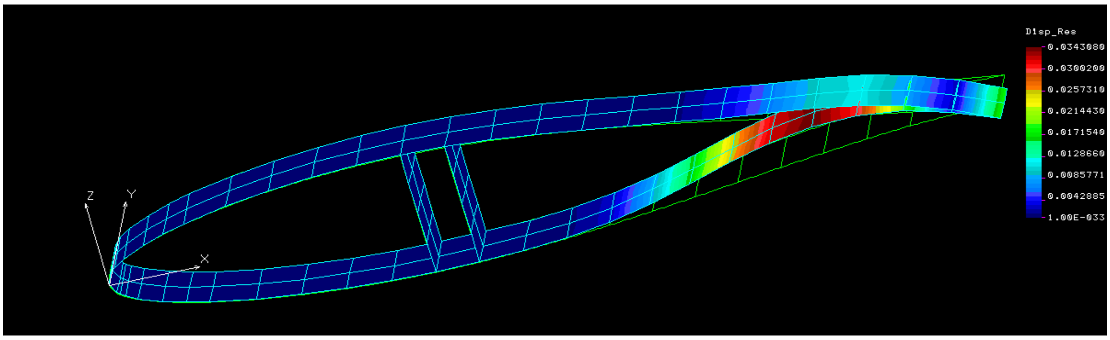
INTERNATIONAL ENERGY AGENCY

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

50th IEA Topical Expert Meeting

The Application of Smart Structures for Large Wind Turbine Rotor

Delft, theNetherlands, December 2006
Organised by: TU Delft



Scientific Co-ordination:
Sven-Erik Thor
Vattenfall AB, 162 87 Stockholm, Sweden

Copies of this document can be obtained from:
Sven-Erik Thor
Vattenfall AB
162 87 Stockholm
Sweden
sven-erik.thor@vattenfall.com

For more information about IEA Wind see www.ieawind.org

CONTENTS

IEA RD&D Wind Task 11

Topical Expert Meeting #50

The application of smart structures for large wind turbine rotor

INTRODUCTORY NOTE

IEA TOPICAL EXPERT MEETING 50

ON

THE APPLICATION OF SMART STRUCTURES FOR LARGE WIND TURBINE ROTOR BLADES

GIJS VAN KUIK, DUWIND

THE TOPIC

Wind turbines become larger and larger. Modern wind turbines designed for offshore application have become the largest rotating machines on earth, with the length of one blade almost equal to the entire span of a Boeing 747. This upscaling has, until now, not led to significant changes in the blade structure: all blades are constructed as one single component, with the blade skin as load carrying element. On the contrary, the control of the blade loads has changed in the past. Until the nineties in the previous century, the 'Danish concept' was very successful. The turbines making use of this concept combine constant rotor speed with stall of the flow around the rotor blades: increasing wind speeds automatically induce increasing drag forces that limit the absorbed power. All other control options were considered too complex. Most modern large wind turbines run at variable rotational speed, combined with the adjustment of the collective pitch angle of the blades to optimize energy yield and to control the loads. This is a big step forward: the control of the blade pitch angle has not only led to power regulation, but also to a significantly lighter blade construction due to the lower load spectrum and a lighter gear box due to shaved torque peaks.

The next step in blade load control is almost ready for commercial application: pitch angle adjustment per blade instead of collective. This will further alleviate the rotor loads, specially the periodic loading due to yaw and wind shear. Not only the blades will benefit from this, but also the drive train and nacelle structure.

A further step, probably for the 2020 wind turbine generation with even larger rotor size, possibly is a much more detailed and faster control of the loads. Control should be possible for each blade at any azimuthal position and any spanwise station, by aerodynamic control devices with embedded intelligence distributed along the span. The correspondence with the control devices at airplane wings (flaps at leading and trailing edge, ailerons) is apparent, but the requirements for blade control devices are probably much more severe. Modern blades are very reliable, and require only limited maintenance at the blade pitch bearing. Future blades with distributed control devices should be as reliable, without adding maintenance requirements.

