time

Challenges:

→ Reliability, reliability, reliability

→ Things can go wrong… What IF? Design Load cases for fault on (active) smart blades?

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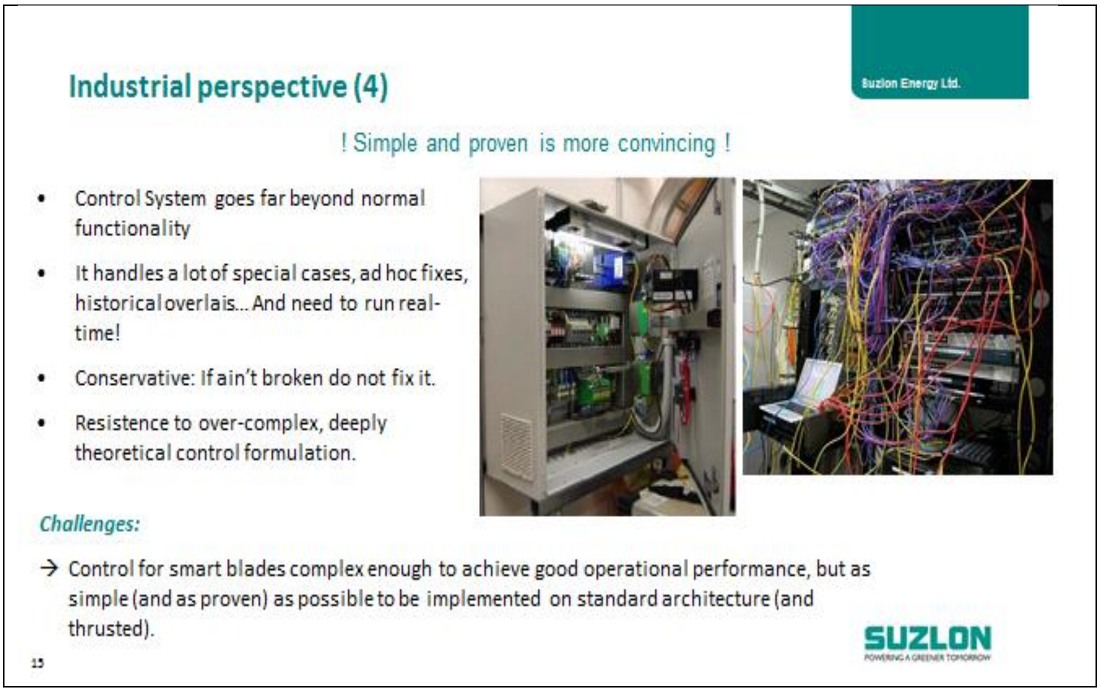

Industrial perspective (4)

! Simple and proven is more convincing !

- Control System goes far beyond normal functionality
- It handles a lot of special cases, ad hoc fixes, historical overlais… And need to run real-time!
- Conservative: If ain't broken do not fix it.
- Resistence to over-complex, deeply theoretical control formulation.

Challenges:

→ Control for smart blades complex enough to achieve good operational performance, but as simple (and as proven) as possible to be implemented on standard architecture (and thrusted).

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Summary of Challenges for Discussion

Challenges:

- → Re-design to "translate" Load Alleviation to more "marketable" performance indicators (grow the rotor)
- → Knowledge of loads design reserve on various WT components
- → Understand how loads on blades and rotor cascade to design loads of other WT components
- → Formulate simple "load-based" cost model for design optimization processes
- → Reliability, reliability, reliability
- → Things can go wrong… What IF? Design Load cases for fault on (active) smart blades?
- → Control for smart blades complex enough to achieve good operational performance, but as simple (and as proven) as possible to be implemented on standard architecture (and thrusted).

Suzlon wind farm in Paracuru, Brazil

SUZLON
POWERING A GREENER TOMORROW

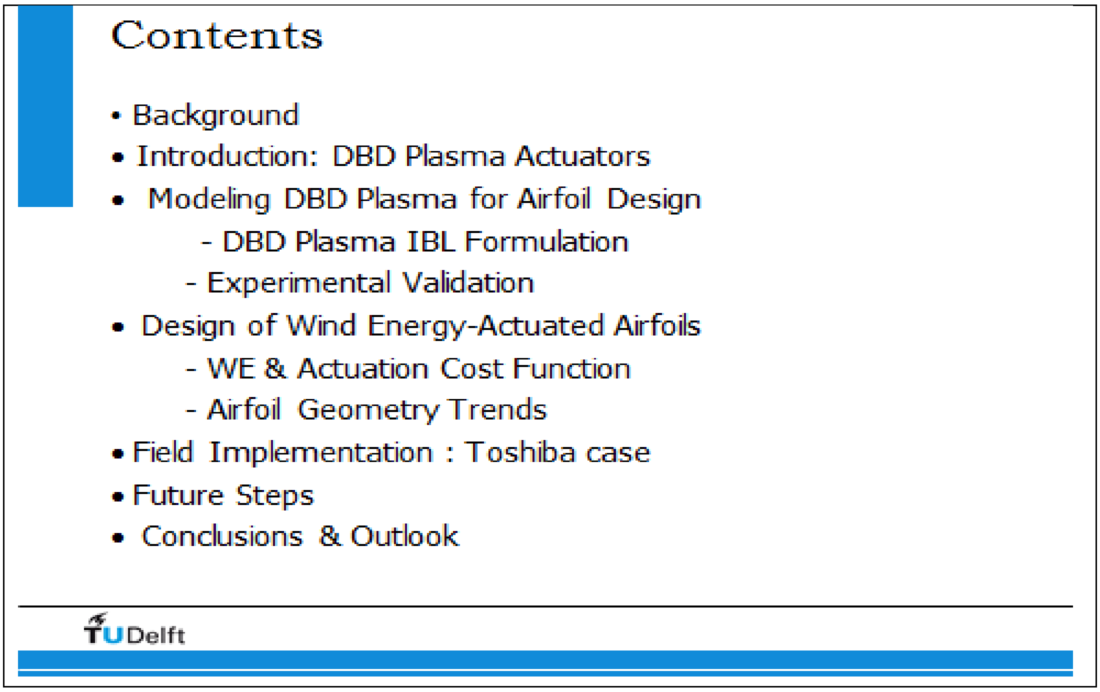
Thank You

Smart Rotor Research using DBD Plasma as Flow Control Actuators : an Overview of TUDelft's Efforts

Ricardo Pereira

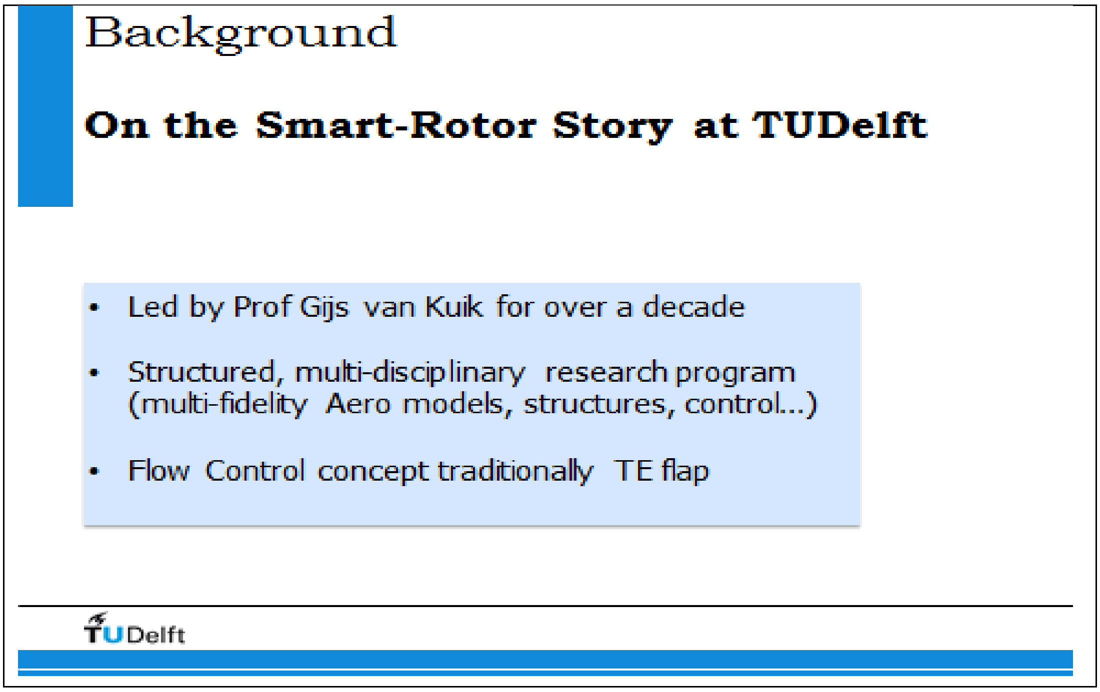
Aerodynamics & Wind Energy Section, Aerospace Faculty - TUDelft

Acknowlodgements : Gaël de Oliveira, Daniele Ragni, Marios Kotsonis and Ernest Carbonell



Contents

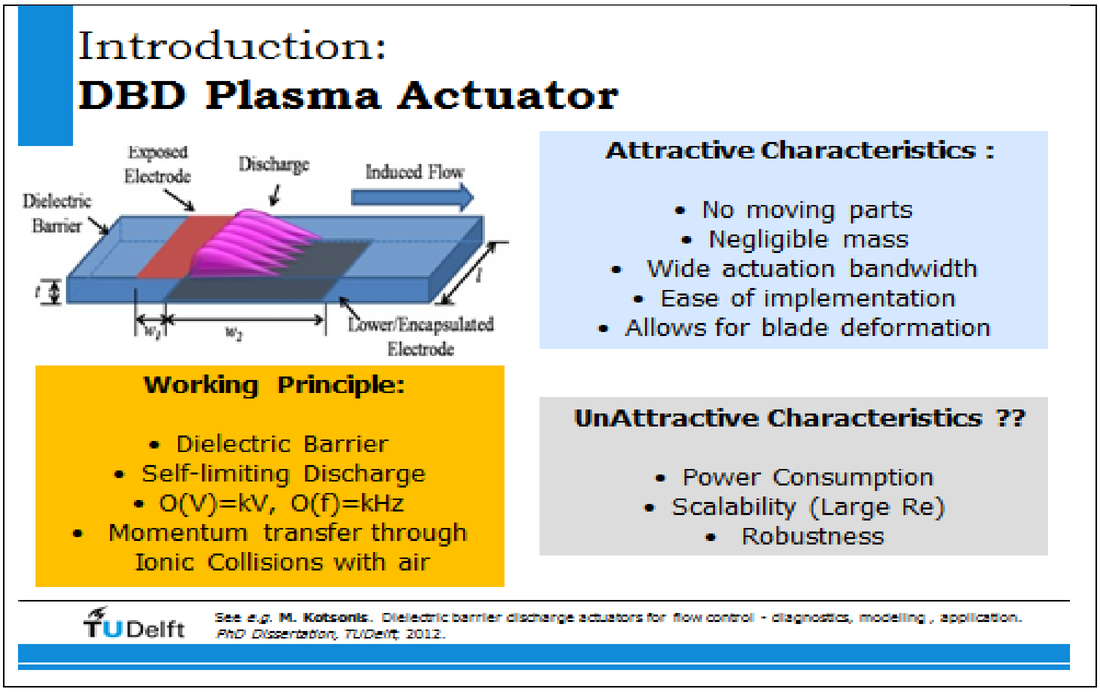
- Background
- Introduction: DBD Plasma Actuators
- Modeling DBD Plasma for Airfoil Design
    - DBD Plasma IBL Formulation
    - Experimental Validation
- Design of Wind Energy-Actuated Airfoils
    - WE & Actuation Cost Function
    - Airfoil Geometry Trends
- Field Implementation : Toshiba case
- Future Steps
- Conclusions & Outlook



Background

On the Smart-Rotor Story at TUDelft

- Led by Prof Gijs van Kuik for over a decade
- Structured, multi-disciplinary research program (multi-fidelity Aero models, structures, control...)
- Flow Control concept traditionally TE flap



Introduction:
DBD Plasma Actuator

Attractive Characteristics :

- No moving parts
- Negligible mass
- Wide actuation bandwidth
- Ease of implementation
- Allows for blade deformation

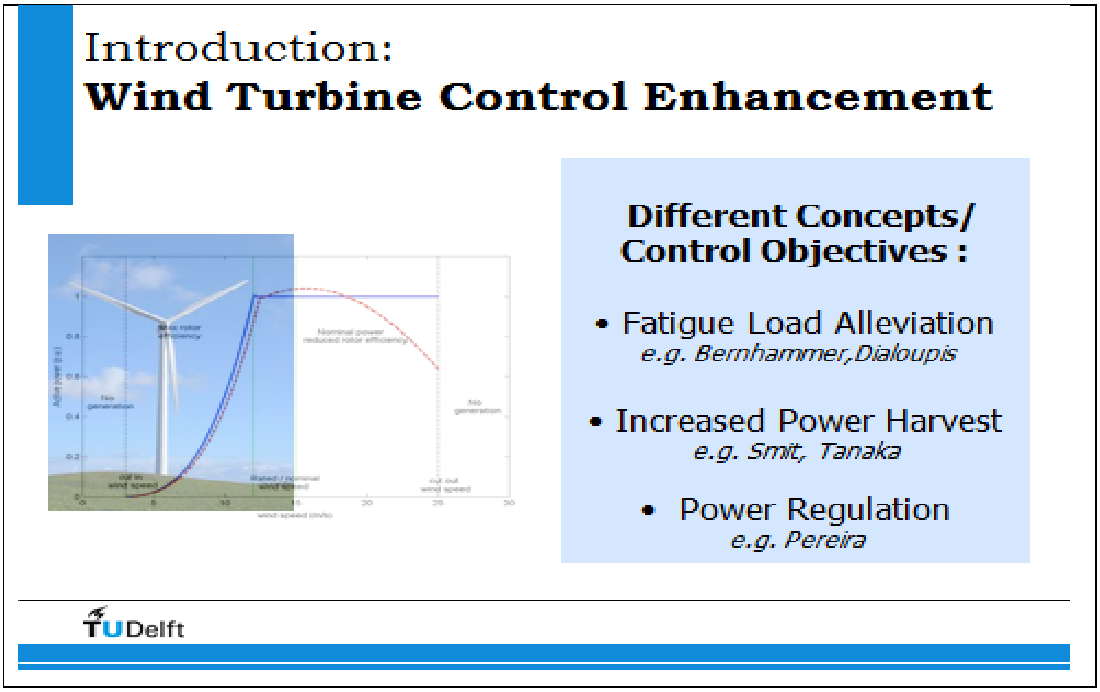
Working Principle:

- Dielectric Barrier
- Self-limiting Discharge
- O(V)=kV, O(f)=kHz
- Momentum transfer through Ionic Collisions with air

UnAttractive Characteristics ??

- Power Consumption
- Scalability (Large Re)
- Robustness

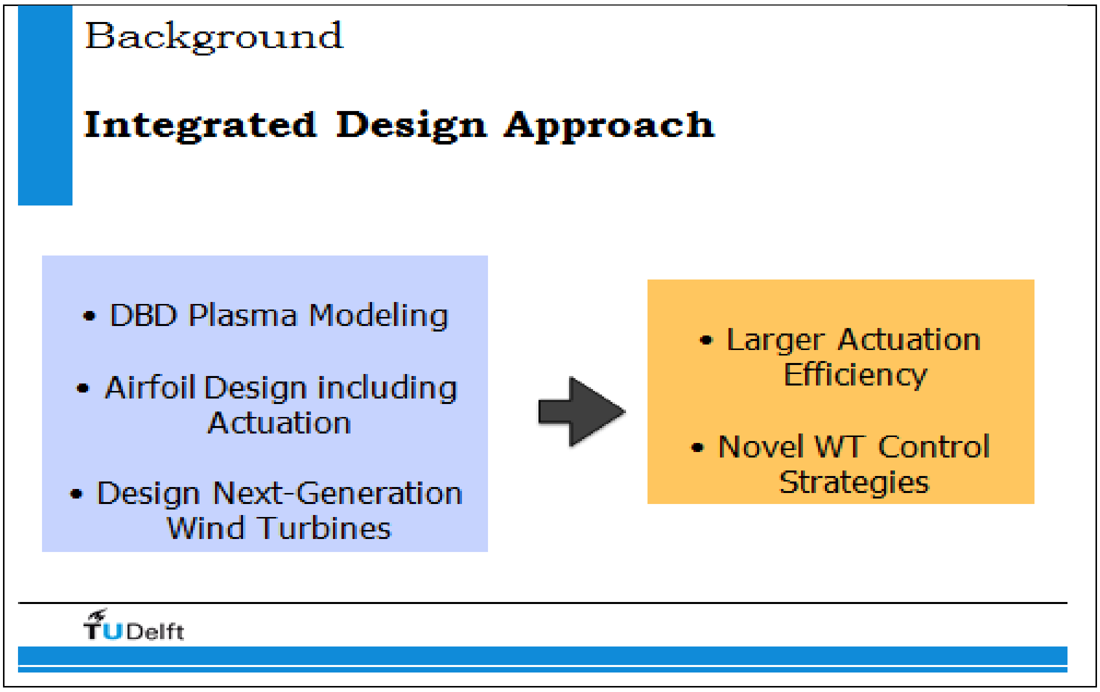
See *e.g.* **M. Kotsonis**. Dielectric barrier discharge actuators for flow control - diagnostics, modelling , application. *PhD Dissertation, TUDelft,* 2012.



Introduction:
Wind Turbine Control Enhancement

Different Concepts/ Control Objectives :

- Fatigue Load Alleviation
  e.g. Bernhammer, Dialoupis
- Increased Power Harvest
  e.g. Smit, Tanaka
- Power Regulation
  e.g. Pereira

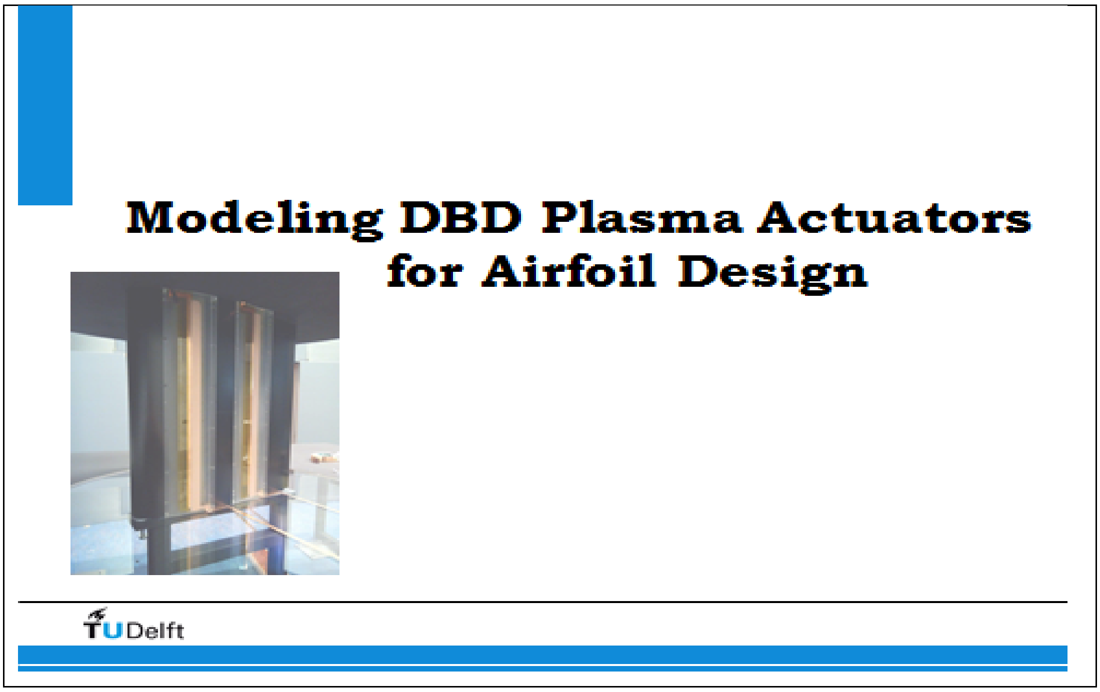


Background

Integrated Design Approach

- DBD Plasma Modeling
- Airfoil Design including Actuation
- Design Next-Generation Wind Turbines

- Larger Actuation Efficiency
- Novel WT Control Strategies



Modeling DBD Plasma Actuators for Airfoil Design

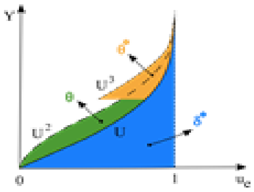
Modeling DBD Plasma Actuators for Airfoil Design

Why IBL Formulation ?

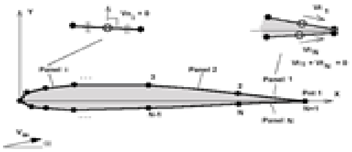
Compact IBL Formulation

$$\delta_1 = \int_0^\infty \left(1 - \frac{U}{U_e}\right) dY$$

$$\delta_2 = \int_0^\infty \frac{U}{U_e}\left(1 - \frac{U}{U_e}\right) dY$$



Panel Methods with
Viscous-Inviscid Interaction



- Not less accurate than CFD
- Suitable for optimization

Modeling DBD Plasma Actuators for Airfoil Design

von Karman Integral Equations with Plasma Coefficients

$$C_{FM} = \int_0^\infty \left(\frac{F_x}{\frac{1}{2}\rho U_\infty^2}\right) dY$$

$$C_{FE} = \int_0^\infty \left(\frac{F_x}{\frac{1}{2}\rho U_\infty^2} u\right) dY$$

- Incompressible,Turbulent Flows
- Assumes Undisturbed Ue
- Steady DBD employment
- Only acting in X

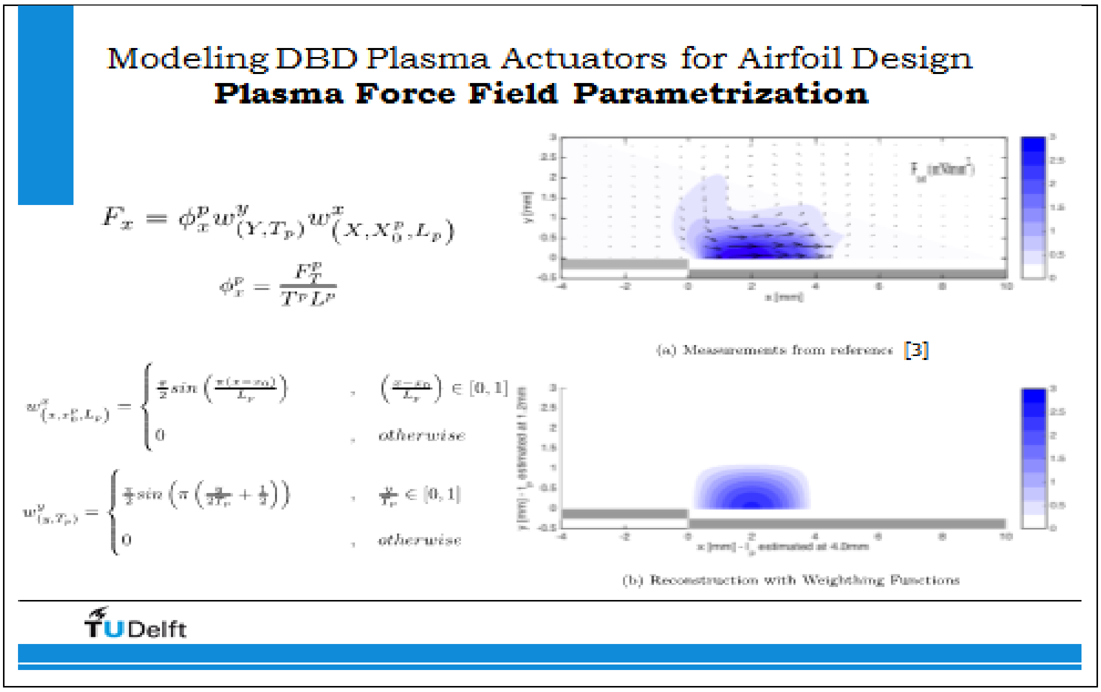
$$\begin{cases} \frac{\partial\theta}{\partial x} = \underbrace{\frac{C_f}{2}}_{Skin\,Friction} \underbrace{-(H_{12}+2)\frac{\theta}{u_e}\frac{\partial u_e}{\partial x}}_{Pressure\,Gradient} + \underbrace{\frac{v_o}{u_e}}_{Transpiration} - \underbrace{\frac{C_{FM}}{2u_e^2}}_{Plasma} \\ \frac{\partial H_{32}}{\partial x} = \underbrace{\frac{2C_D}{\theta} - \frac{H_{32}}{\theta}\frac{C_f}{2}}_{Dissipation} + \underbrace{(H_{12}-1)\frac{H_{32}}{u_e}\frac{\partial u_e}{\partial x}}_{Pressure\,Gradient} - \frac{1}{\theta}\underbrace{(H_{32}+1)\frac{v_o}{u_e}}_{Transpiration} + \frac{1}{\theta}\underbrace{\left(H_{32}\frac{C_{FM}}{2u_e^2} - \frac{C_{FE}}{u_e^3}\right)}_{Plasma} \end{cases}$$

Momentum Cons.

Energy Cons.

Closure Relations ?

See: **de Oliveira G, Pereira R, Ragni D, Kotsonis M.** Modeling DBD plasma actuators in integral boundary layer formulation for application in panel methods. *AIAA - Fluid Dynamics Conference, Dallas* 2015



Modeling DBD Plasma Actuators for Airfoil Design
Plasma Force Field Parametrization

$$F_x = \phi_x^p w^y_{(Y,T_p)} w^x_{(X,X_0^p,L_p)}$$

$$\phi_x^p = \frac{F_T^p}{T^p L^p}$$

$$w^x_{(x,x_0^p,L_p)} = \begin{cases} \frac{\pi}{2} sin\left(\frac{\pi(x-x_0)}{L_p}\right) & , \left(\frac{x-x_0}{L_p}\right) \in [0,1] \\ 0 & , otherwise \end{cases}$$

$$w^y_{(y,T_p)} = \begin{cases} \frac{\pi}{2} sin\left(\pi\left(\frac{y}{2T_p}+\frac{1}{2}\right)\right) & , \frac{y}{T_p} \in [0,1] \\ 0 & , otherwise \end{cases}$$

(a) Measurements from reference [3]

(b) Reconstruction with Weighthing Functions

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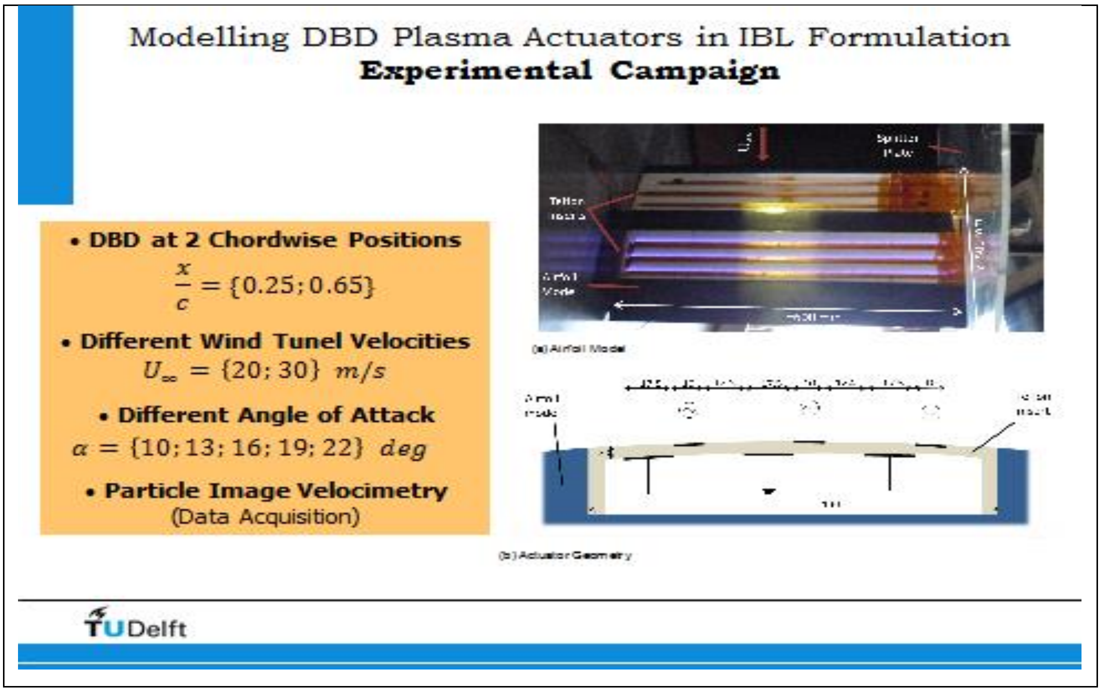

Modelling DBD Plasma Actuators in IBL Formulation
Experimental Campaign

- **DBD at 2 Chordwise Positions**
  $\frac{x}{c} = \{0.25; 0.65\}$
- **Different Wind Tunel Velocities**
  $U_\infty = \{20; 30\}\ m/s$
- **Different Angle of Attack**
  $\alpha = \{10; 13; 16; 19; 22\}\ deg$
- **Particle Image Velocimetry**
  (Data Acquisition)

(a) Airfoil Model

(b) Actuator Geometry

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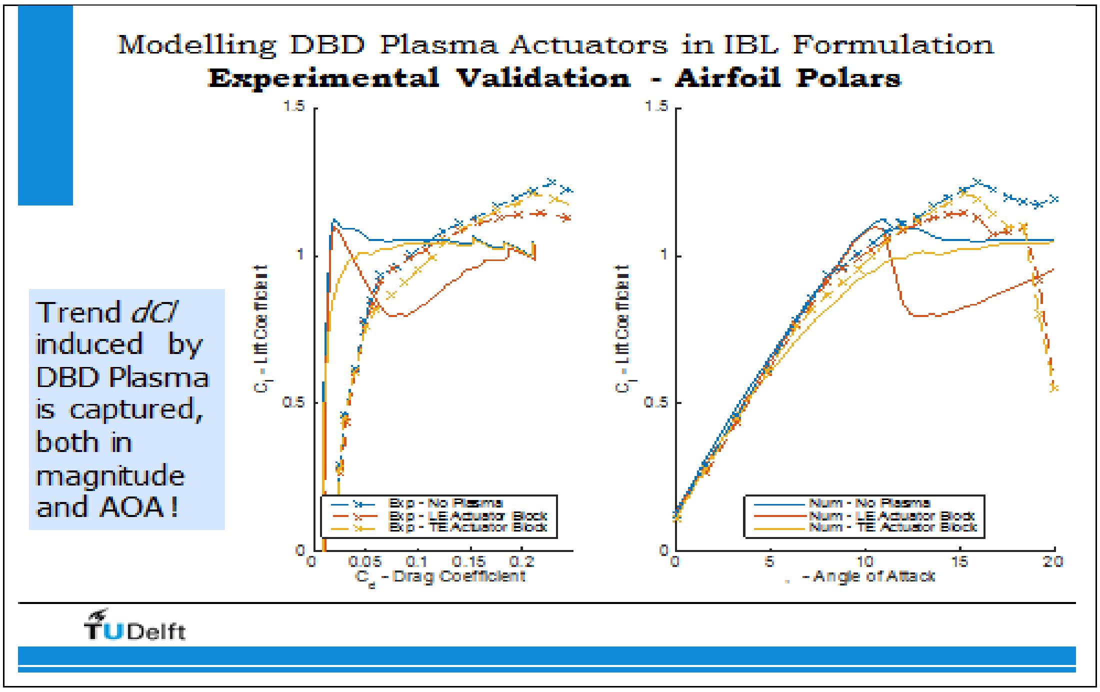
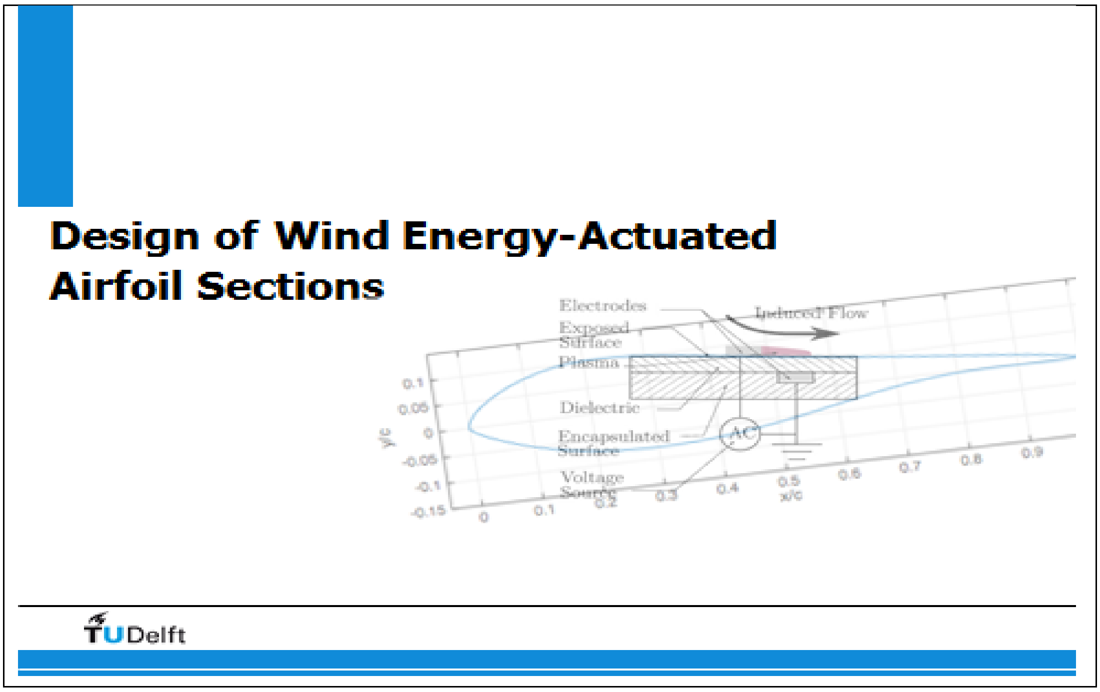


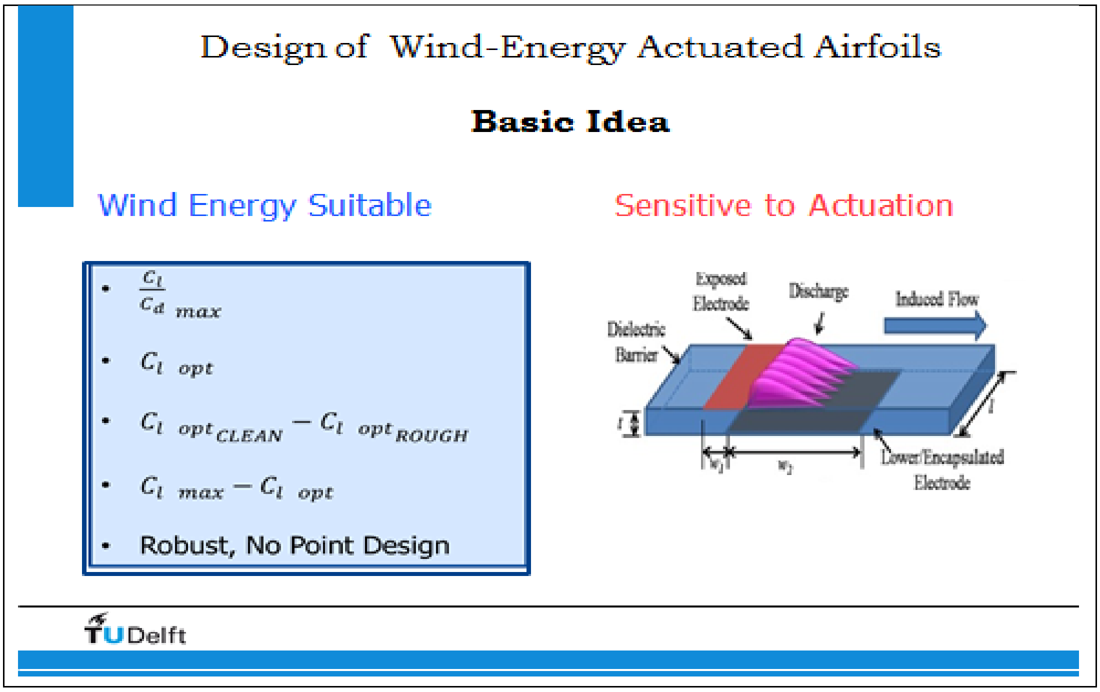
Modelling DBD Plasma Actuators in IBL Formulation

Experimental Validation - Airfoil Polars

Trend *dCl* induced by DBD Plasma is captured, both in magnitude and AOA!



Design of Wind Energy-Actuated Airfoil Sections



Design of Wind-Energy Actuated Airfoils

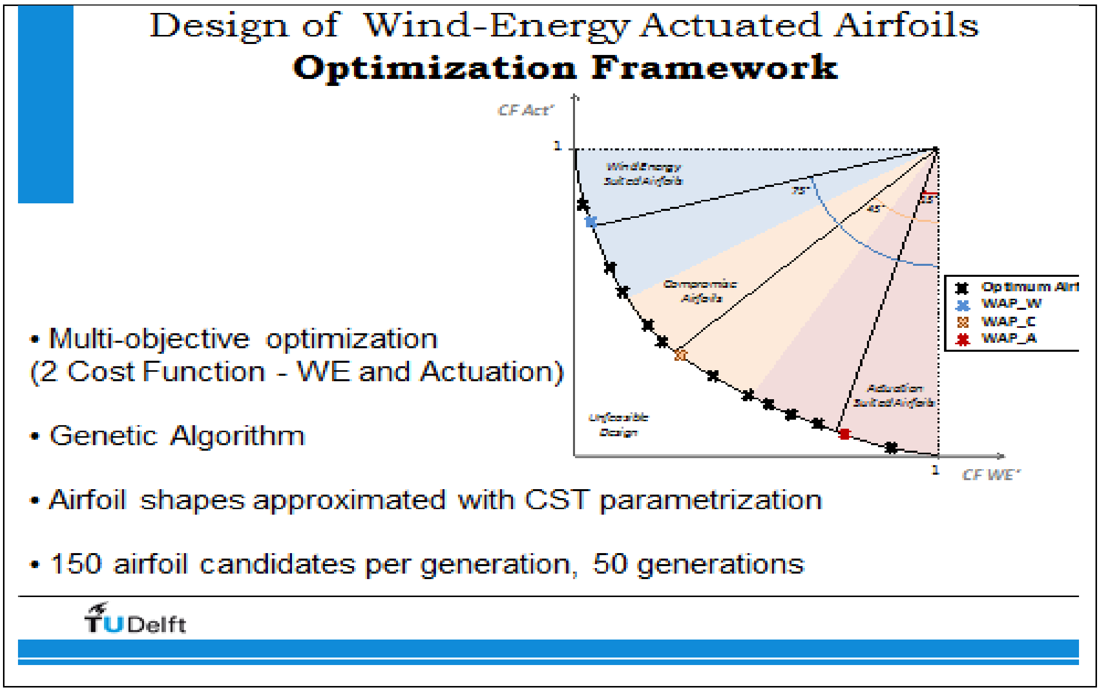
Basic Idea

Wind Energy Suitable

- $\frac{C_l}{C_d}\ max$
- $C_l\ \ opt$
- $C_l\ \ opt_{CLEAN} - C_l\ \ opt_{ROUGH}$
- $C_l\ \ max - C_l\ \ opt$
- Robust, No Point Design

Sensitive to Actuation

TU Delft



Design of Wind-Energy Actuated Airfoils

Optimization Framework

- Multi-objective optimization (2 Cost Function - WE and Actuation)
- Genetic Algorithm
- Airfoil shapes approximated with CST parametrization
- 150 airfoil candidates per generation, 50 generations

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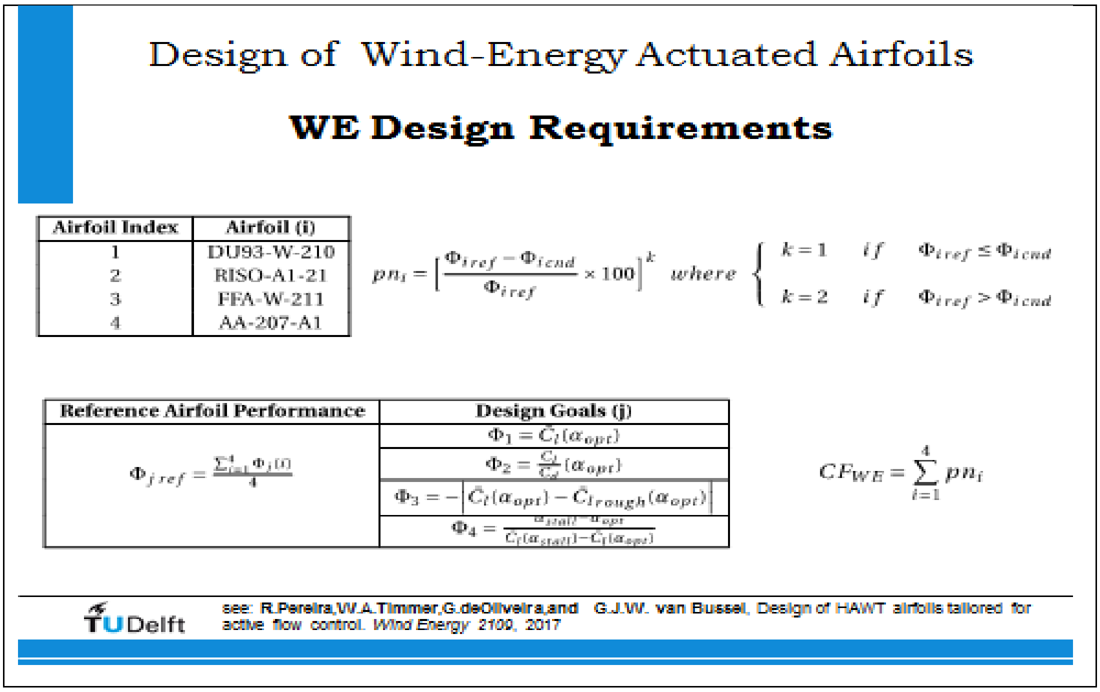


Design of Wind-Energy Actuated Airfoils

WE Design Requirements

Airfoil Index	Airfoil (i)
1	DU93-W-210
2	RISO-A1-21
3	FFA-W-211
4	AA-207-A1

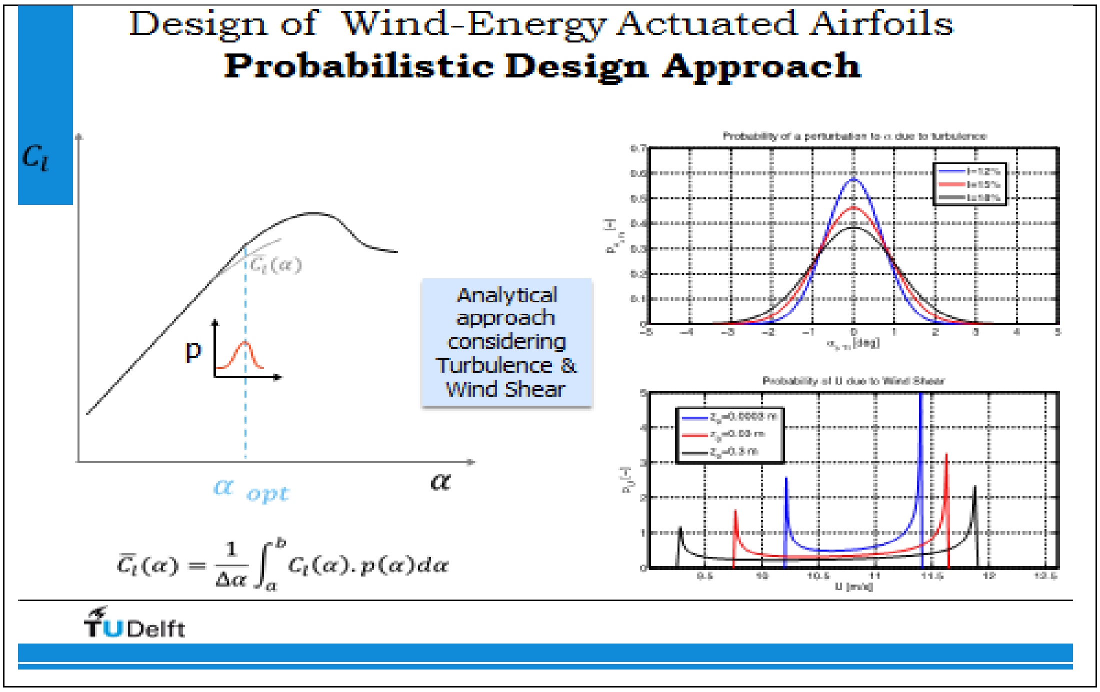
$$pn_i = \left[\frac{\Phi_{iref} - \Phi_{icnd}}{\Phi_{iref}} \times 100\right]^k \quad where \quad \begin{cases} k=1 & if \quad \Phi_{iref} \leq \Phi_{icnd} \\ k=2 & if \quad \Phi_{iref} > \Phi_{icnd} \end{cases}$$

Reference Airfoil Performance	Design Goals (j)
$\Phi_{jref} = \frac{\sum_{i=1}^{4} \Phi_j(i)}{4}$	$\Phi_1 = \bar{C}_l(\alpha_{opt})$
	$\Phi_2 = \frac{C_l}{C_d}(\alpha_{opt})$
	$\Phi_3 = -\left\|\bar{C}_l(\alpha_{opt}) - \bar{C}_{l\,rough}(\alpha_{opt})\right\|$
	$\Phi_4 = \frac{\alpha_{stall} - \alpha_{opt}}{\bar{C}_l(\alpha_{stall}) - \bar{C}_l(\alpha_{opt})}$

$$CF_{WE} = \sum_{i=1}^{4} pn_i$$

TU Delft

see: R.Pereira,W.A.Timmer,G.deOliveira,and G.J.W. van Bussel, Design of HAWT airfoils tailored for active flow control. *Wind Energy 2100*, 2017



Design of Wind-Energy Actuated Airfoils

Probabilistic Design Approach

Analytical approach considering Turbulence & Wind Shear

$$\bar{C}_l(\alpha) = \frac{1}{\Delta\alpha}\int_a^b C_l(\alpha).\,p(\alpha)d\alpha$$

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Design of Wind-Energy Actuated Airfoils

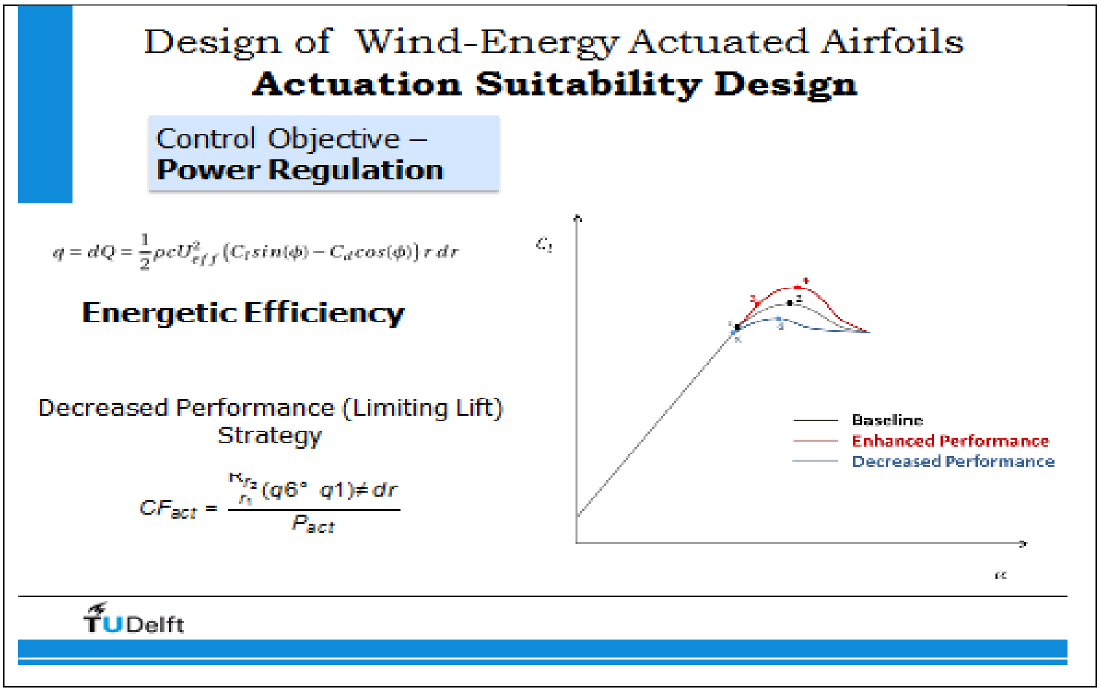
Actuation Suitability Design

How to define

Actuation Suitability ?

Depends on

Control Objective



Design of Wind-Energy Actuated Airfoils

Actuation Suitability Design

Control Objective –
Power Regulation

$$q = dQ = \frac{1}{2}\rho c U_{eff}^2 \left(C_l sin(\phi) - C_d cos(\phi)\right) r\, dr$$

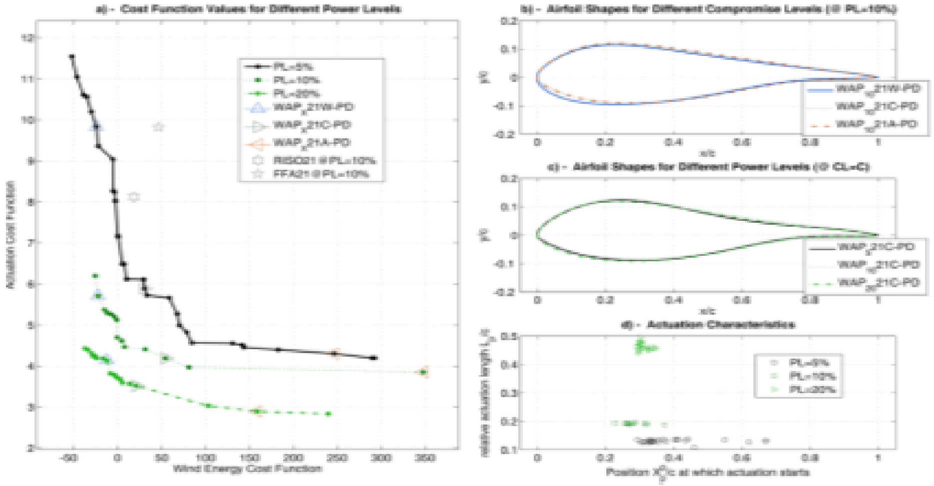
Energetic Efficiency

Decreased Performance (Limiting Lift)
Strategy

$$CF_{act} = \frac{\mathrm{K}_{r_1}^{r_2}(q6^\circ\ \ q1)\neq dr}{P_{act}}$$

Design of Wind-Energy Actuated Airfoils

Results – Power Regulation


a) - Cost Function Values for Different Power Levels

b) - Airfoil Shapes for Different Compromise Levels (@ PL=10%)

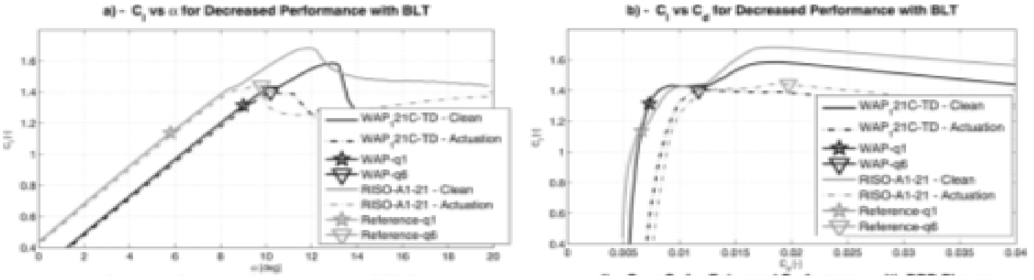
c) - Airfoil Shapes for Different Power Levels (@ CL=C)

d) - Actuation Characteristics

TU Delft

Design of Wind-Energy Actuated Airfoils

Results - Airfoil Polars


a) - C_l vs α for Decreased Performance with BLT

b) - C_l vs C_d for Decreased Performance with BLT

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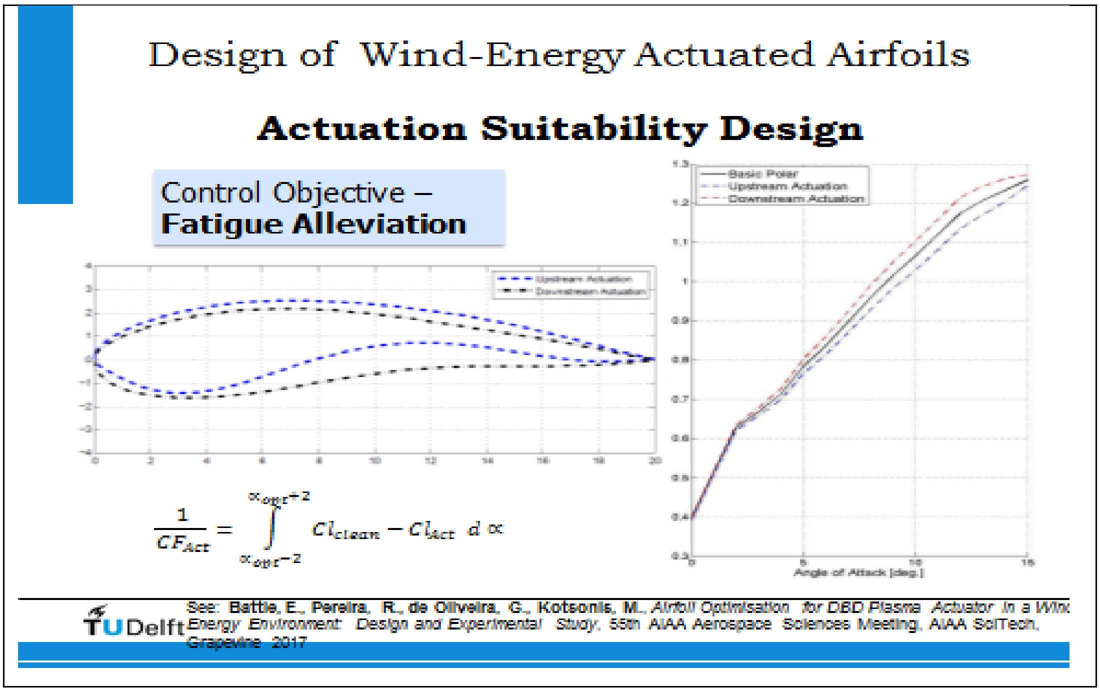


Design of Wind-Energy Actuated Airfoils

Actuation Suitability Design

Control Objective –
Fatigue Alleviation

$$\frac{1}{CF_{Act}} = \int_{\propto_{opt}-2}^{\propto_{opt}+2} Cl_{clean} - Cl_{Act} \; d\propto$$

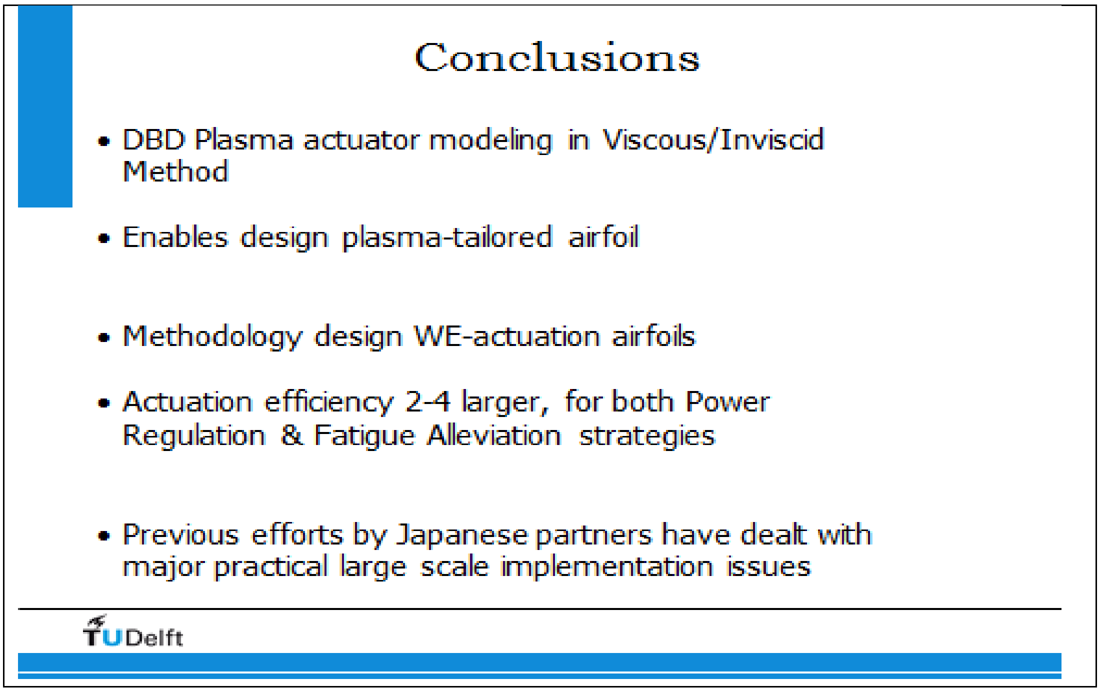
See: **Battle, E., Pereira, R., de Oliveira, G., Kotsonis, M.**, *Airfoil Optimisation for DBD Plasma Actuator in a Wind Energy Environment: Design and Experimental Study*, 55th AIAA Aerospace Sciences Meeting, AIAA SciTech, Grapevine 2017

Field Implementation: ***Toshiba* Case**
(Aiming at Increased Power Capture)

- Laboratory environment (-2012)
- Field test 30 kW machine (2013)
- "World's 1st trial… on commercial scale WT" (2014)
- Long term testing (+1 year) – 2015/2016
- Currently machine at AIST center in Fukushima

- No Lightning Issues
- DC=1%
- Silicon-Rubber DBD actuator
- System failure approx 1/year

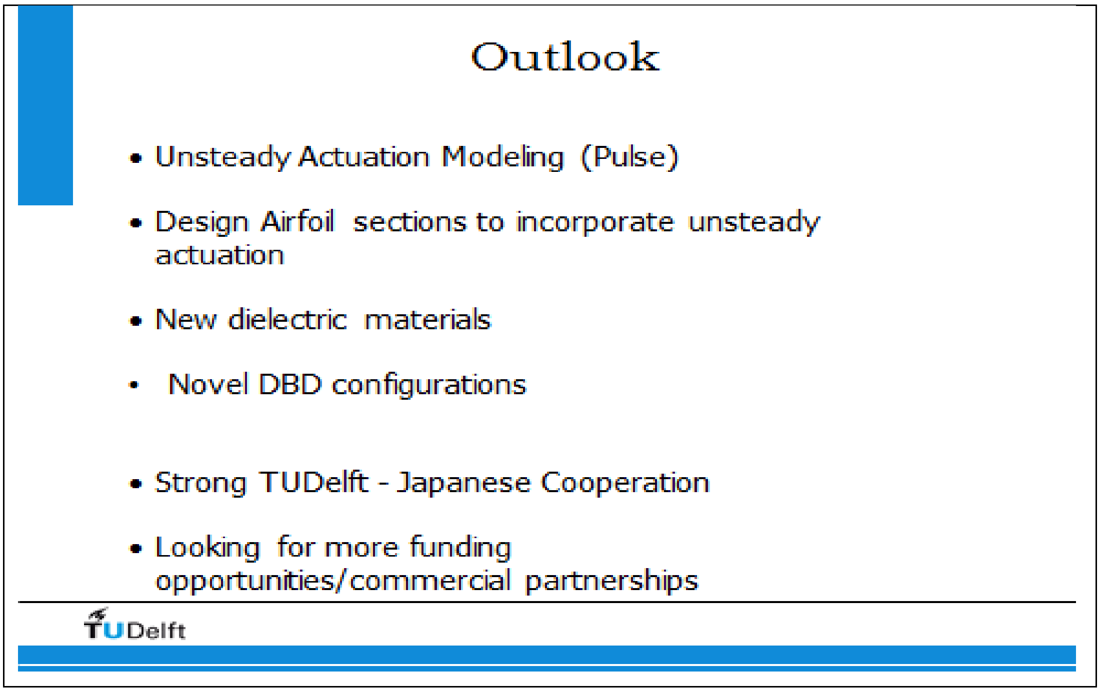
see: **M. Tanaka, K. Amemori, H. Matsuda, N. Shimura, H. Yasui, and T. Osako.** Field test of plasma aerodynamic controlled wind turbine. *EWEA Conference*, 2013. & **M. Tanaka, T. Osako, H. Matsuda, K. Yamazaki, N. Shimura, M. Asayama, Y. Oryu, and S. Yoshida.** The world's first trial for application of plasma aero- dynamic control on commercial scale turbine. *EWEA conference*, PO.ID - 005, 2014.



Conclusions

- DBD Plasma actuator modeling in Viscous/Inviscid Method
- Enables design plasma-tailored airfoil
- Methodology design WE-actuation airfoils
- Actuation efficiency 2-4 larger, for both Power Regulation & Fatigue Alleviation strategies
- Previous efforts by Japanese partners have dealt with major practical large scale implementation issues

TUDelft



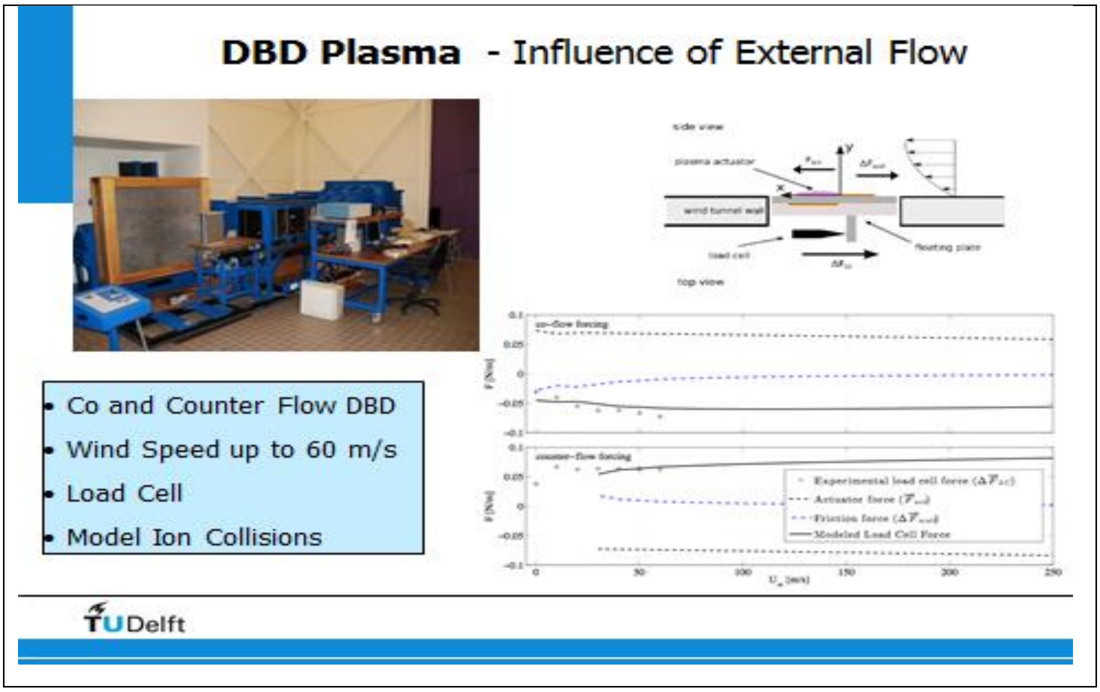
Outlook

- Unsteady Actuation Modeling (Pulse)
- Design Airfoil sections to incorporate unsteady actuation
- New dielectric materials
- Novel DBD configurations
- Strong TUDelft - Japanese Cooperation
- Looking for more funding opportunities/commercial partnerships

TUDelft

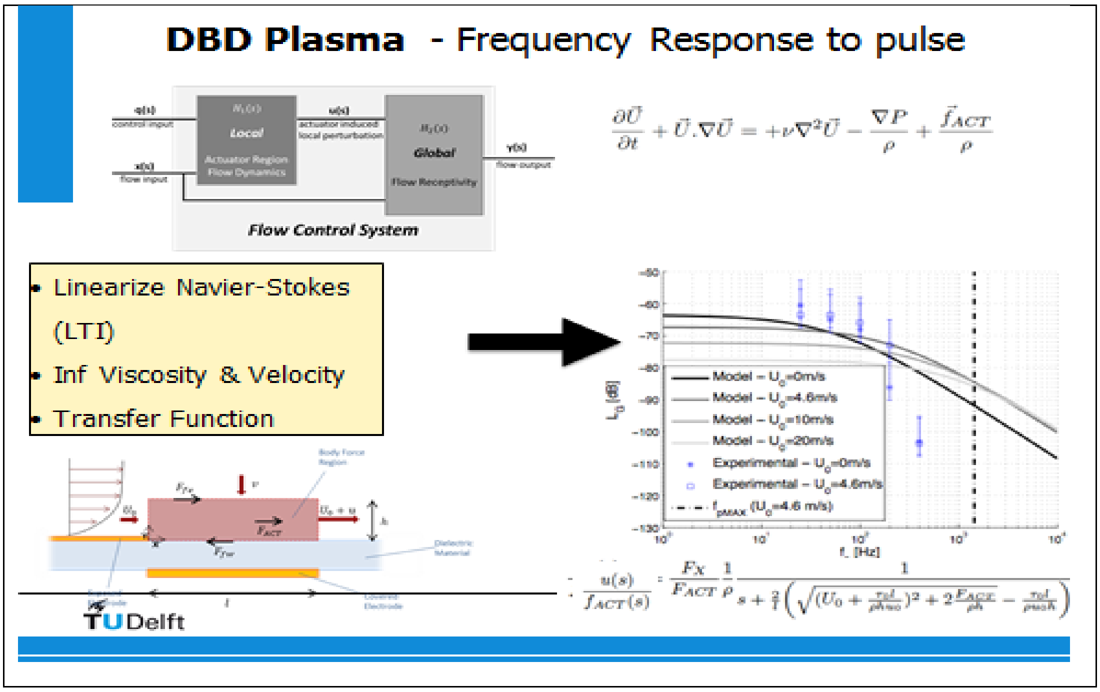
Thank you for your attention !

Questions ???



DBD Plasma - Influence of External Flow

- Co and Counter Flow DBD
- Wind Speed up to 60 m/s
- Load Cell
- Model Ion Collisions



DBD Plasma - Frequency Response to pulse

$$\frac{\partial\vec{U}}{\partial t}+\vec{U}.\nabla\vec{U}=+\nu\nabla^2\vec{U}-\frac{\nabla P}{\rho}+\frac{\vec{f}_{ACT}}{\rho}$$

- Linearize Navier-Stokes (LTI)
- Inf Viscosity & Velocity
- Transfer Function

$$\frac{u(s)}{f_{ACT}(s)}=\frac{F_X}{F_{ACT}}\frac{1}{\rho}\frac{1}{s+\frac{2}{l}\left(\sqrt{(U_0+\frac{\tau_0 l}{\rho h\nu_0})^2+2\frac{F_{ACT}}{\rho h}}-\frac{\tau_0 l}{\rho\nu_0 h}\right)}$$

TU Delft

Active trailing edge flaps in turbine design – a mature technology?

IEA Wind, Smart Blade, Technical Expert Meeting - 27 April 2017

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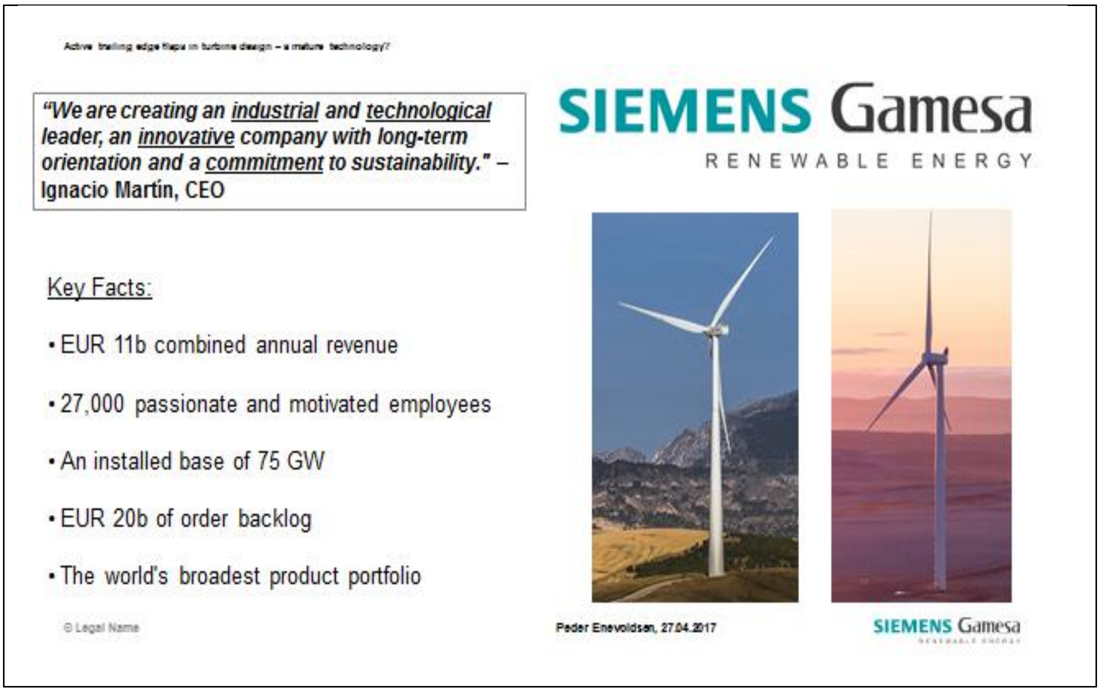

> *"We are creating an industrial and technological leader, an innovative company with long-term orientation and a commitment to sustainability."* – Ignacio Martín, CEO

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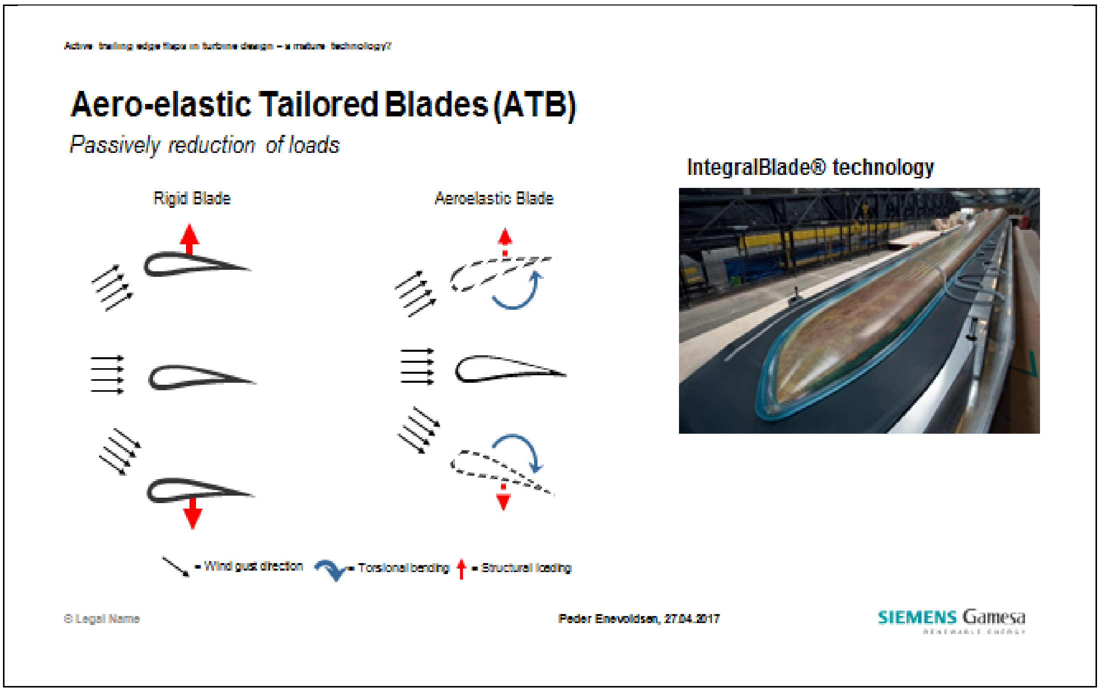
Key Facts:

- EUR 11b combined annual revenue
- 27,000 passionate and motivated employees
- An installed base of 75 GW
- EUR 20b of order backlog
- The world's broadest product portfolio



Aero-elastic Tailored Blades (ATB)

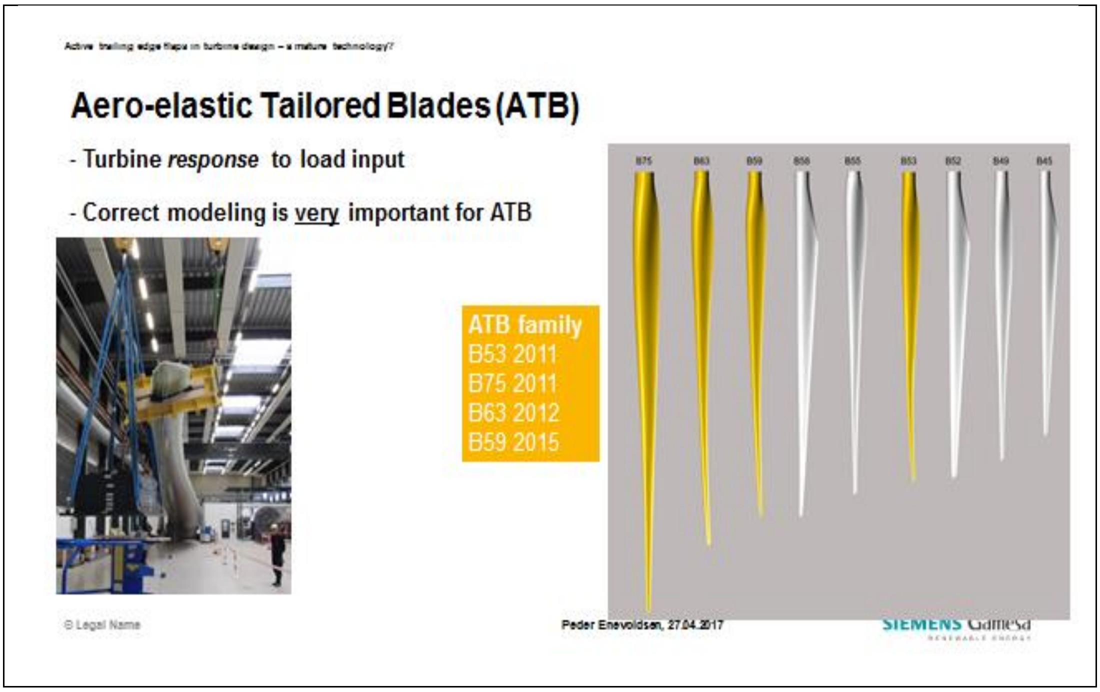
Passively reduction of loads

Rigid Blade

Aeroelastic Blade

= Wind gust direction
= Torsional bending
= Structural loading

IntegralBlade® technology



Active trailing edge flaps in turbine design – a mature technology?

Aero-elastic Tailored Blades (ATB)

- Turbine *response* to load input
- Correct modeling is <u>very</u> important for ATB

ATB family
B53 2011
B75 2011
B63 2012
B59 2015

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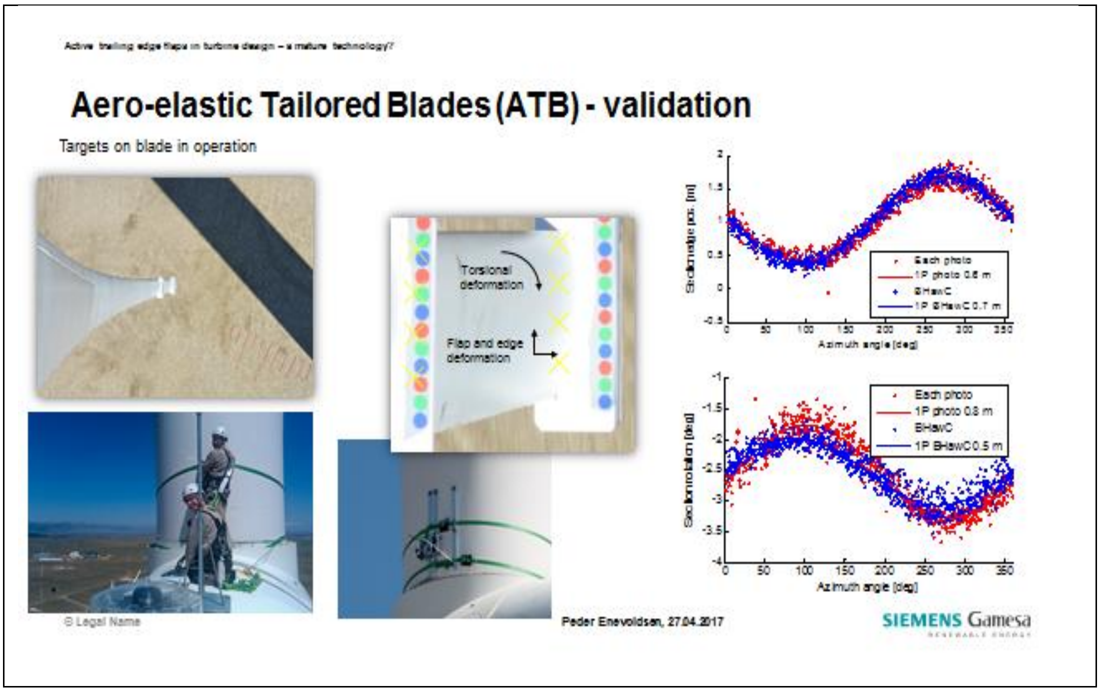

Active trailing edge flaps in turbine design – a mature technology?

Aero-elastic Tailored Blades (ATB) - validation

Targets on blade in operation

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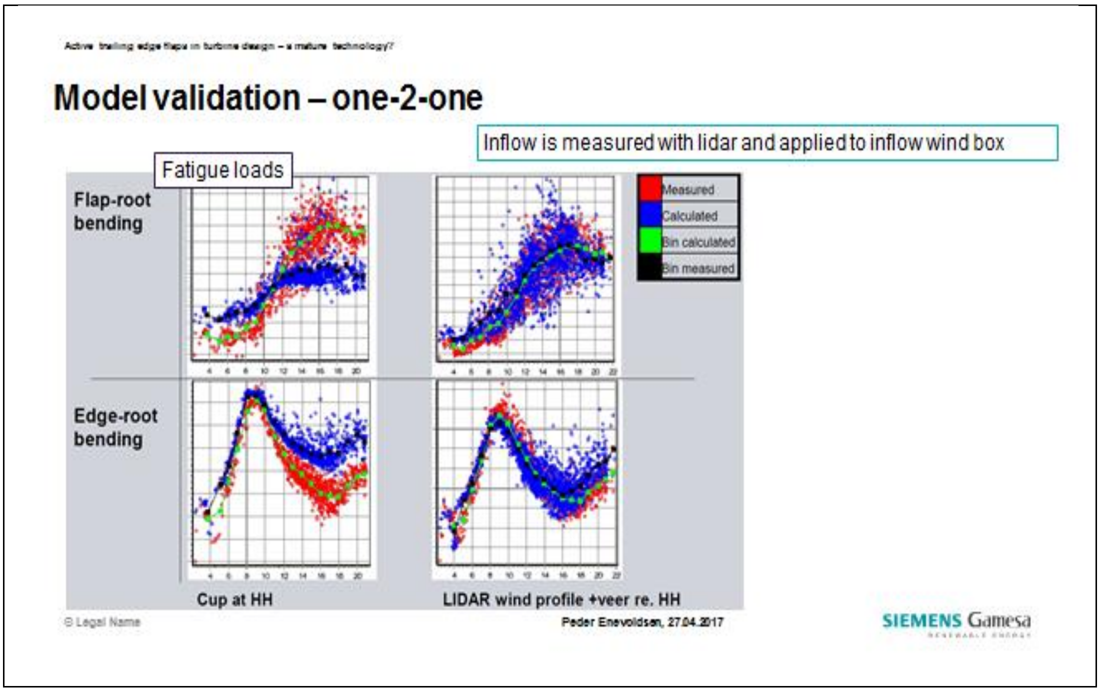

Active trailing edge flaps in turbine design – a mature technology?

Model validation – one-2-one

Inflow is measured with lidar and applied to inflow wind box

Fatigue loads

🟥	Measured
🟦	Calculated
🟩	Bin calculated
⬛	Bin measured

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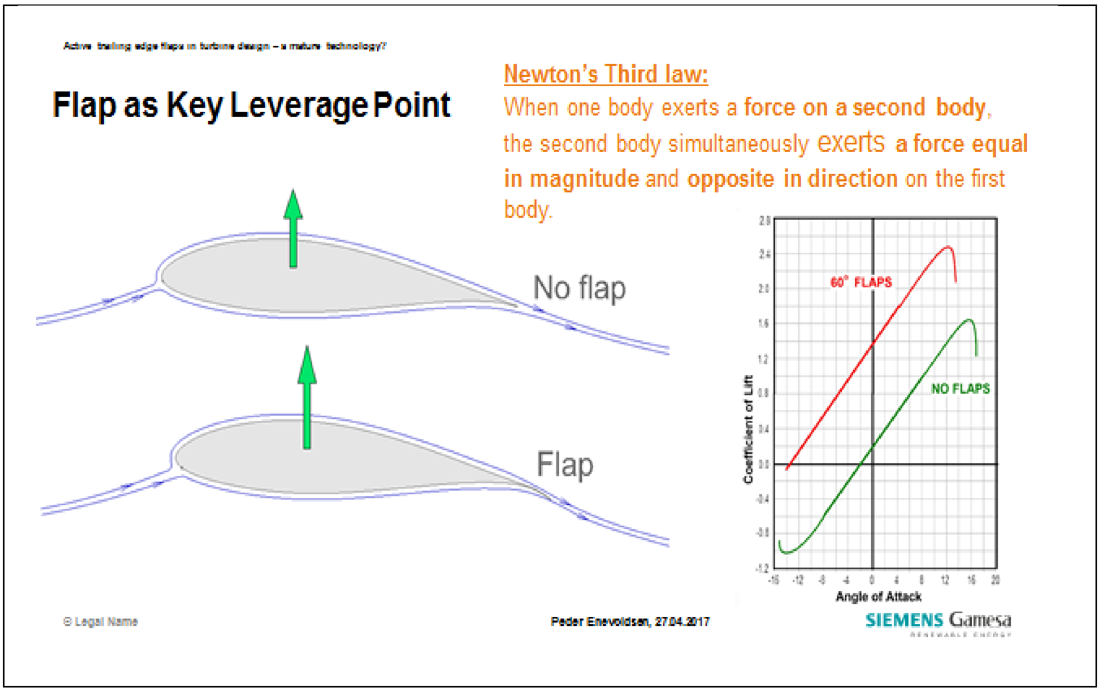

Active trailing edge flaps in turbine design – a mature technology?

Flap as Key Leverage Point

Newton's Third law:

When one body exerts a **force on a second body**, the second body simultaneously exerts **a force equal in magnitude** and **opposite in direction** on the first body.

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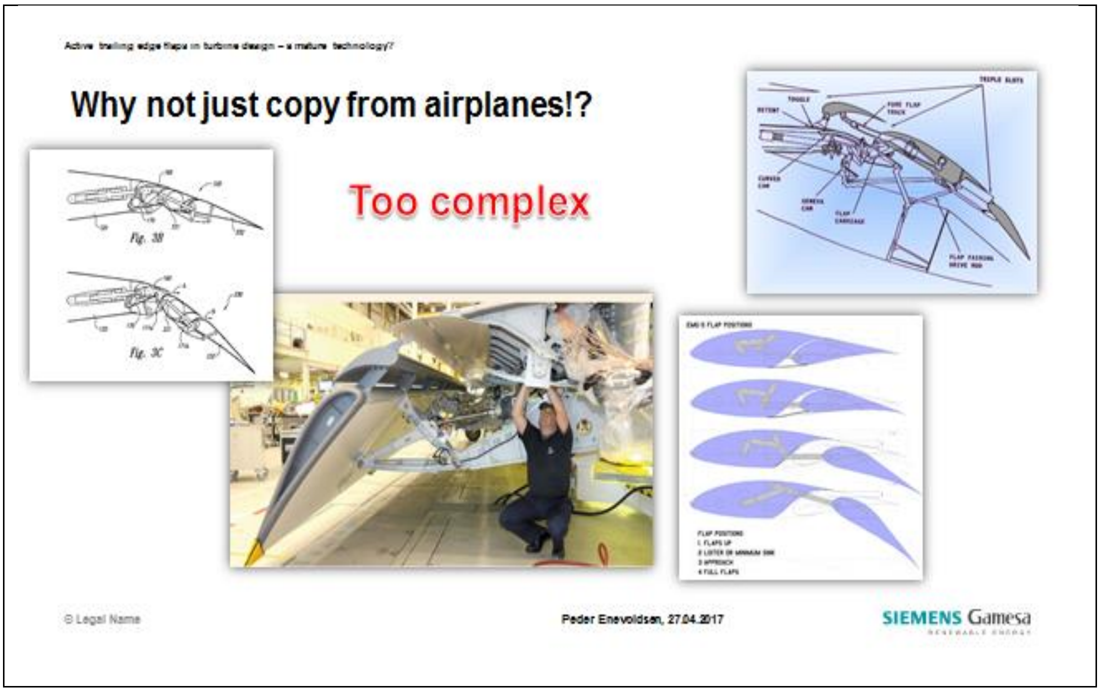

Active trailing edge flaps in turbine design – a mature technology?

Why not just copy from airplanes!?

Too complex

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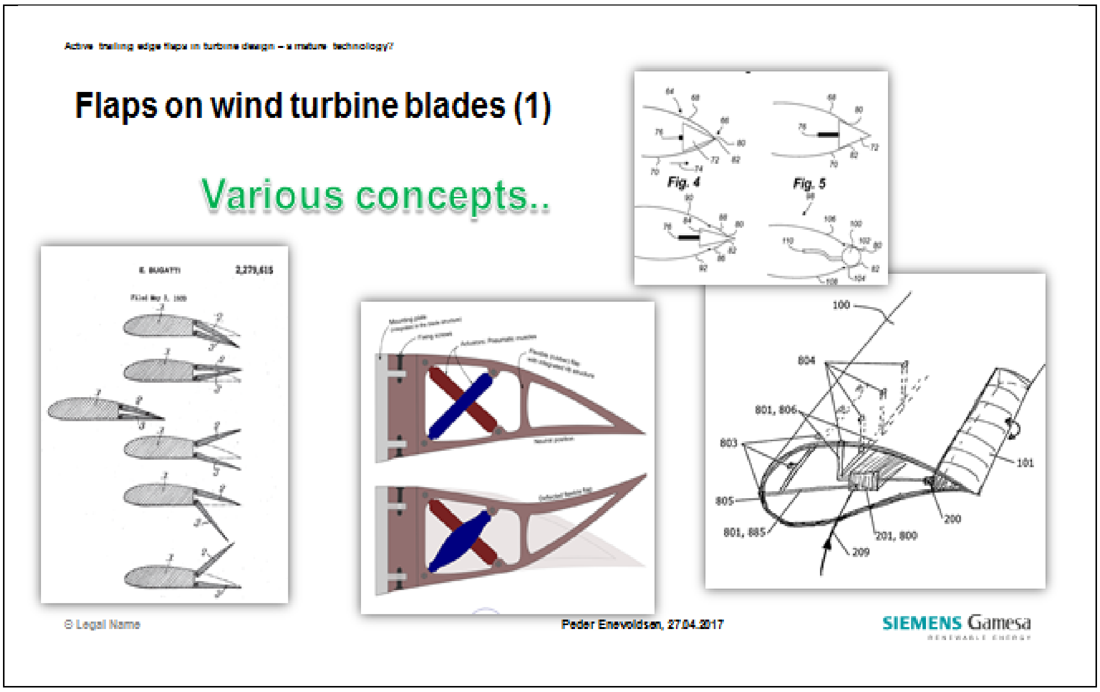

Active trailing edge flaps in turbine design – a mature technology?

Flaps on wind turbine blades (1)

Various concepts..

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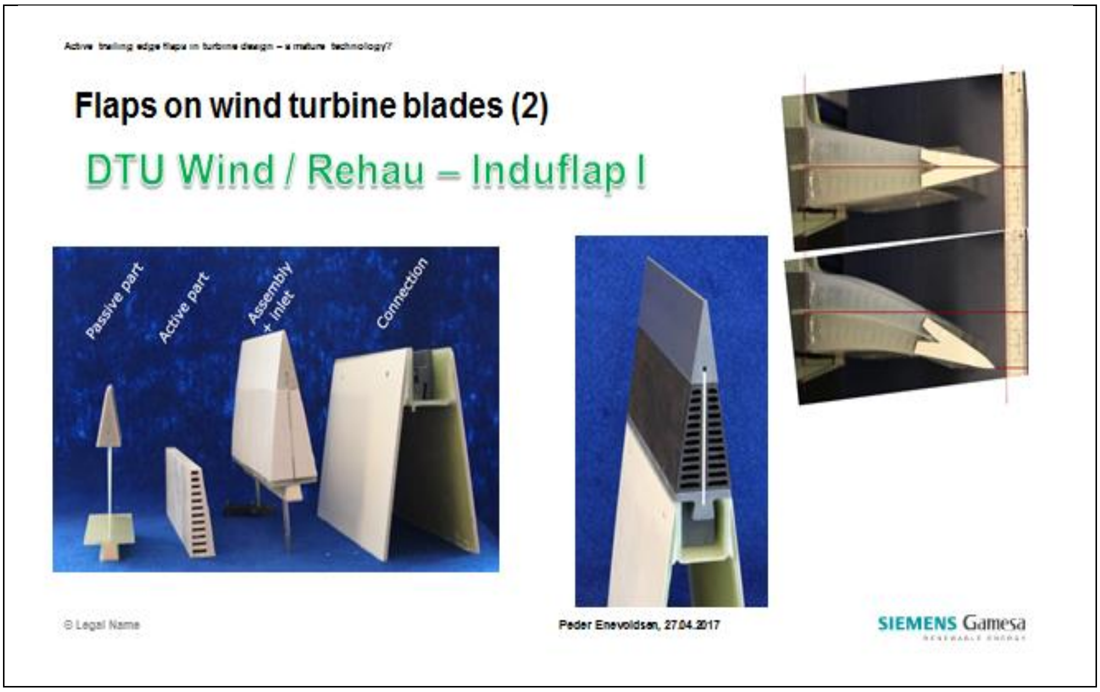

Active trailing edge flaps in turbine design – a mature technology?

Flaps on wind turbine blades (2)

DTU Wind / Rehau – Induflap !

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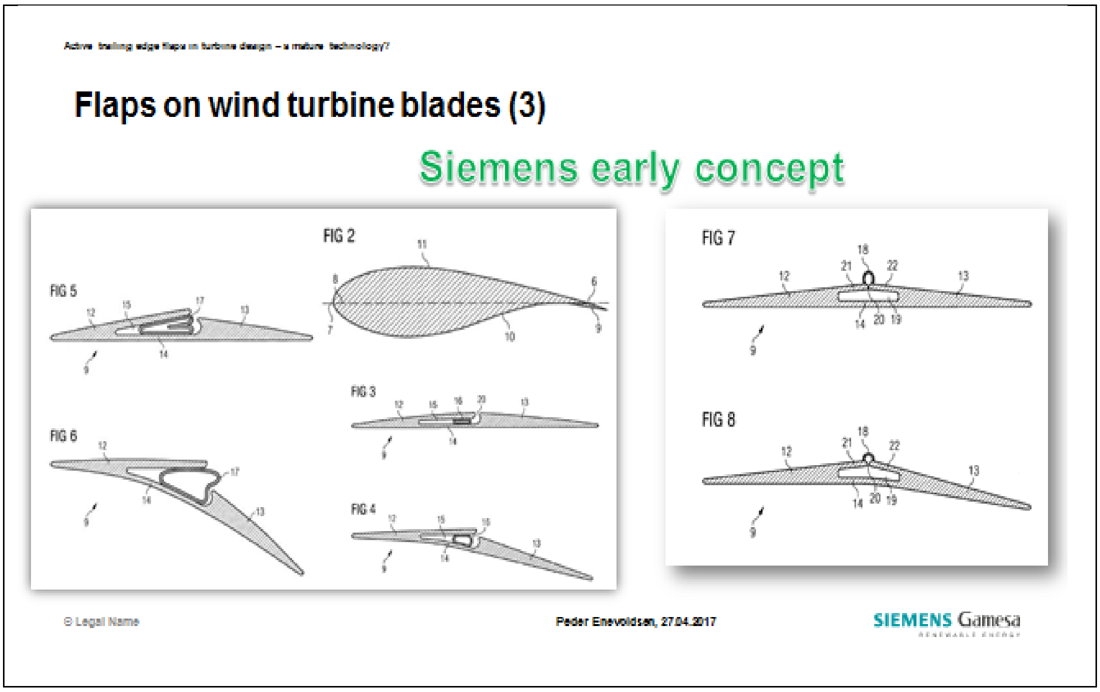

Active trailing edge flaps in turbine design – a mature technology?

Flaps on wind turbine blades (3)

Siemens early concept

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Active trailing edge flaps in turbine design – a mature technology?

“Welcome - to the real world”

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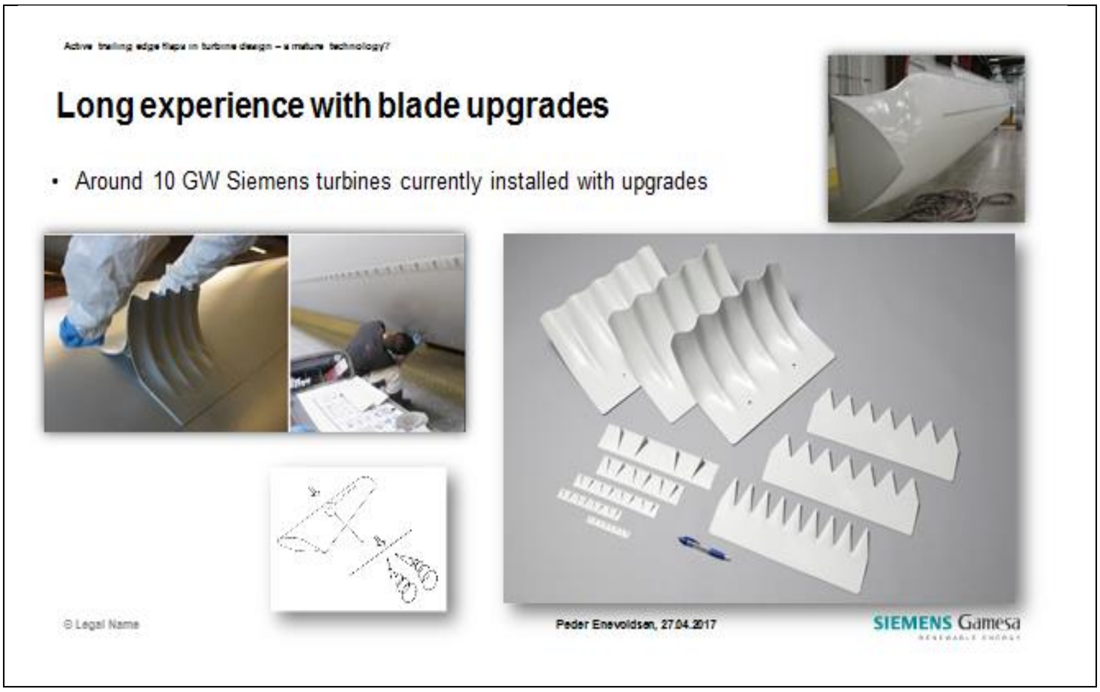

Active trailing edge flaps in turbine design – a mature technology?

Long experience with blade upgrades

- Around 10 GW Siemens turbines currently installed with upgrades

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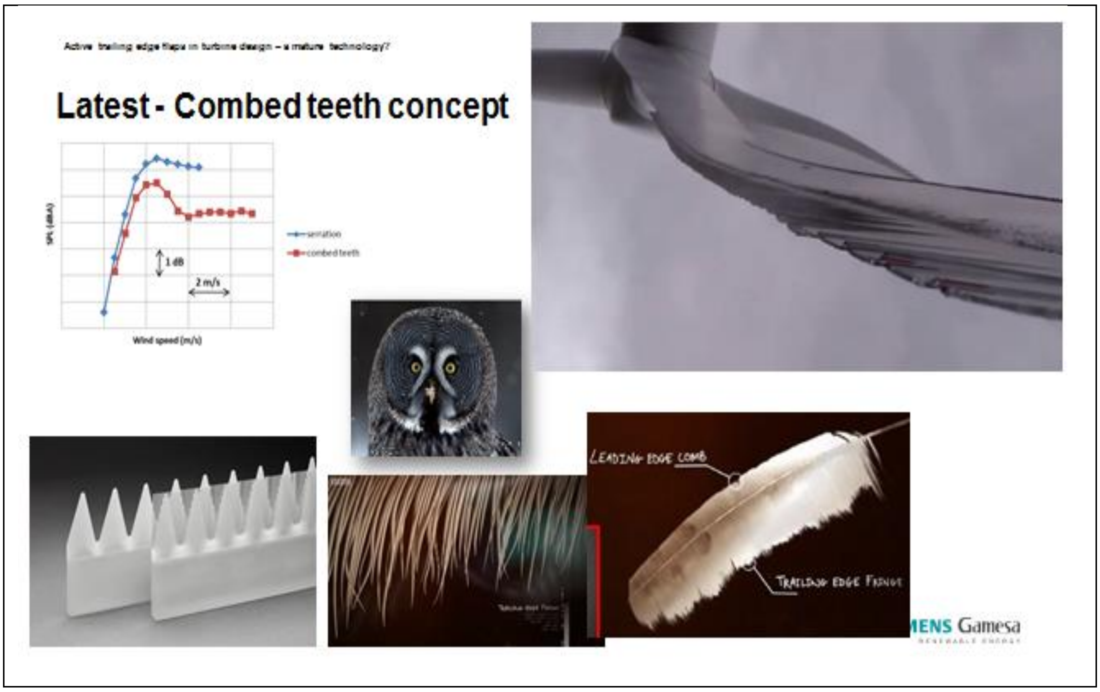
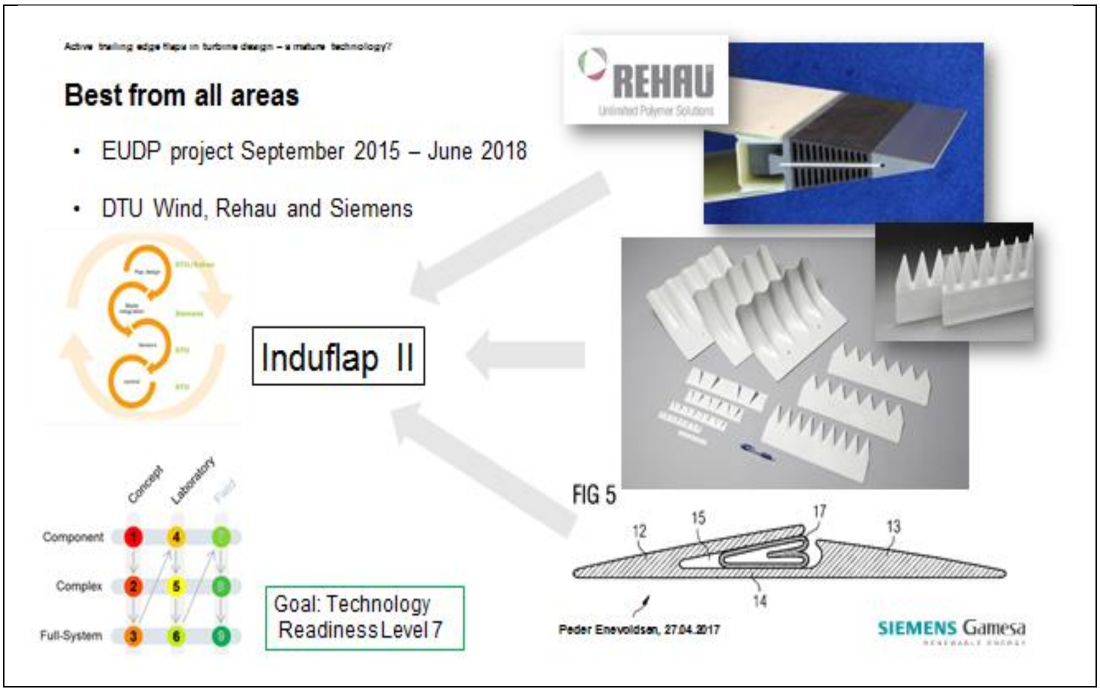


Active trailing edge flaps in turbine design – a mature technology?

Latest - Combed teeth concept



Active trailing edge flaps in turbine design – a mature technology?

Best from all areas

- EUDP project September 2015 – June 2018
- DTU Wind, Rehau and Siemens

Induflap II

Goal: Technology Readiness Level 7

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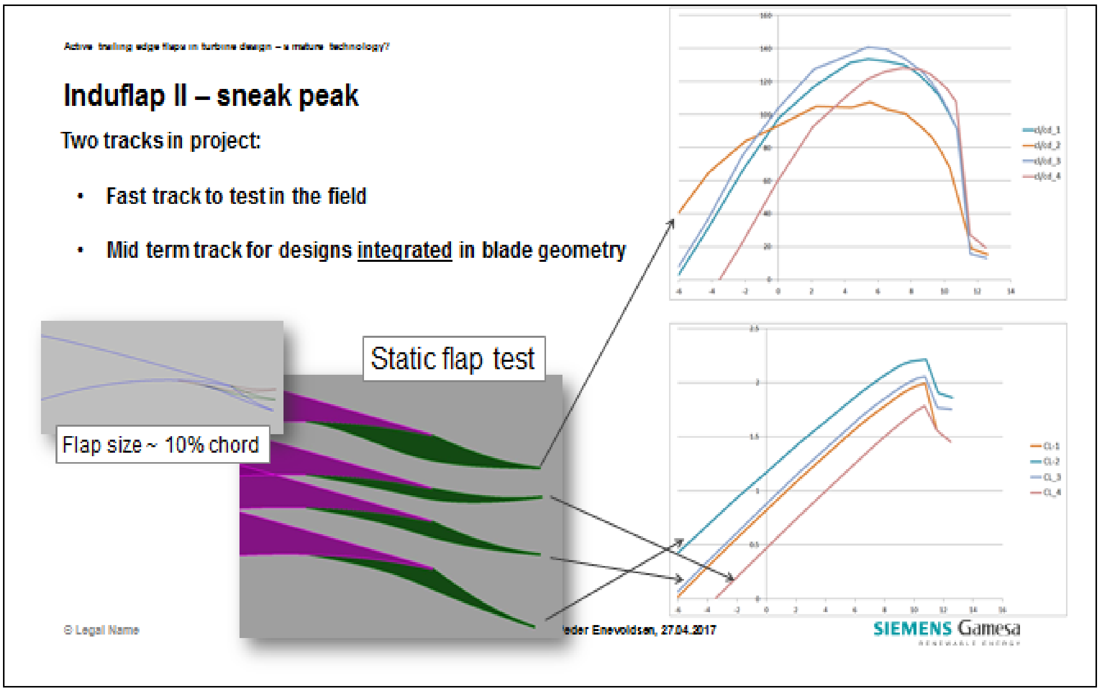

Active trailing edge flaps in turbine design – a mature technology?

Induflap II – sneak peak

Two tracks in project:

- Fast track to test in the field
- Mid term track for designs integrated in blade geometry

Flap size ~ 10% chord

Static flap test

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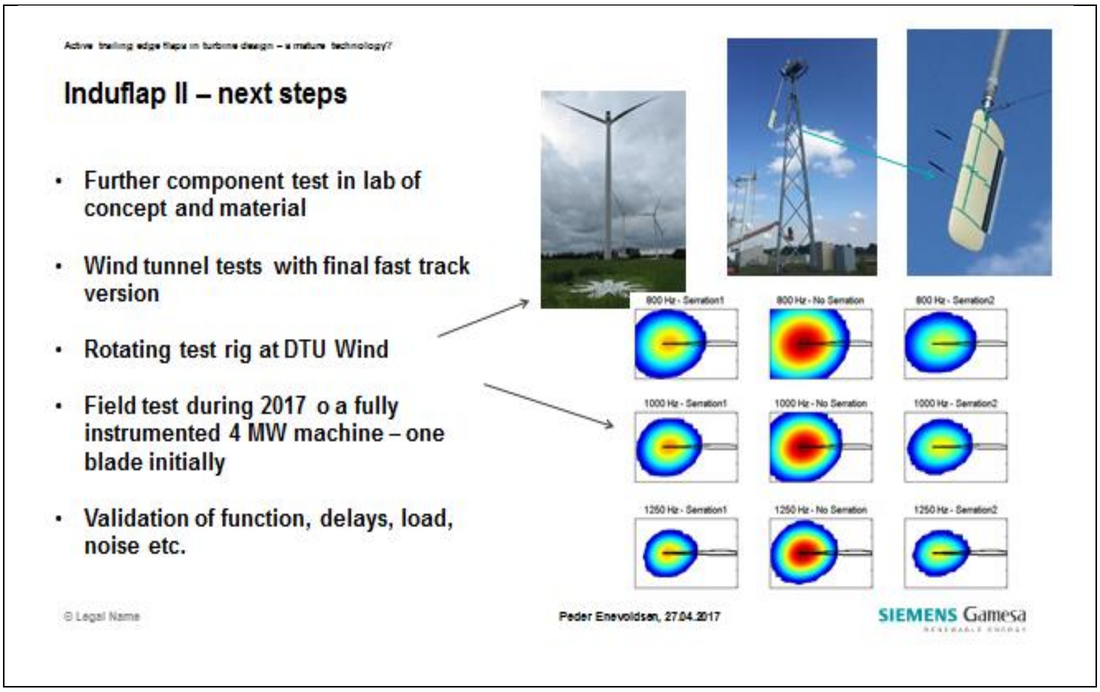

Active trailing edge flaps in turbine design – a mature technology?

Induflap II – next steps

- Further component test in lab of concept and material
- Wind tunnel tests with final fast track version
- Rotating test rig at DTU Wind
- Field test during 2017 o a fully instrumented 4 MW machine – one blade initially
- Validation of function, delays, load, noise etc.

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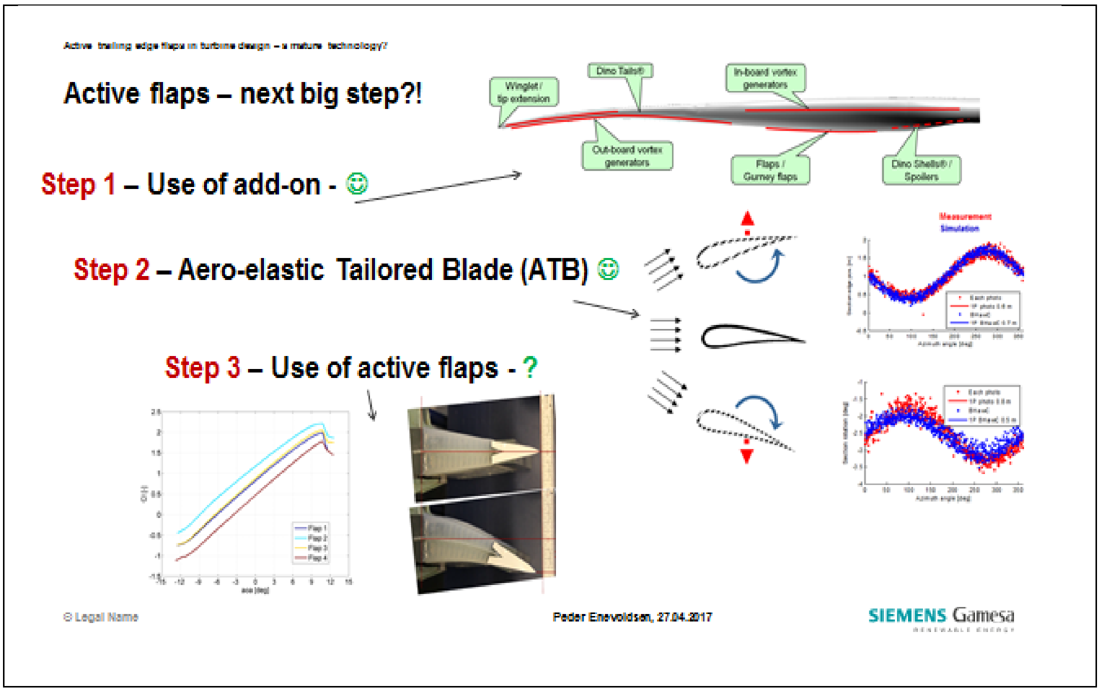

Active flaps – next big step?!

Step 1 – Use of add-on - ☺

Step 2 – Aero-elastic Tailored Blade (ATB) ☺

Step 3 – Use of active flaps - ?

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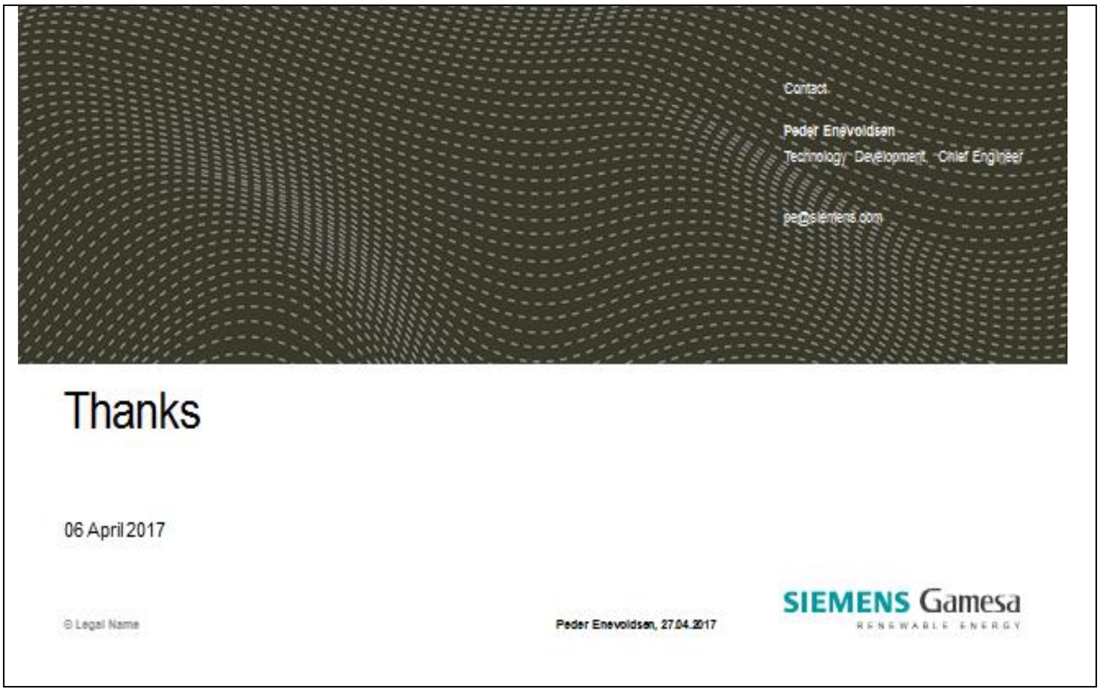
So - is active flaps on wind turbines a mature technology?

No – not yet!

Can it become a mature technology?

Perhaps – if kept simple, robust and safe!

We should know in a few years time ☺



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Thanks

06 April 2017

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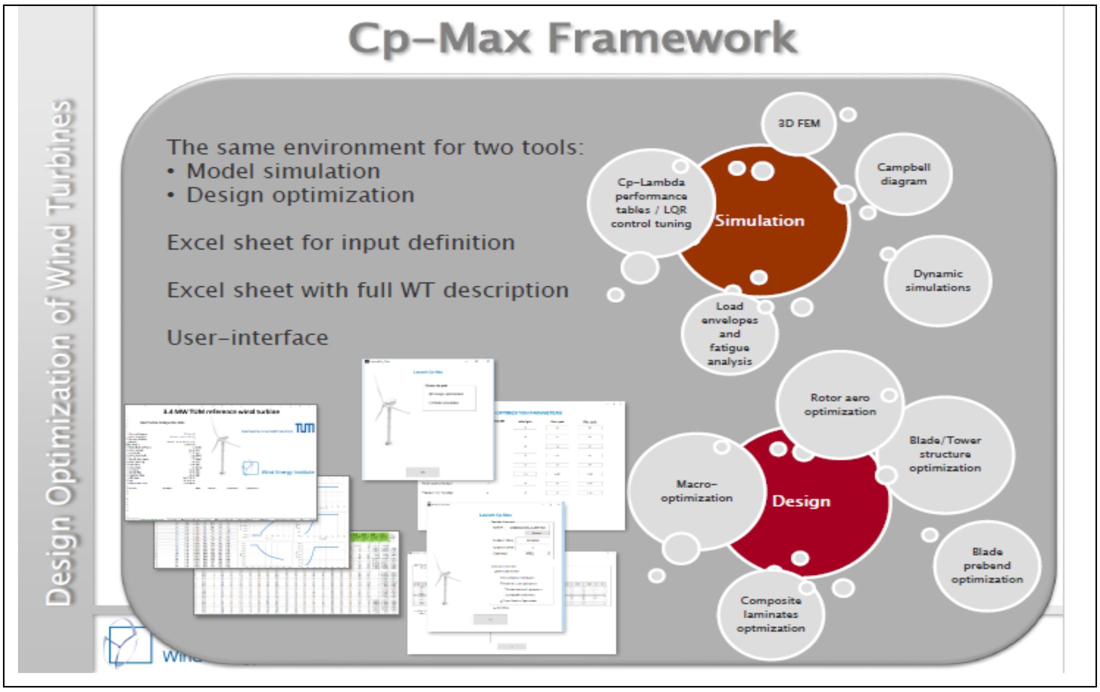
Technische Universität München
Wind Energy Institute

Integrated Design Optimization of Wind Turbines: Challenges, Methods, Applications

Carlo L. Bottasso, Pietro Bortolotti
Technische Universität München

TEM on Smart Blades
DTU Risø, 28 April 2017



Cp-Max Framework

The same environment for two tools:
- Model simulation
- Design optimization

Excel sheet for input definition

Excel sheet with full WT description

User-interface

Simulation

3D FEM

Campbell diagram

Cp-Lambda performance tables / LQR control tuning

Dynamic simulations

Load envelopes and fatigue analysis

Design

Rotor aero optimization

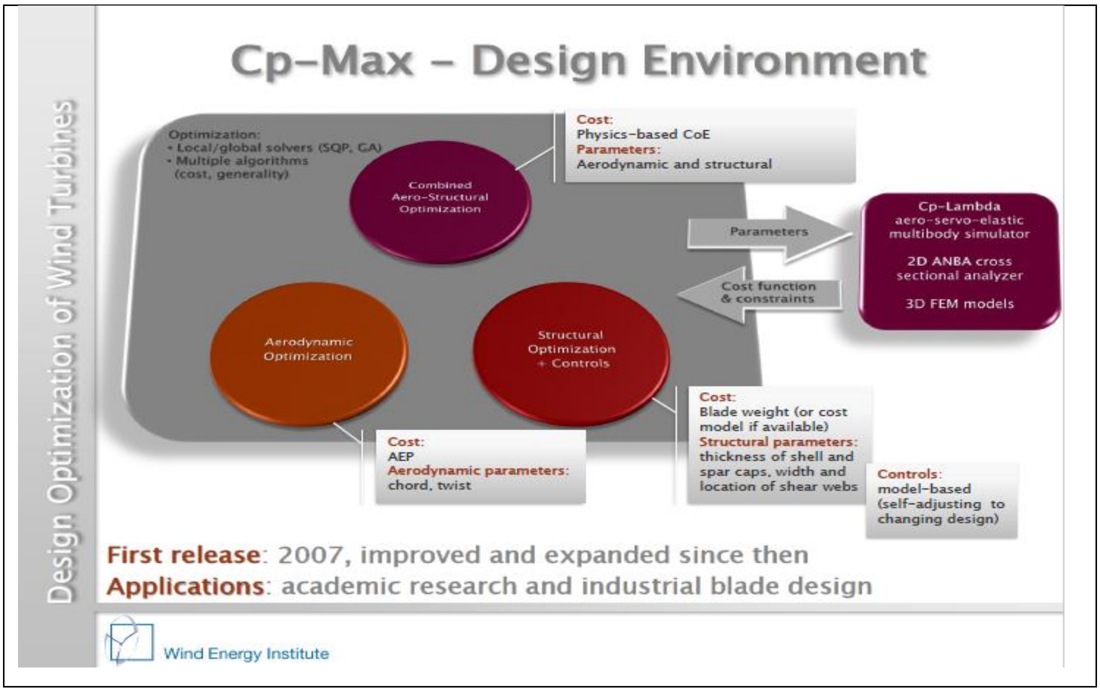
Blade/Tower structure optimization

Macro-optimization

Blade prebend optimization

Composite laminates optmization

3.4 MW TUM reference wind turbine



Cp-Max – Design Environment

Optimization:
- Local/global solvers (SQP, GA)
- Multiple algorithms (cost, generality)

Combined Aero-Structural Optimization

Cost: Physics-based CoE
Parameters: Aerodynamic and structural

Parameters

Cost function & constraints

Cp-Lambda aero-servo-elastic multibody simulator

2D ANBA cross sectional analyzer

3D FEM models

Aerodynamic Optimization

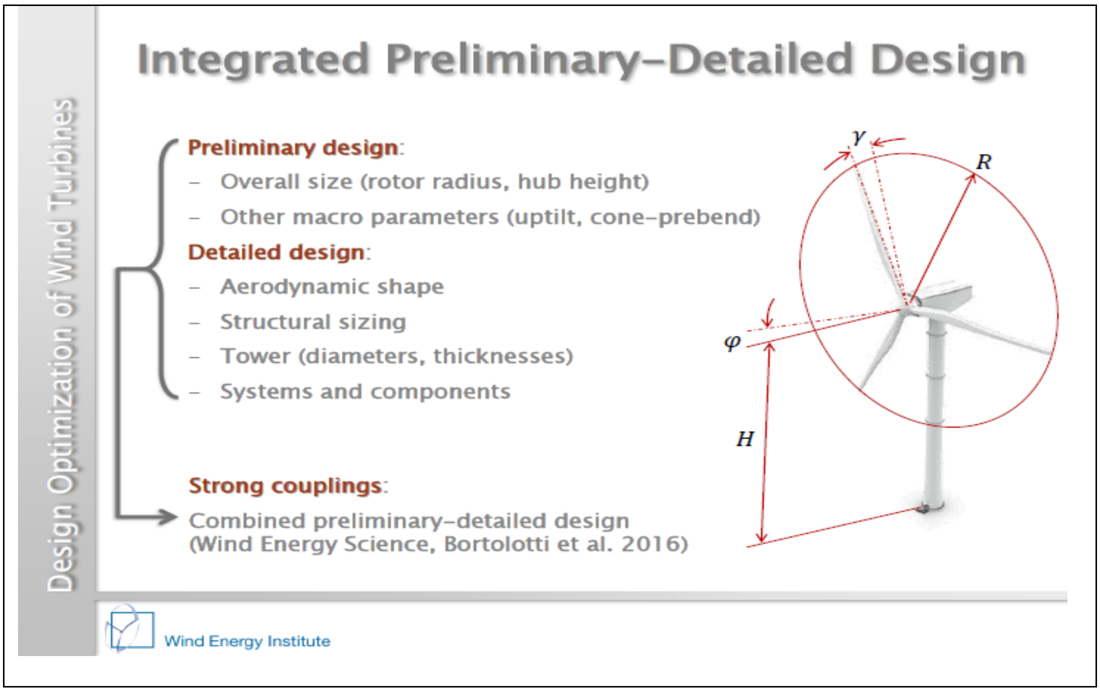
Cost: AEP
Aerodynamic parameters: chord, twist

Structural Optimization + Controls

Cost: Blade weight (or cost model if available)
Structural parameters: thickness of shell and spar caps, width and location of shear webs

Controls: model-based (self-adjusting to changing design)

First release: 2007, improved and expanded since then
Applications: academic research and industrial blade design



Design Optimization of Wind Turbines

Integrated Preliminary–Detailed Design

Preliminary design:
- Overall size (rotor radius, hub height)
- Other macro parameters (uptilt, cone–prebend)

Detailed design:
- Aerodynamic shape
- Structural sizing
- Tower (diameters, thicknesses)
- Systems and components

Strong couplings:
Combined preliminary–detailed design
(Wind Energy Science, Bortolotti et al. 2016)

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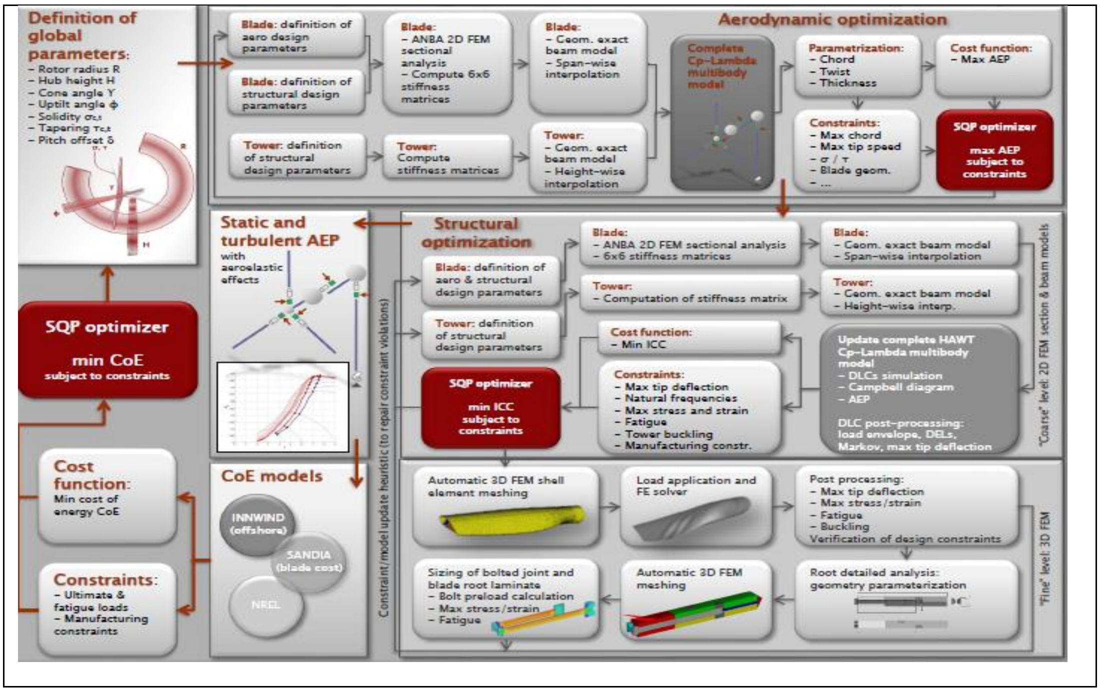


Definition of global parameters:
- Rotor radius R
- Hub height H
- Cone angle Υ
- Uptilt angle ϕ
- Solidity $\sigma_{c,t}$
- Tapering $\tau_{c,t}$
- Pitch offset δ

Blade: definition of aero design parameters

Blade: definition of structural design parameters

Tower: definition of structural design parameters

Blade:
- ANBA 2D FEM sectional analysis
- Compute 6x6 stiffness matrices

Tower:
Compute stiffness matrices

Blade:
- Geom. exact beam model
- Span–wise interpolation

Tower:
- Geom. exact beam model
- Height–wise interpolation

Aerodynamic optimization

Complete Cp–Lambda multibody model

Parametrization:
- Chord
- Twist
- Thickness

Cost function:
- Max AEP

Constraints:
- Max chord
- Max tip speed
- σ / τ
- Blade geom.
- ...

SQP optimizer

max AEP
subject to constraints

Static and turbulent AEP
with aeroelastic effects

SQP optimizer

min CoE
subject to constraints

Cost function:
Min cost of energy CoE

Constraints:
- Ultimate & fatigue loads
- Manufacturing constraints

CoE models

INNWIND (offshore)
SANDIA (blade cost)
NREL

Constraint/model update heuristic (to repair constraint violations)

Structural optimization

Blade: definition of aero & structural design parameters

Tower: definition of structural design parameters

SQP optimizer

min ICC
subject to constraints

Blade:
- ANBA 2D FEM sectional analysis
- 6x6 stiffness matrices

Tower:
- Computation of stiffness matrix

Blade:
- Geom. exact beam model
- Span–wise interpolation

Tower:
- Geom. exact beam model
- Height–wise interp.

Cost function:
- Min ICC

Constraints:
- Max tip deflection
- Natural frequencies
- Max stress and strain
- Fatigue
- Tower buckling
- Manufacturing constr.

Update complete HAWT Cp–Lambda multibody model
- DLCs simulation
- Campbell diagram
- AEP

DLC post–processing:
load envelope, DELs, Markov, max tip deflection

"Coarse" level: 2D FEM section & beam models

Automatic 3D FEM shell element meshing

Load application and FE solver

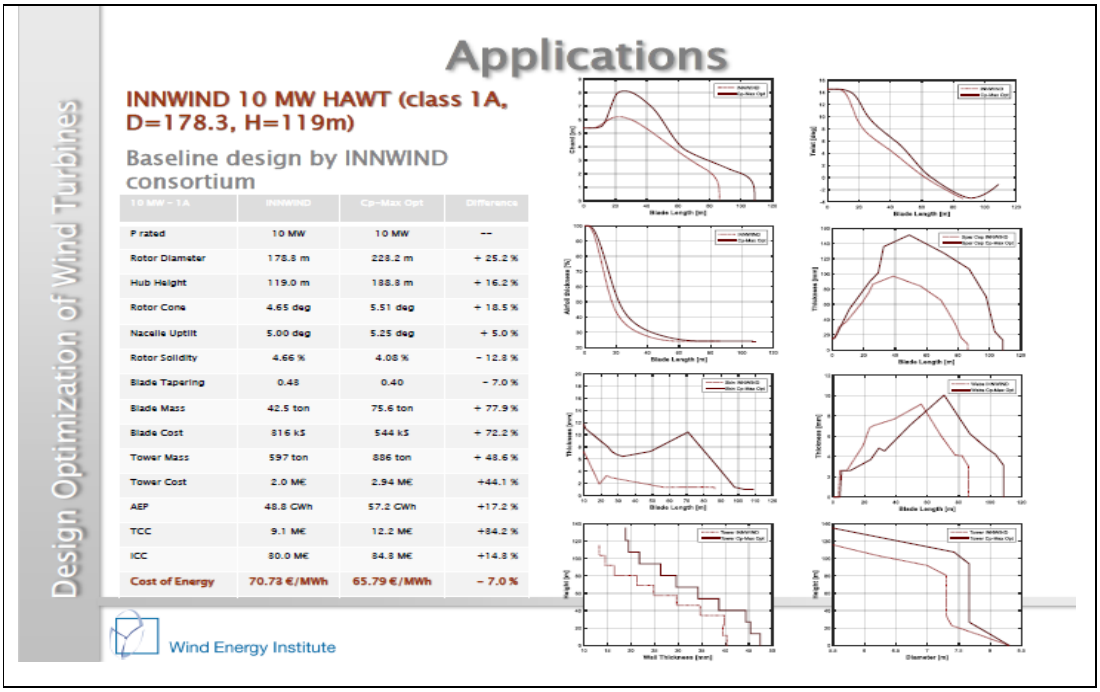
Post processing:
- Max tip deflection
- Max stress/strain
- Fatigue
- Buckling
Verification of design constraints

Root detailed analysis:
geometry parameterization

Automatic 3D FEM meshing

Sizing of bolted joint and blade root laminate
- Bolt preload calculation
- Max stress/strain
- Fatigue

"Fine" level: 3D FEM



Design Optimization of Wind Turbines

Applications

INNWIND 10 MW HAWT (class 1A, D=178.3, H=119m)

Baseline design by INNWIND consortium

10 MW – 1A	INNWIND	Cp-Max Opt	Difference
P rated	10 MW	10 MW	--
Rotor Diameter	178.8 m	228.2 m	+ 25.2 %
Hub Height	119.0 m	188.8 m	+ 16.2 %
Rotor Cone	4.65 deg	5.51 deg	+ 18.5 %
Nacelle Uptilt	5.00 deg	5.25 deg	+ 5.0 %
Rotor Solidity	4.66 %	4.08 %	- 12.8 %
Blade Tapering	0.43	0.40	- 7.0 %
Blade Mass	42.5 ton	75.6 ton	+ 77.9 %
Blade Cost	316 k$	544 k$	+ 72.2 %
Tower Mass	597 ton	886 ton	+ 48.6 %
Tower Cost	2.0 M€	2.94 M€	+44.1 %
AEP	48.8 GWh	57.2 GWh	+17.2 %
TCC	9.1 M€	12.2 M€	+34.2 %
ICC	30.0 M€	34.8 M€	+14.8 %
Cost of Energy	**70.73 €/MWh**	**65.79 €/MWh**	**- 7.0 %**

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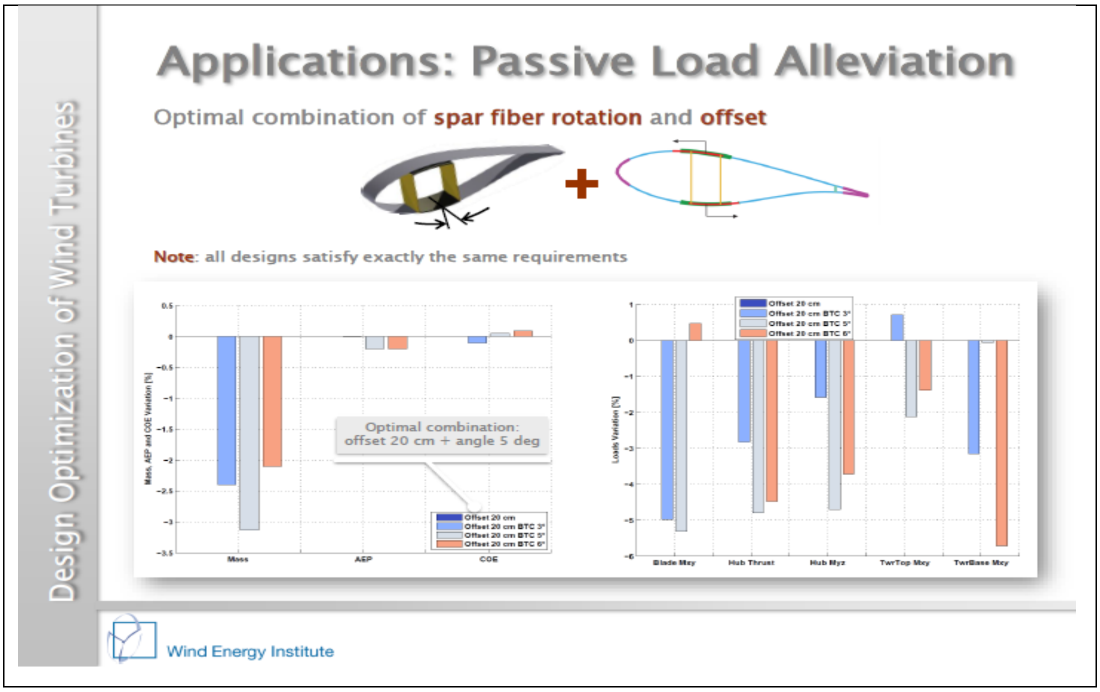

Design Optimization of Wind Turbines

Applications: Passive Load Alleviation

Optimal combination of **spar fiber rotation** and **offset**

Note: all designs satisfy exactly the same requirements

Optimal combination:
offset 20 cm + angle 5 deg

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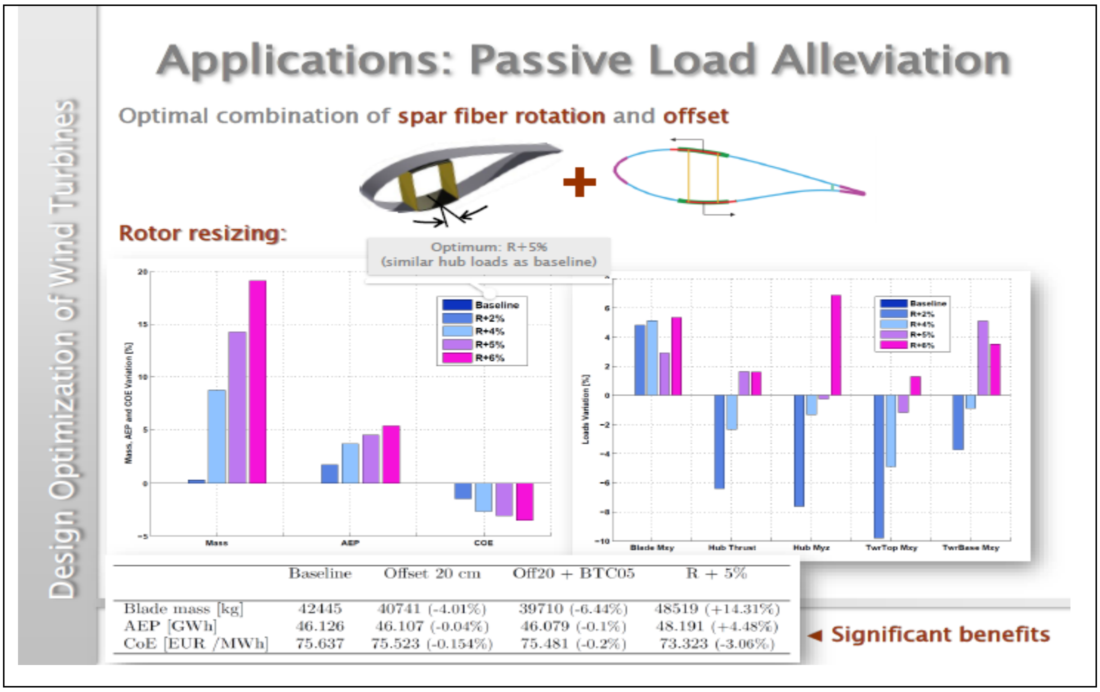


Design Optimization of Wind Turbines

Applications: Passive Load Alleviation

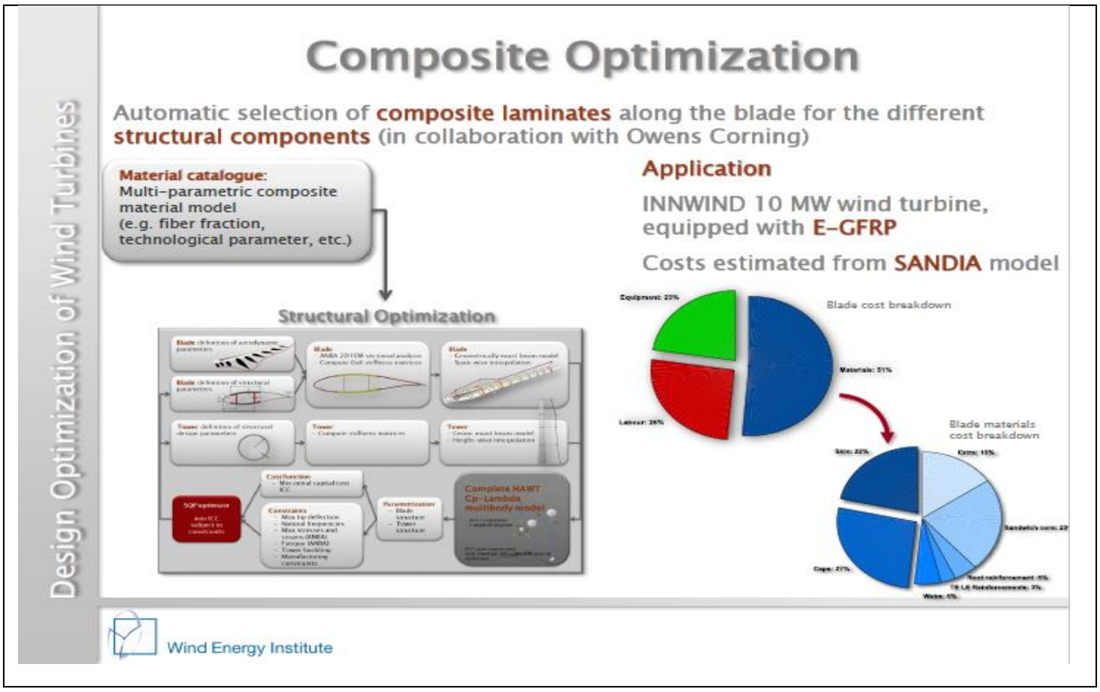
Optimal combination of **spar fiber rotation** and **offset**

Rotor resizing:

Optimum: R+5%
(similar hub loads as baseline)

	Baseline	Offset 20 cm	Off20 + BTC05	R + 5%
Blade mass [kg]	42445	40741 (-4.01%)	39710 (-6.44%)	48519 (+14.31%)
AEP [GWh]	46.126	46.107 (-0.04%)	46.079 (-0.1%)	48.191 (+4.48%)
CoE [EUR /MWh]	75.637	75.523 (-0.154%)	75.481 (-0.2%)	73.323 (-3.06%)

◄ **Significant benefits**



Design Optimization of Wind Turbines

Composite Optimization

Automatic selection of **composite laminates** along the blade for the different **structural components** (in collaboration with Owens Corning)

Material catalogue:
Multi-parametric composite material model
(e.g. fiber fraction,
technological parameter, etc.)

Structural Optimization

Application

INNWIND 10 MW wind turbine, equipped with **E-GFRP**

Costs estimated from **SANDIA** model

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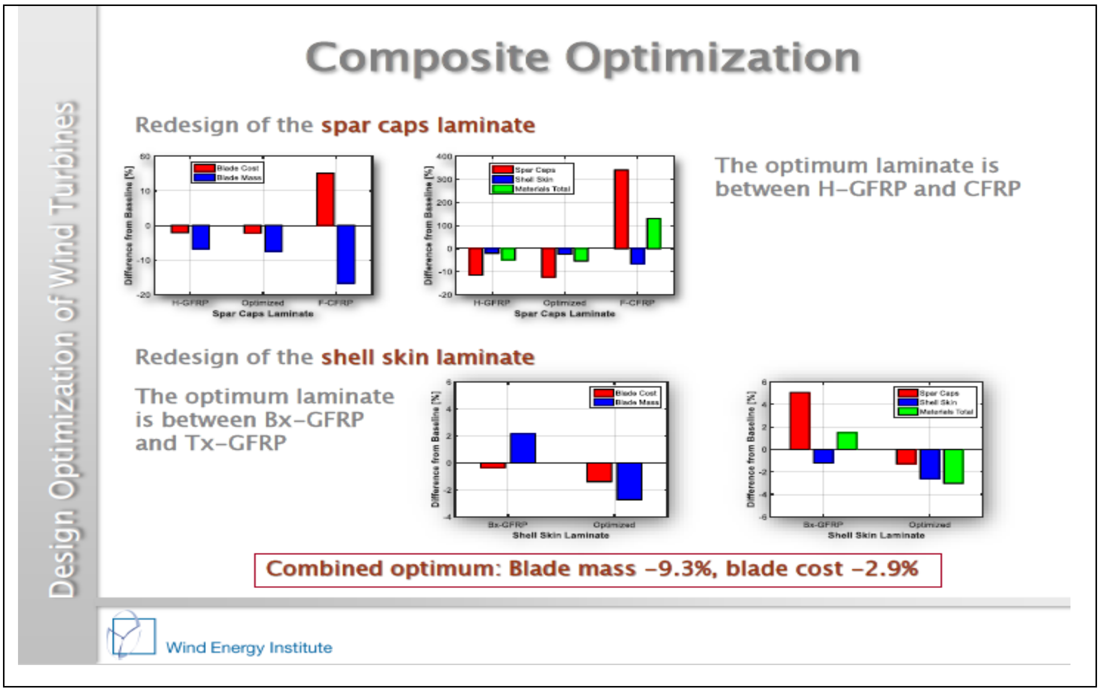

Design Optimization of Wind Turbines

Composite Optimization

Redesign of the **spar caps laminate**

The optimum laminate is between H–GFRP and CFRP

Redesign of the **shell skin laminate**

The optimum laminate is between Bx–GFRP and Tx–GFRP

Combined optimum: Blade mass –9.3%, blade cost –2.9%

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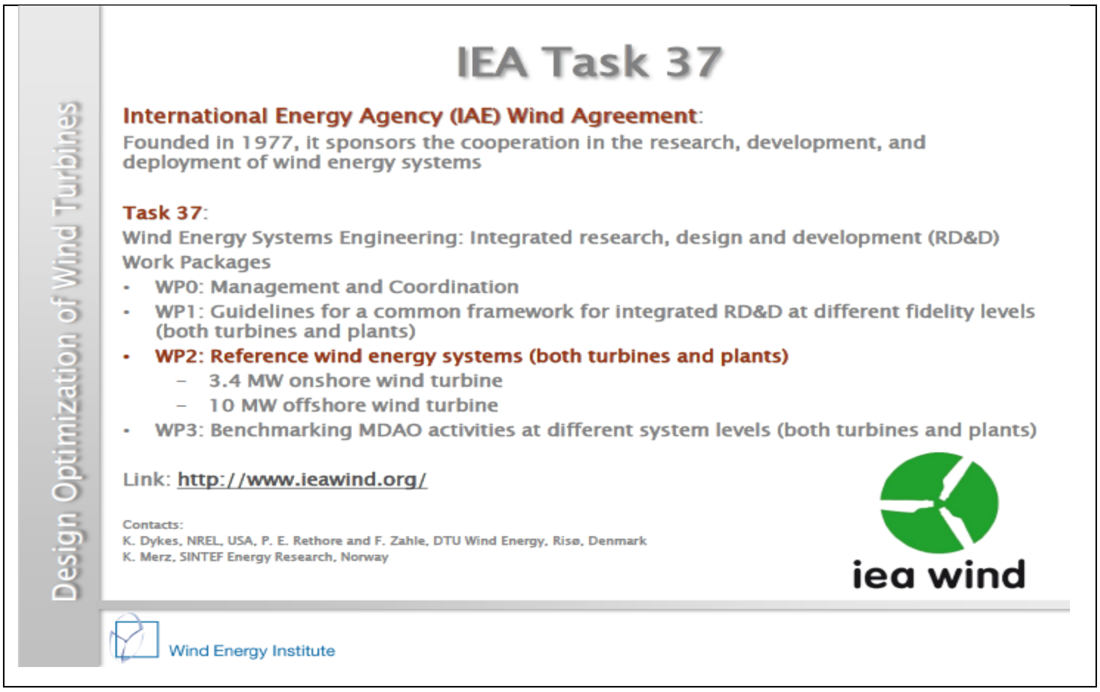

Design Optimization of Wind Turbines

IEA Task 37

International Energy Agency (IAE) Wind Agreement:
Founded in 1977, it sponsors the cooperation in the research, development, and deployment of wind energy systems

Task 37:
Wind Energy Systems Engineering: Integrated research, design and development (RD&D)
Work Packages

- WP0: Management and Coordination
- WP1: Guidelines for a common framework for integrated RD&D at different fidelity levels (both turbines and plants)
- **WP2: Reference wind energy systems (both turbines and plants)**
  - 3.4 MW onshore wind turbine
  - 10 MW offshore wind turbine
- WP3: Benchmarking MDAO activities at different system levels (both turbines and plants)

Link: http://www.ieawind.org/

Contacts:
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K. Merz, SINTEF Energy Research, Norway

iea wind

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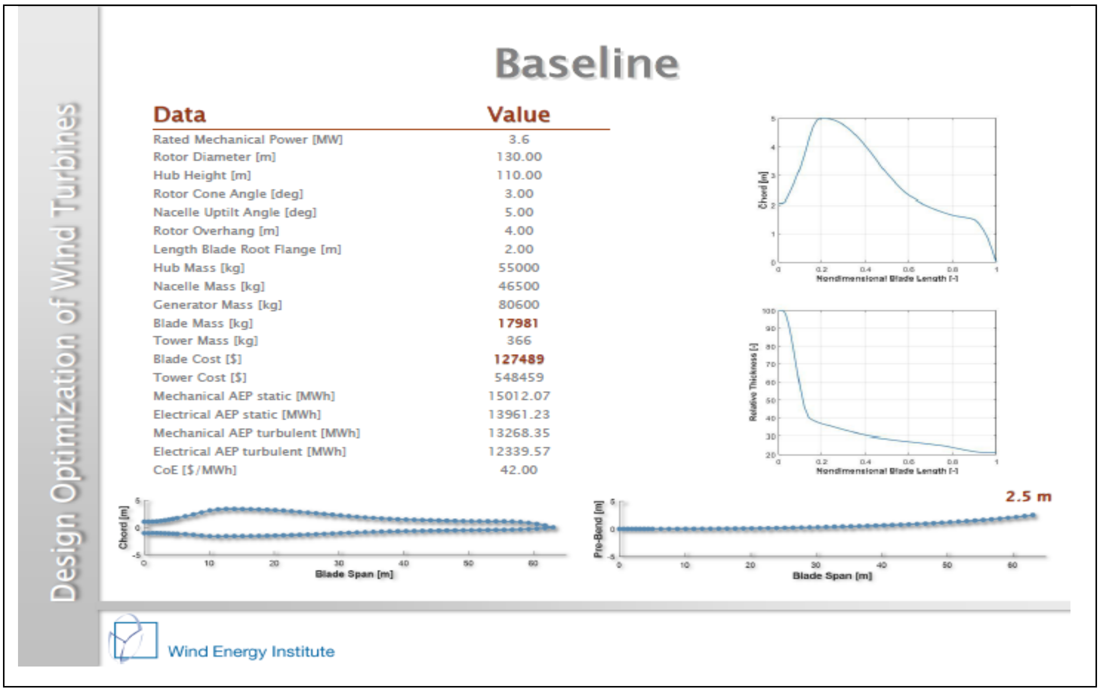

Design Optimization of Wind Turbines

Baseline

Data	Value
Rated Mechanical Power [MW]	3.6
Rotor Diameter [m]	130.00
Hub Height [m]	110.00
Rotor Cone Angle [deg]	3.00
Nacelle Uptilt Angle [deg]	5.00
Rotor Overhang [m]	4.00
Length Blade Root Flange [m]	2.00
Hub Mass [kg]	55000
Nacelle Mass [kg]	46500
Generator Mass [kg]	80600
Blade Mass [kg]	**17981**
Tower Mass [kg]	366
Blade Cost [$]	**127489**
Tower Cost [$]	548459
Mechanical AEP static [MWh]	15012.07
Electrical AEP static [MWh]	13961.23
Mechanical AEP turbulent [MWh]	13268.35
Electrical AEP turbulent [MWh]	12339.57
CoE [$/MWh]	42.00

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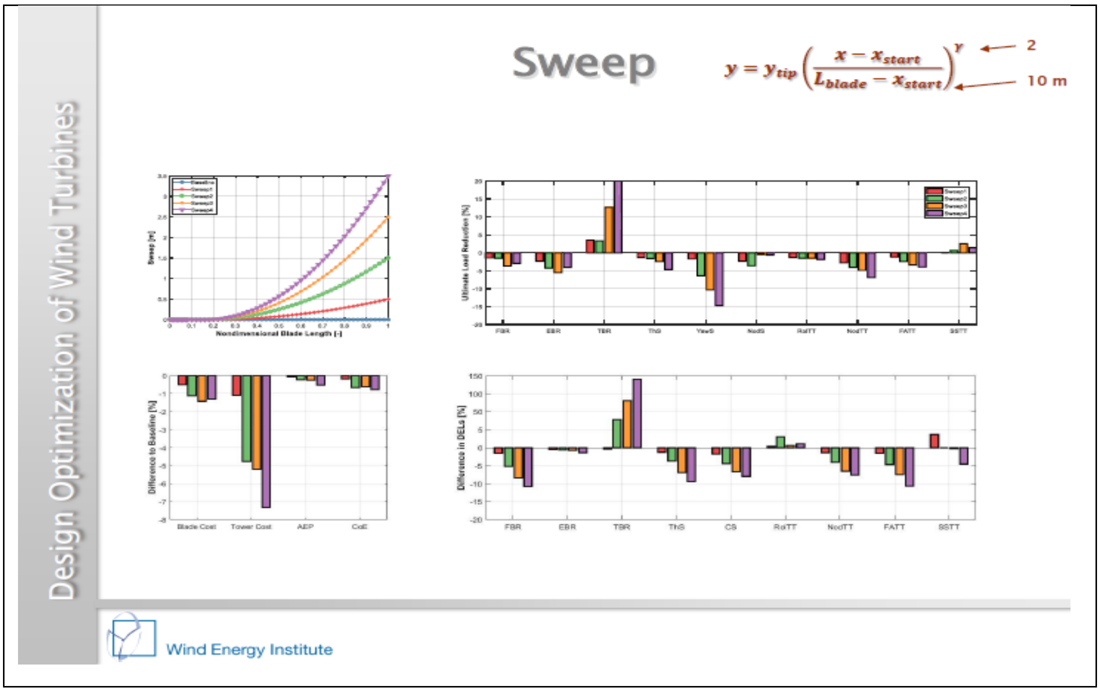

Design Optimization of Wind Turbines

Sweep

$$y = y_{tip}\left(\frac{x - x_{start}}{L_{blade} - x_{start}}\right)^{\gamma}$$

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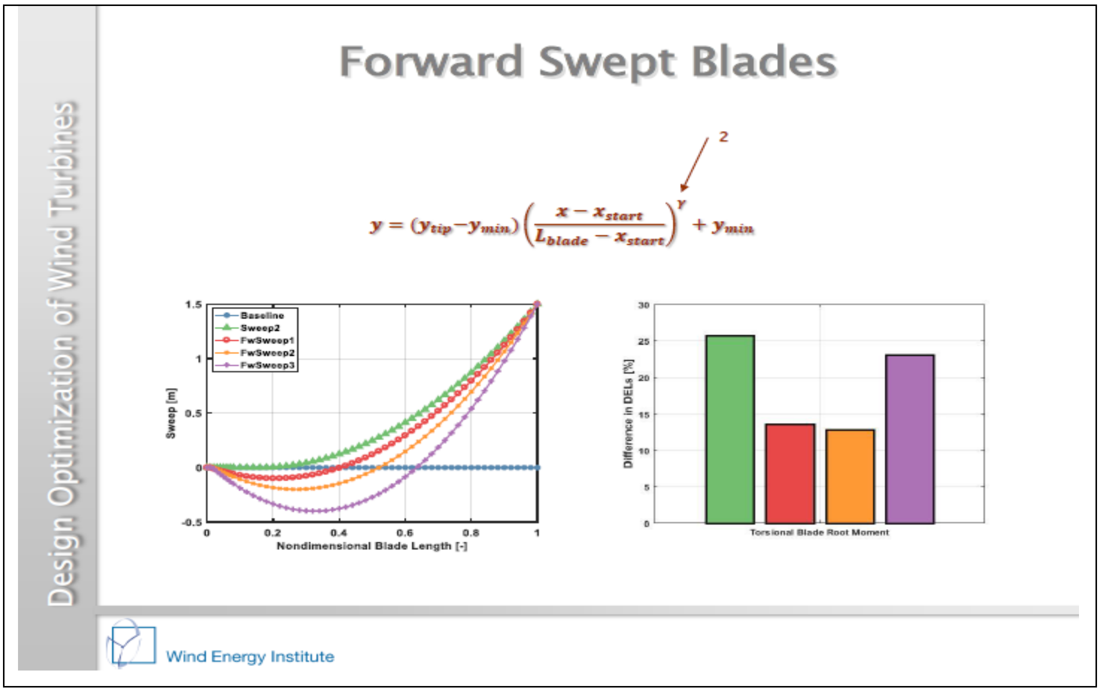
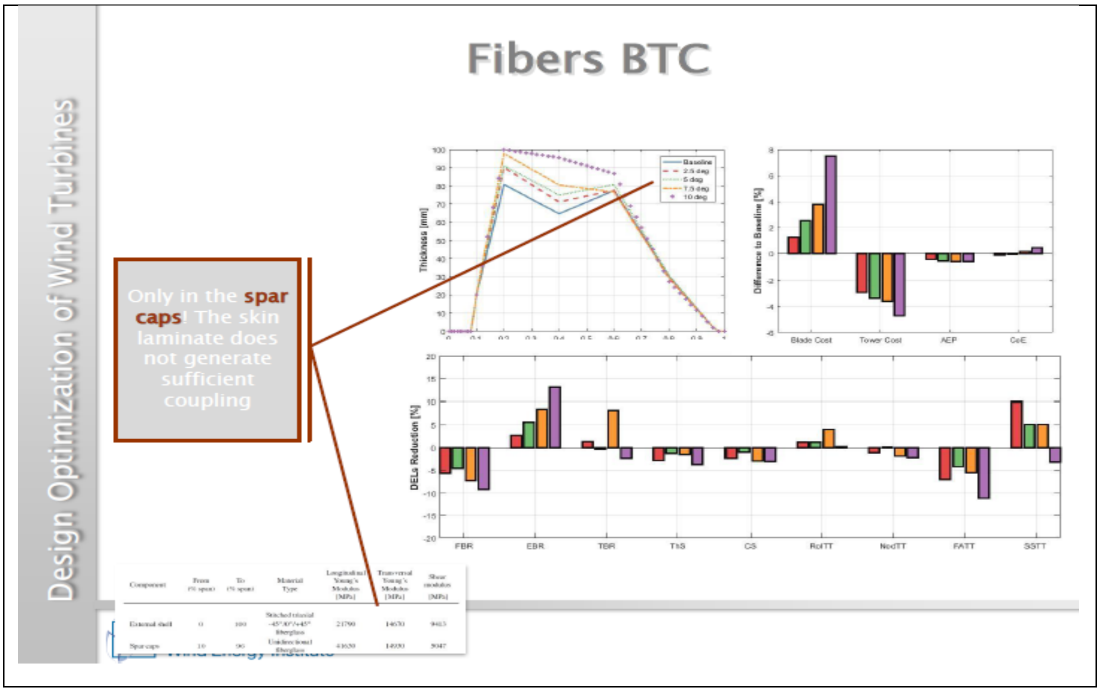


Forward Swept Blades

$$y = (y_{tip} - y_{min})\left(\frac{x - x_{start}}{L_{blade} - x_{start}}\right)^{\gamma} + y_{min}$$

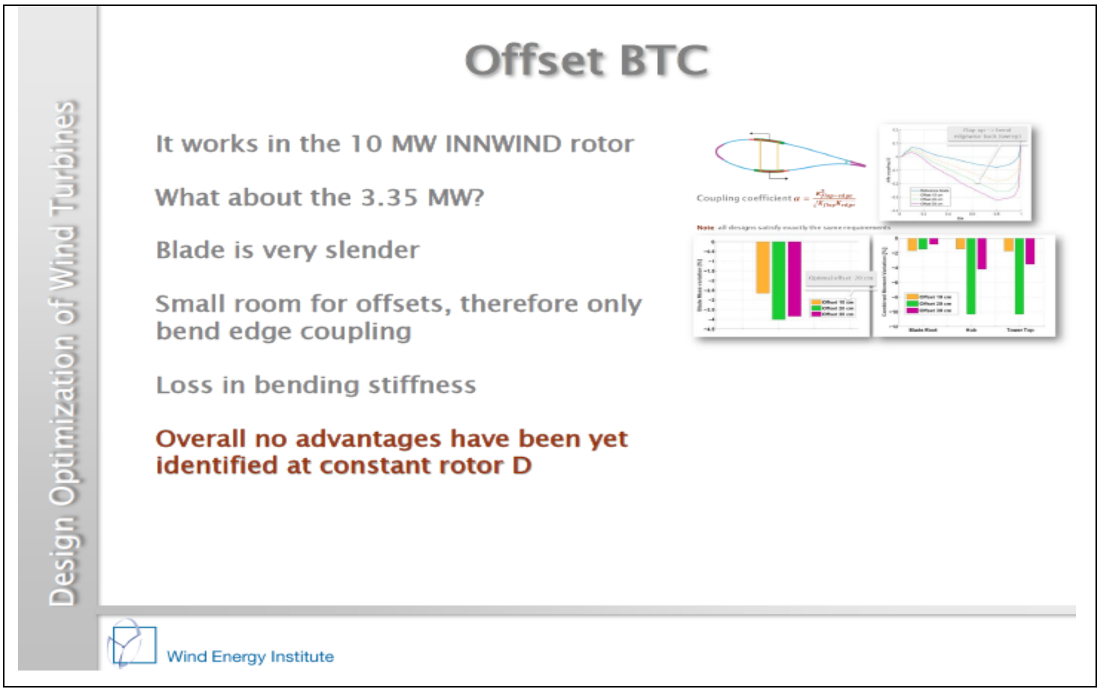
2



Fibers BTC

Only in the **spar caps**! The skin laminate does not generate sufficient coupling

Component	From (% span)	To (% span)	Material Type	Longitudinal Young's Modulus [MPa]	Transversal Young's Modulus [MPa]	Shear modulus [MPa]
External shell	0	100	Stitched triaxial -45°/0°/+45° fiberglass	21790	14670	9413
Spar caps	10	90	Unidirectional fiberglass	41630	14930	5047



Design Optimization of Wind Turbines

Offset BTC

It works in the 10 MW INNWIND rotor

What about the 3.35 MW?

Blade is very slender

Small room for offsets, therefore only bend edge coupling

Loss in bending stiffness

Overall no advantages have been yet identified at constant rotor D

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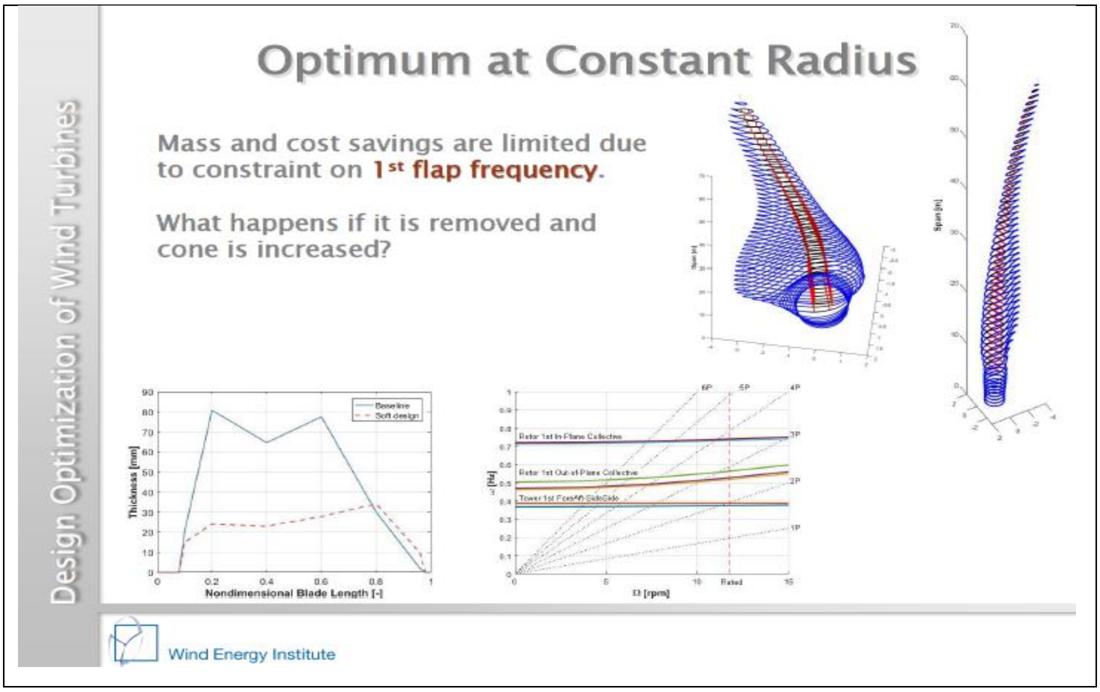

Design Optimization of Wind Turbines

Optimum at Constant Radius

Mass and cost savings are limited due to constraint on **1st flap frequency**.

What happens if it is removed and cone is increased?

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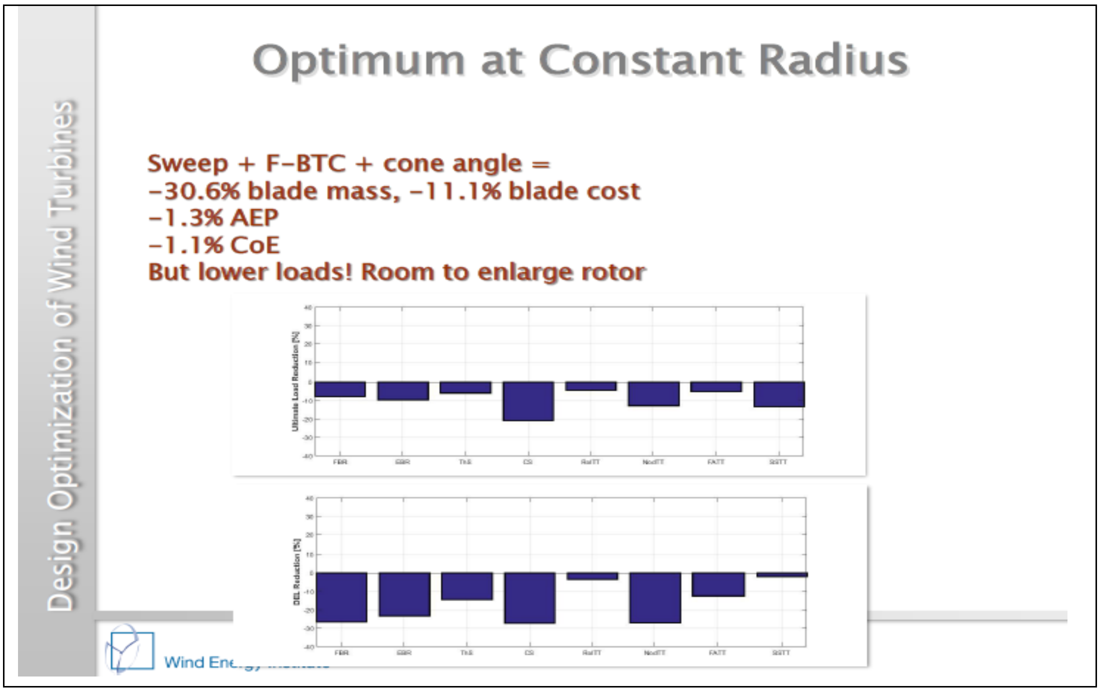
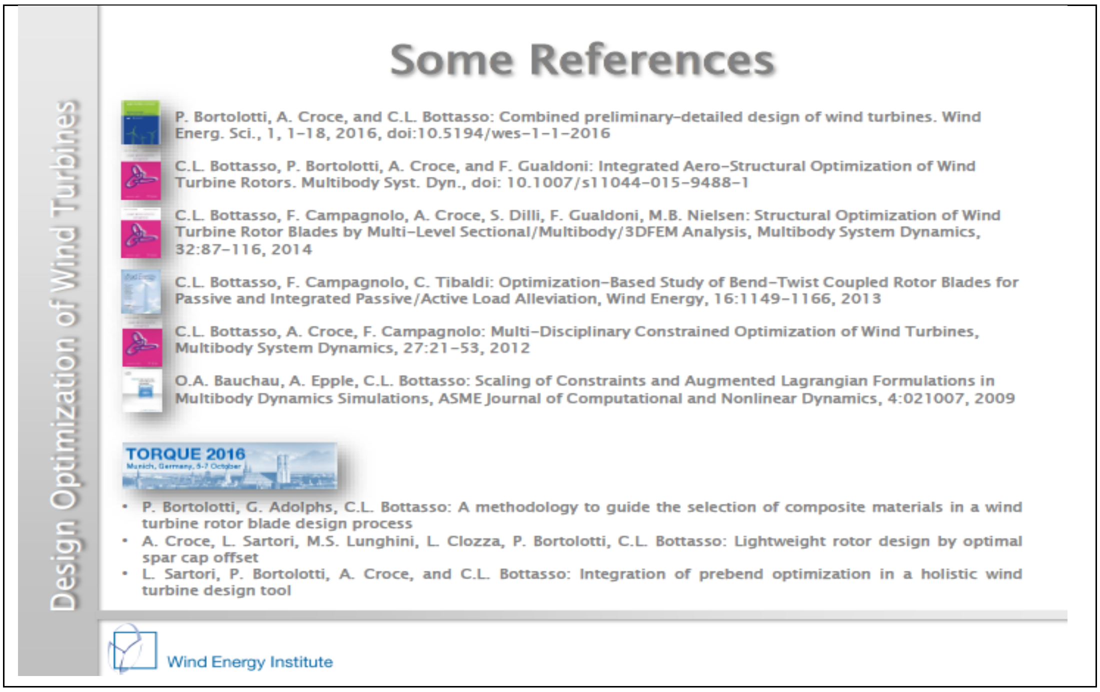


Optimum at Constant Radius

Sweep + F-BTC + cone angle =
−30.6% blade mass, −11.1% blade cost
−1.3% AEP
−1.1% CoE
But lower loads! Room to enlarge rotor



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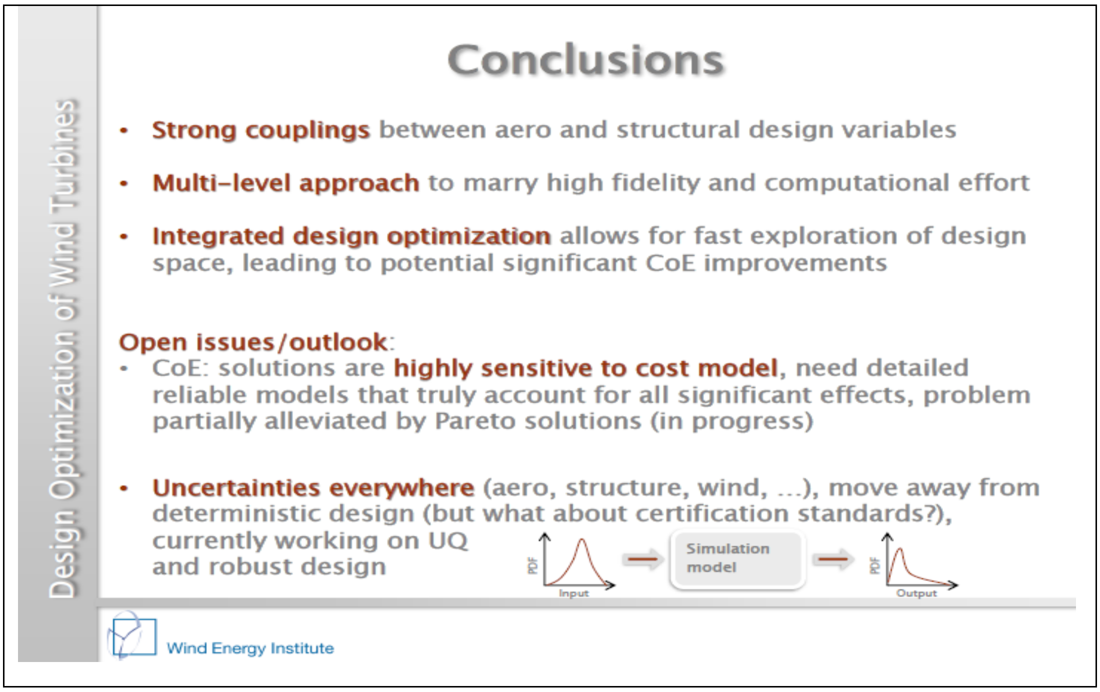
- L. Sartori, P. Bortolotti, A. Croce, and C.L. Bottasso: Integration of prebend optimization in a holistic wind turbine design tool



Design Optimization of Wind Turbines

Conclusions

- **Strong couplings** between aero and structural design variables
- **Multi-level approach** to marry high fidelity and computational effort
- **Integrated design optimization** allows for fast exploration of design space, leading to potential significant CoE improvements

Open issues/outlook:

- CoE: solutions are **highly sensitive to cost model**, need detailed reliable models that truly account for all significant effects, problem partially alleviated by Pareto solutions (in progress)
- **Uncertainties everywhere** (aero, structure, wind, ...), move away from deterministic design (but what about certification standards?), currently working on UQ and robust design

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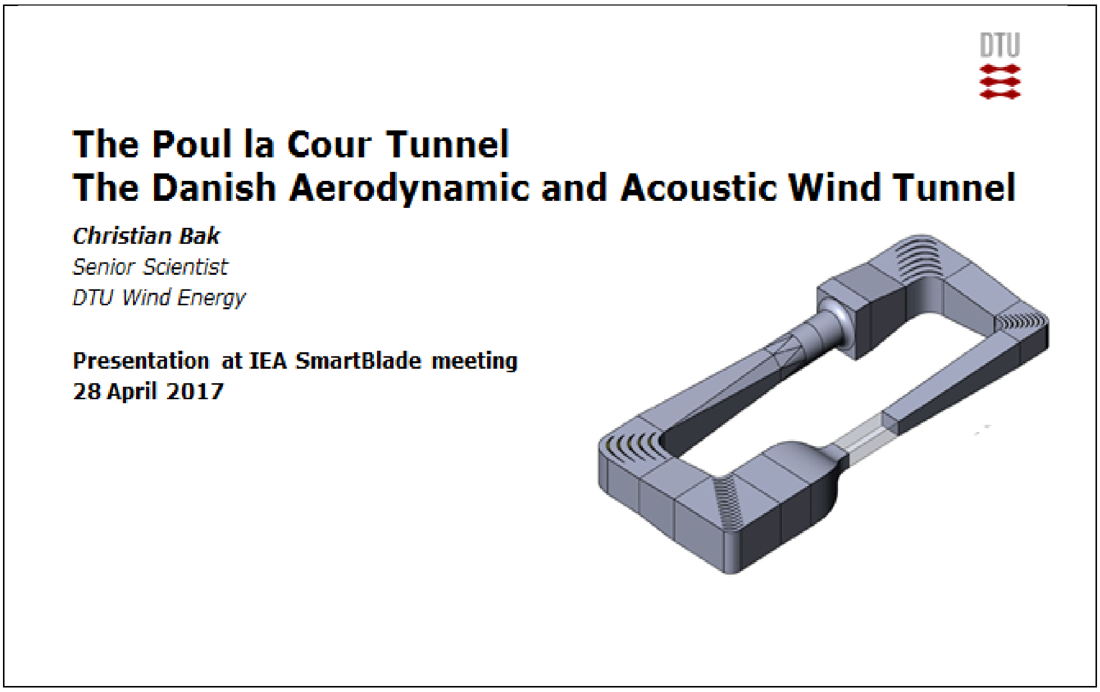


The Poul la Cour Tunnel
The Danish Aerodynamic and Acoustic Wind Tunnel

Christian Bak
Senior Scientist
DTU Wind Energy

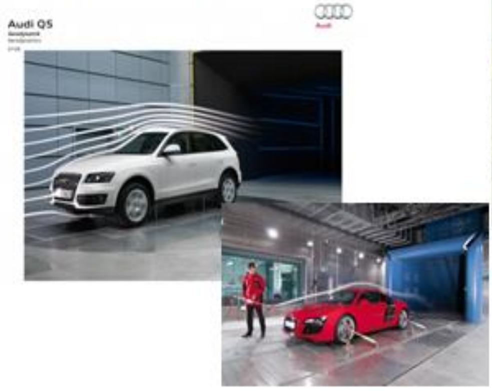
Presentation at IEA SmartBlade meeting
28 April 2017

The history of the Danish National Wind Tunnel

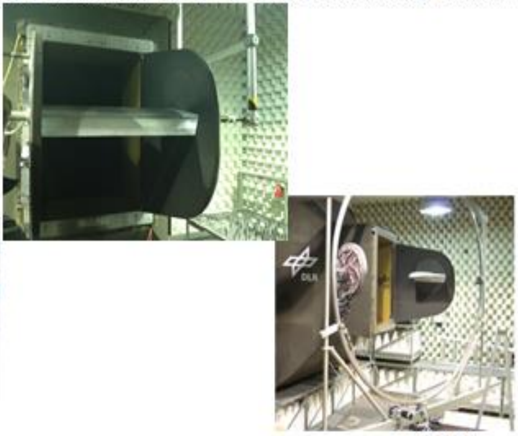
- 2011, April:
  - DTU got green light from the Research and Innovation Agency to get national support to establish a wind tunnel as a national research infrastructure.
- 2011, December:
  - After discussions with the Danish wind turbine manufacturers, universities, GTS institutes and other relevant stakeholders a project description was submitted to the Research and Innovation Agency
  - Vestas, Siemens, LM, Envision, Suzlon, FORCE, Aalborg University
  - Budget: 74 million DKK
- 2012, May:
  - Funding to establish a wind tunnel was granted from the Research and Innovation Agency and Region Sjælland
- 2014, April
  - Basic design concept finalized
- Now
  - Constructing!
- 2017, August
  - Wind tunnel finalized

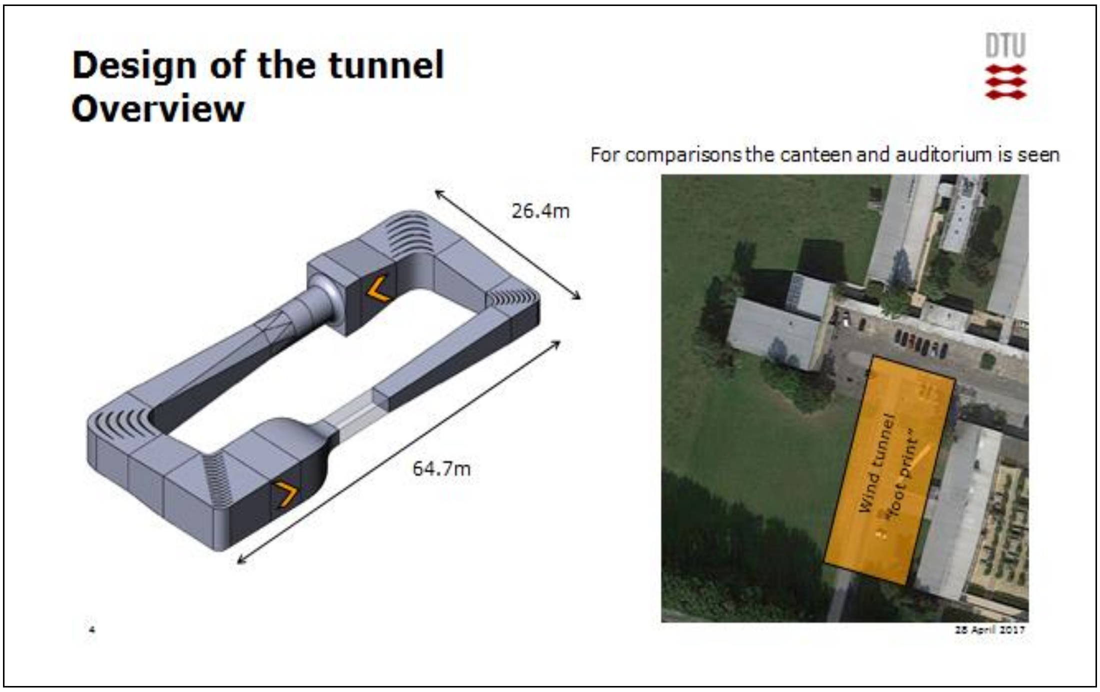
Design of the tunnel
Besøg i andre tunneller

AUDI wind tunnel in Ingolstadt, Germany



Acoustic wind tunnel AWB at DLR, Braunschweig, Germany





Design of the tunnel
Overview

For comparisons the canteen and auditorium is seen

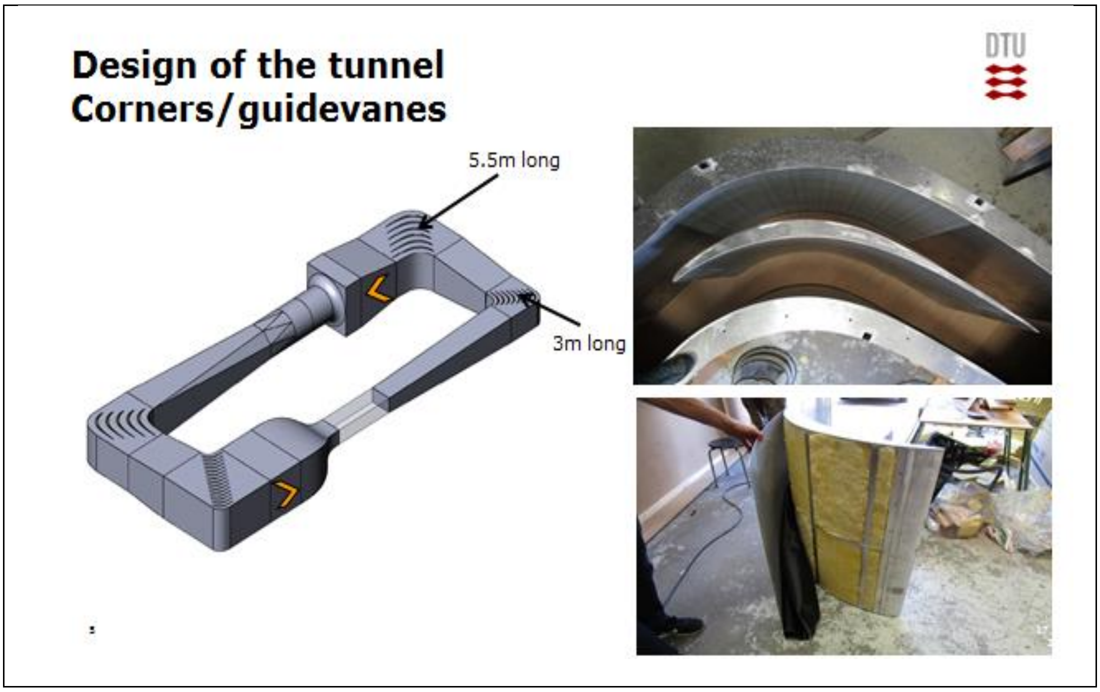
26.4m

64.7m

Wind tunnel "foot-print"

4

28 April 2017

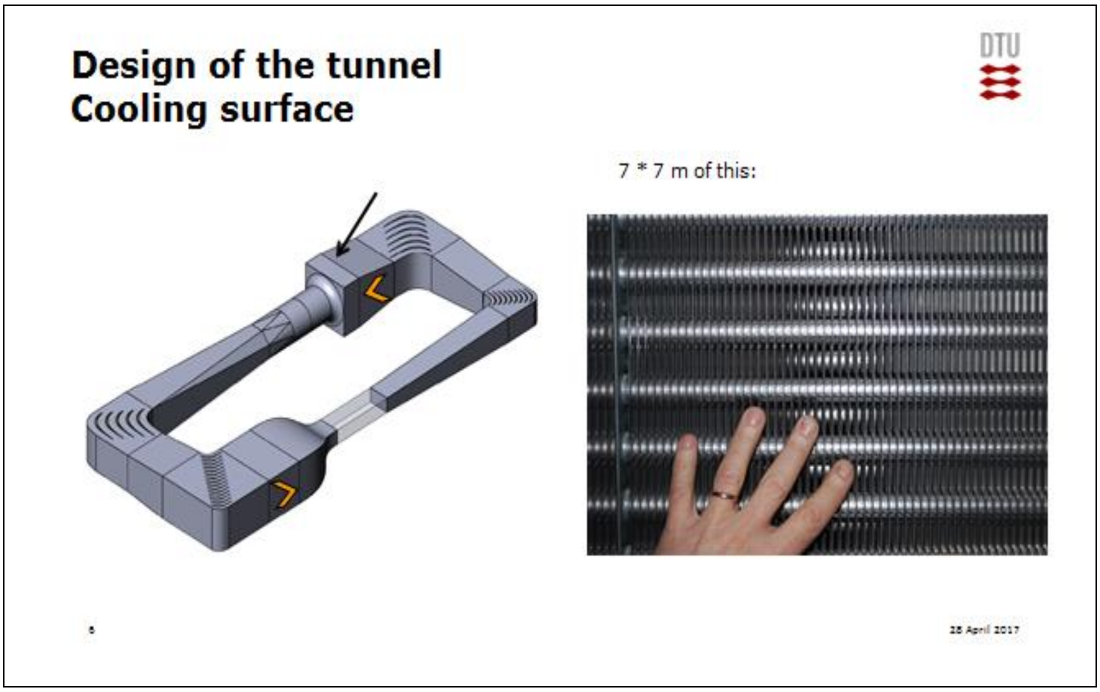


Design of the tunnel
Corners/guidevanes

5.5m long

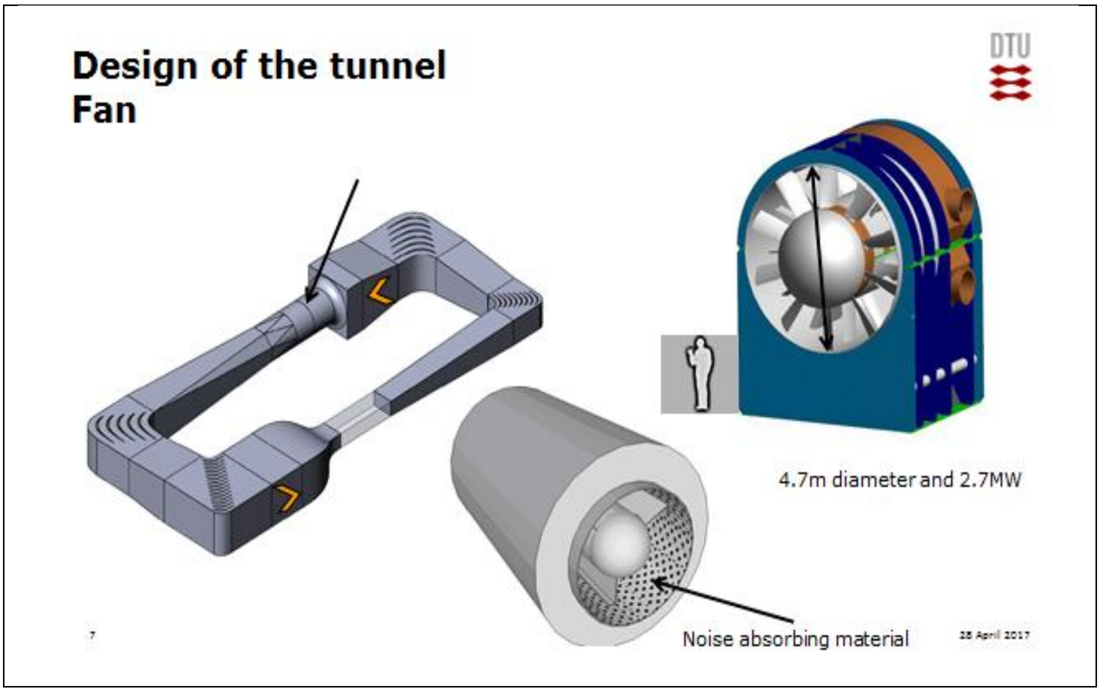
3m long

5



Design of the tunnel
Cooling surface

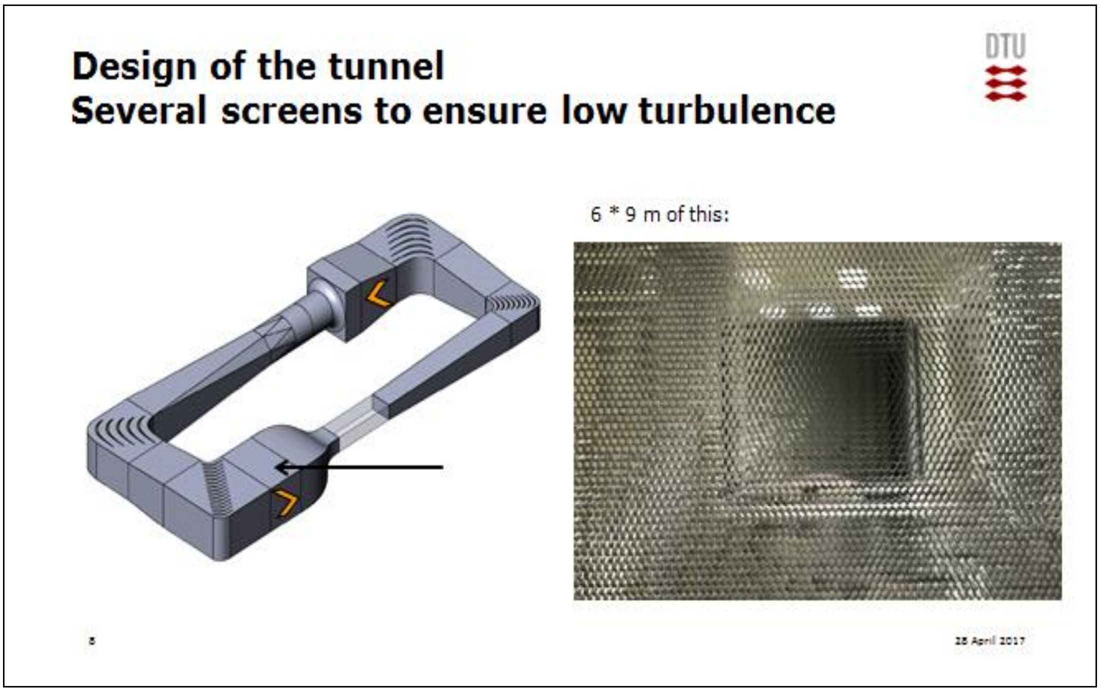
7 * 7 m of this:



Design of the tunnel
Fan

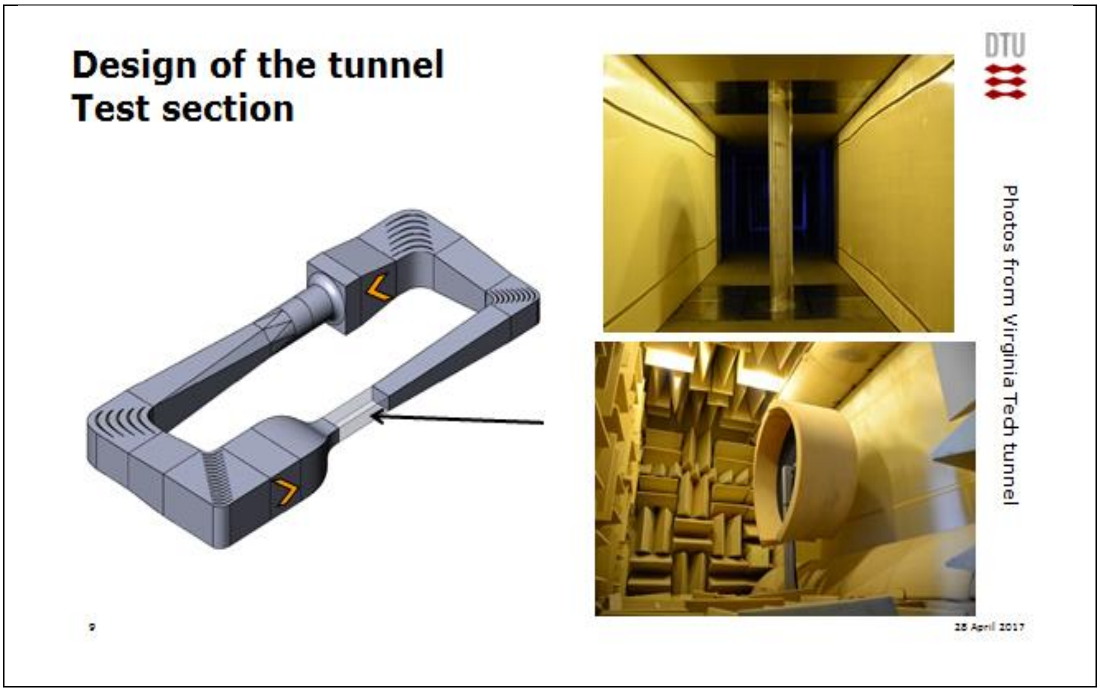
4.7m diameter and 2.7MW

Noise absorbing material



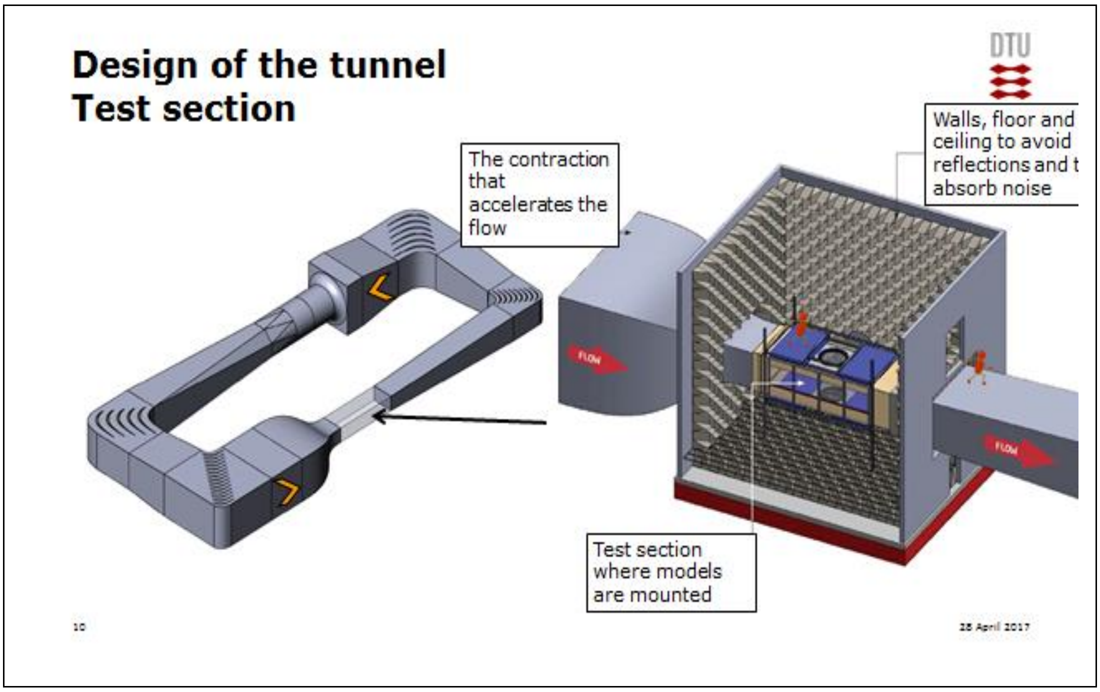
Design of the tunnel
Several screens to ensure low turbulence

6 * 9 m of this:



Design of the tunnel
Test section

Photos from Virginia Tech tunnel

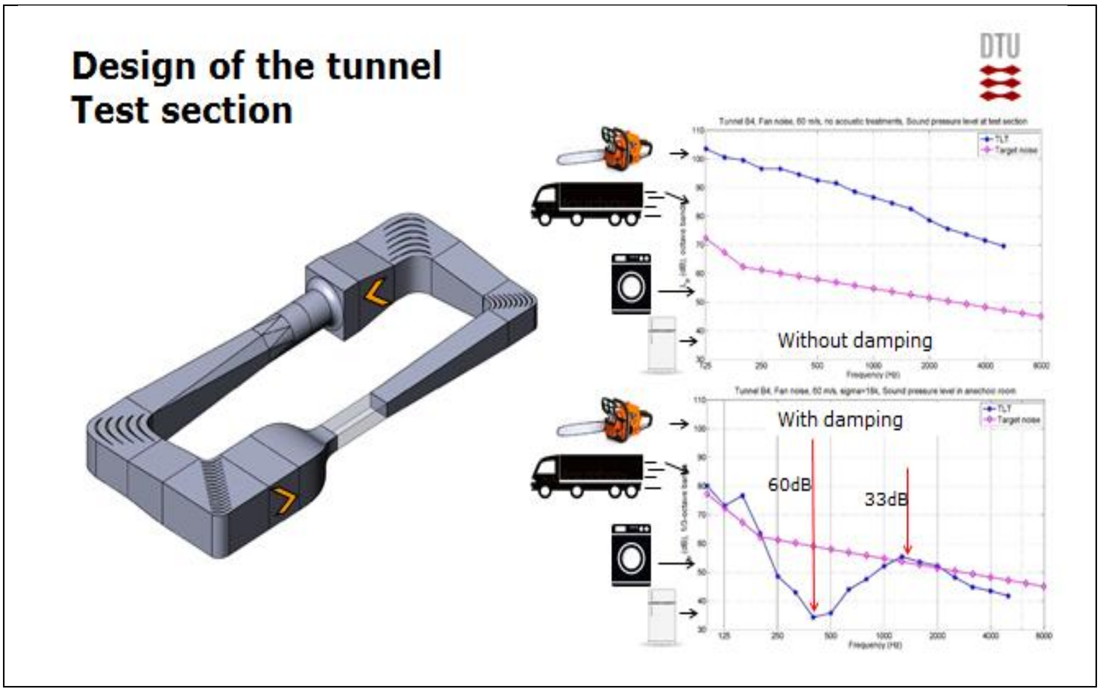


Design of the tunnel
Test section

The contraction that accelerates the flow

Walls, floor and ceiling to avoid reflections and t absorb noise

Test section where models are mounted



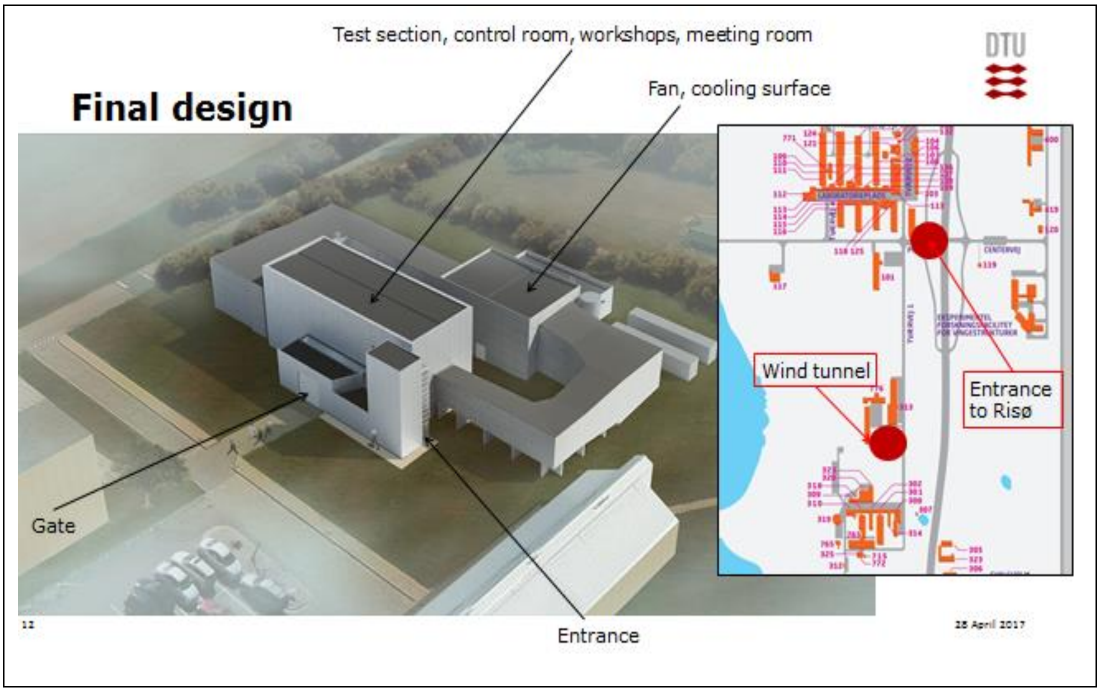
Design of the tunnel
Test section

Without damping

With damping

60dB

33dB



Final design

Test section, control room, workshops, meeting room

Fan, cooling surface

Gate

Entrance

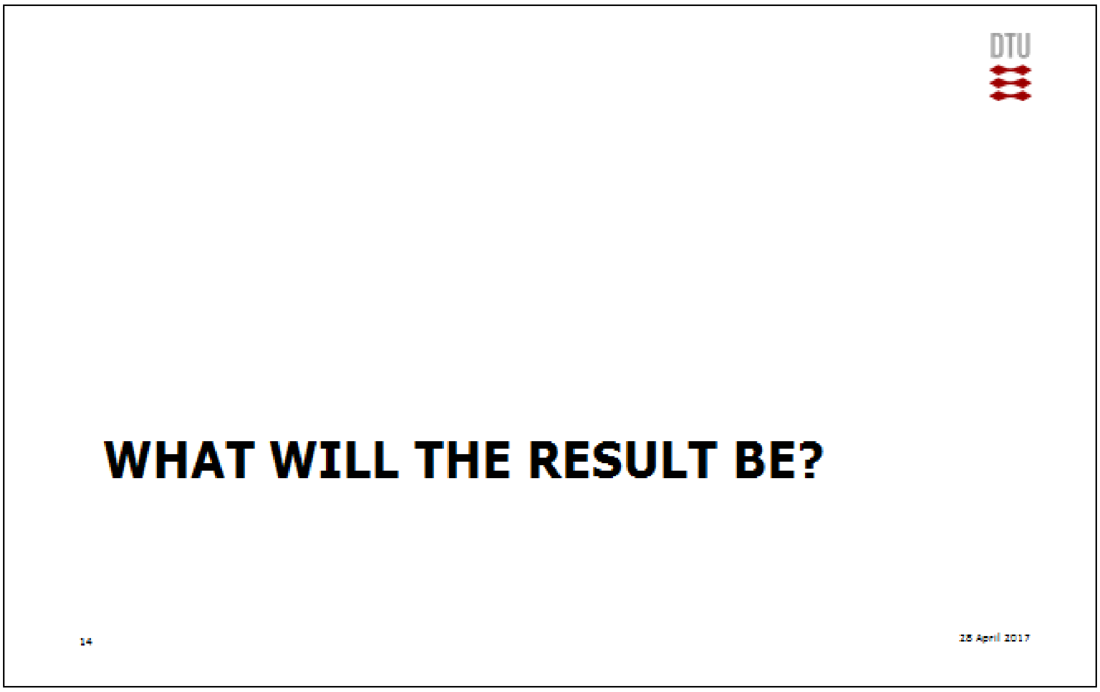
Wind tunnel

Entrance to Risø

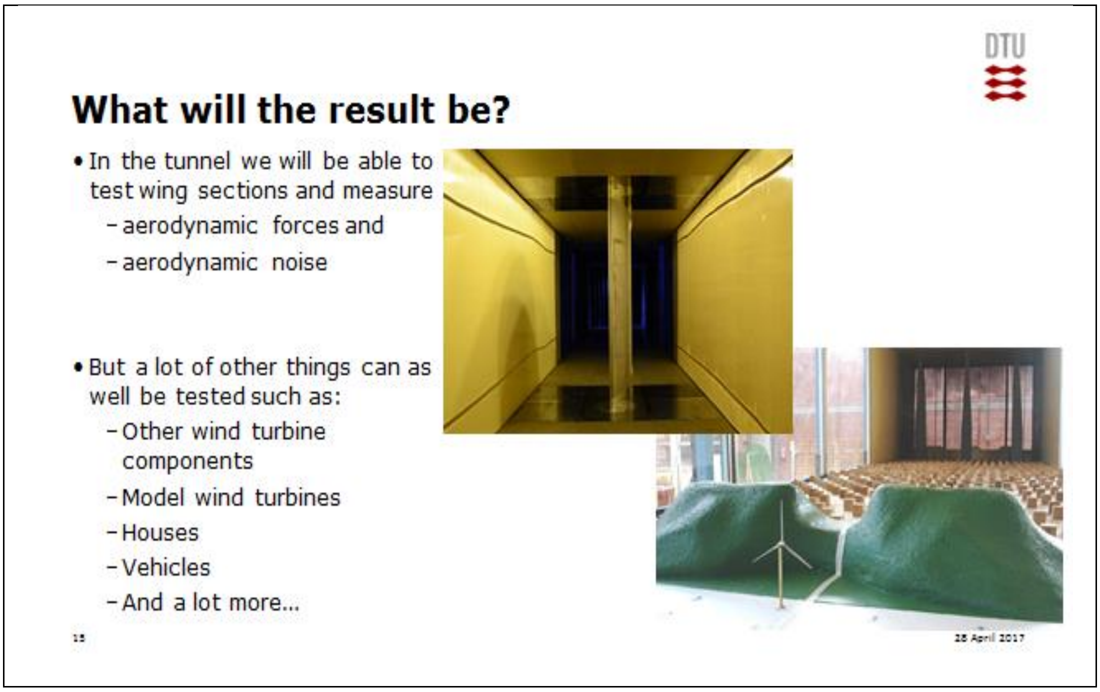
Status

- The concrete part is finalised
- Components inside the tunnel will be installed until summer 2017. Guidevanes, contraction, inlet/outlet to fan is ongoing
- A parallel activity is the design and construction of the test section – and of the instrumentation

Start April 2017

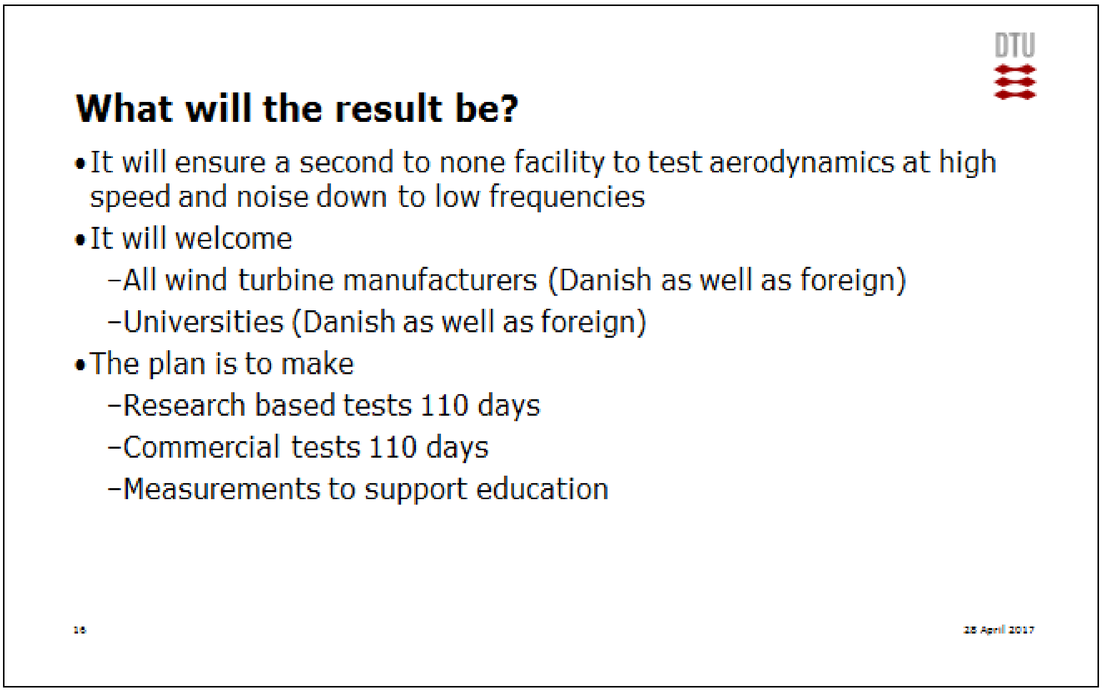


WHAT WILL THE RESULT BE?



What will the result be?

- In the tunnel we will be able to test wing sections and measure
  - aerodynamic forces and
  - aerodynamic noise
- But a lot of other things can as well be tested such as:
  - Other wind turbine components
  - Model wind turbines
  - Houses
  - Vehicles
  - And a lot more...



What will the result be?

- It will ensure a second to none facility to test aerodynamics at high speed and noise down to low frequencies
- It will welcome
  - –All wind turbine manufacturers (Danish as well as foreign)
  - –Universities (Danish as well as foreign)
- The plan is to make
  - –Research based tests 110 days
  - –Commercial tests 110 days
  - –Measurements to support education

Thank you!