The development of this kind of technology, often named in popular terms 'smart structures' or 'smart technology', is an interdisciplinary development par excellence. It requires a joint effort in many disciplines:

- An aerodynamics of aerofoils with control elements. Several options are available for the adjustment of lift and drag: flaps, microtabs, boundary layer suction or blowing or other means of influencing it, variable camber.
- Actuators. The activation of the aerodynamic devices has to be fast and reliable with as little as possible power use. Well known options are piezo-electric elements and shape-memory alloys.
- Control. The control algorithms for this type of control are not yet available. Fast, real time load identification algorithms, allowing application of predictive control techniques is a challenging

task. Algorithms like self-learning and adaptive algorithms will be used to design a fault-tolerant controller.
- Communication and power supply. The power supply and communication between the control devices should not increase the sensitivity for lightning strikes.
- Blade material and construction. Preferably all devices should be embedded in the blade material, without creating slots in the blade surface to avoid contamination of the inner structure. The embedding can lead to new blade constructions, like the use of spars and ribs.
- Blade design tools. All available design tools do not include distributed control options, nor allow for totally different blade constructions.

OBJECTIVES OF THE MEETING

The objective is to report and discuss progress of R&D on all of the above mentioned topics. Since this area of research is relatively new (for wind turbines), many challenges and solutions are still to be discussed and tested. It is expected that the expert meeting will result in new and challenging directions in R&D due to the discussions between experts of different origin.

EXPECTED OUTCOMES

Compilation of the most recent information on the topic.
Input to define IEA Wind R&D's future possible role in this topic.

TENTATIVE AGENDA

Participants in the meeting are expected to discuss the subject in detail and give a short presentation relevant to the topic. Presentation length is usually around 15minutes, depending on the number of presentations in the meeting.

The tentative agenda covers the following items:
1. Introduction by host
2. Introduction by Operating Agent, Recognition of Participants
3. Collect titles of presentations and compile presentation order
4. Presentation of Introductory Note
5. Individual presentations
6. Discussion
7. Summary of meeting

INTENDED AUDIENCE

The national members will invite potential participants from research institutions, utilities, manufacturers and any other organizations willing to participate in the meeting by means of presenting proposals, studies, achievements, lessons learned, and others. This means then that the symposia will be wide open, taking into account that it is the first time that this subject will be discussed within the framework of the IEA Wind RD&D.

Topical Expert Meeting

THE APPLICATION OF SMART STRUCTURES FOR LARGE WIND TURBINE ROTOR BLADES

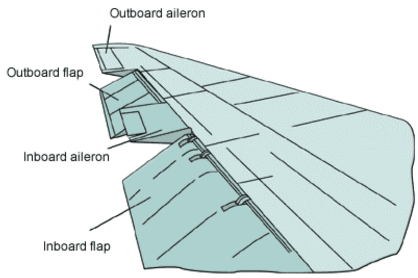
11-12 December 2006, TU-Delft

Objective

Significant blade load alleviation
by
applying spanwise-distributed load control devices
without
accepting a lower reliability or higher maintenance

In other words

We want this control capability



without compromising the robustness of current blade technology

History of load control in commercial turbines

Fixed speed
- fixed pitch (passive stall)
- adjustable collective pitch (active stall)

Variable speed
- adjustable collective pitch
- variable collective pitch
- variable individual, harmonic pitch
- variable individual pitch

All full span

Time,
Rotor size

History of load control in R&D/experimental turbines

Several attempts of flexible concepts, passively controlled by centrifugal forces, stall, teeters, flexbeams:

Germany:	Hütter, Flair turbine, 10 m Ø
US:	Carter, up to 20 m Ø
Netherlands:	Flexhat, 25 m Ø
UK:	WEG, 25 m Ø

All full span

No (commercial) success, why not?

DUWIND

Previous experience

- It worked: blade fatigue loadspectrum halved
- Too complicated: guy wires, springs, hinges, elastomeric bumpers
- So: Not reliable enough
- Too far away from commercial technology
- In case of stall (WEG, Carter) aerodynamics not yet sufficiently understood
- Not all concepts are up-scalable

DUWIND

Now, 10-15 years later

- Size has gone up!
- Turbines are too large for passive control: load control should be fast and detailed
- Blade & turbine manufacturers encounter load- and scale limits
- Along-the-span control would help
- Reliability requirements are very severe
- Increased knowledge on aerodynamics, dynamics, control, material, …

New approach: ‘smart’ rotor blades with active rotor control

Key challenges:

- Efficient aerodynamic control devices and
- Dedicated aerofoils
- Smart sensors, actuators, materials
- New control algorithms
- New aerodynamic/elastic rotor design models
- Integration of all in smart rotor design

But:

- Current safety & reliability should not be compromised
- Technology should not be too far off manufacturers experience

Several phases

analyses, laboratory testing ← now

medium size prototype testing

large size prototype testing

commercial application

Time,

Rotor size

Blank page

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

Introduction

DUWIND's involvement in smart structure applications for wind turbines:

- 4 PhDs:
  - Wind Energy
  - Design and Production of Composite Structures
  - Design of Aircraft and Rotorcraft
  - Delft Center for Systems and Control
- 2 projects:
  - UpWind (WP1B3 - Smart Rotor Blades and Rotor Control)
  - STW (Smart Dynamic Rotor Control for Large Offshore Wind Turbines)

Investigation of:
- Concepts - feasibility - integrated design ⟵
- Aerodynamics
- Structural integration
- Control / Identification

Development of models – Experimental investigation

Smart Rotor Blades and Rotor Control

Introduction

•Development of power regulation-load reduction technology for wind turbine over the years:

Constant rot. speed-Stall regulation → Variable rot. speed – Collective Pitch regulation → Variable rot. Speed – Individual Pitch regulation

up scaling →

→ Variable rot. Speed – Individual Pitch regulation to deal with high frequency k*p (e.g. 3p) loads? →

•Pitch actuator not fast enough / excessive use

•Stochastic loads

•Variable distribution of loads in the azimuth and spanwise direction

Introduction

→ Variable rot. Speed – Advanced Control in :

-every blade

-every azimuth position

-every spanwise position

→ •Aerodynamic control devices (surfaces) along the blades controlled actively and independently

→ •Integrated solutions

•No complex mechanical parts – robust blade design

•Fast actuation – broadband response - small weight – low energy

•Advanced control & identification

→ •Smart material-based actuation systems

•Aerodynamic efficient concepts for control devices

•Advanced control methods

↓

"Smart rotor"

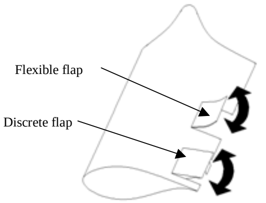
Target: use actively controlled aerodynamic devices integrated along the blade span to alleviate fatigue loads

Integrated design of a smart rotor

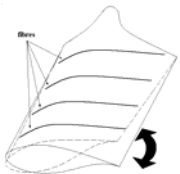
Control devices

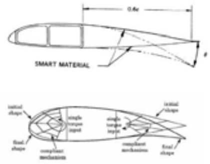
•Affect aerodynamics using : -Deformable blade shape

: -Manipulation of boundary layer

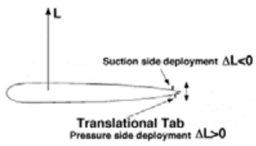


Trailing edge flaps

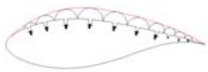

Active twist

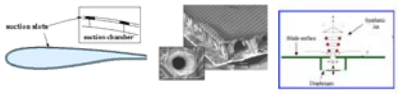


Camber control



Micro tabs


Inflatable structures

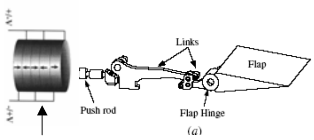

BL Suction – Synthetic jets

Integrated design of a smart rotor

Actuators

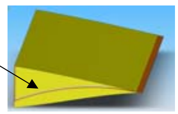
•Discrete → Actuation of: discrete TE flaps, Microtabs, BL control, Camber Change (compliant mechanisms)

•Embedded → Actuation of: flexible TE (flaps), Camber Change, Active Twist

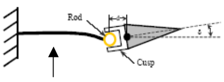


Piezo stack

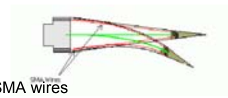
Piezo bender



discrete ⟷ embedded



Piezo bender (bimorph)


SMA wires

Integrated design of a smart rotor

Sensors-Control

Control issues

•Control over unsteady flow

•Passive control (open loop)

•Active control (closed loop): measurements of the state
↓
model of the state
(reduced order model)
↓
control to alter the system state to the desired value

controllability and observability important factors

•Classical Feedback Control (PI, PID)

•Modern Control Techniques (H_2/LQG, H_{∞})

•Optimal Control (minimize objective function based on mathematical formulations)

Sensor issues

Target: Measurement of loads on blades for feedback control

•Loads measured indirectly: -strains
-accelerations

•Electrical strain gauges

•Optical strain gauges

•Accelerometers

Load measurements + actuator response + controller response

fast enough for fast inflow fluctuations?

(time lag in aerodynamics big issue)

Smart Rotor Blades and Rotor Control

UpWind DUWIND TUDelft

Integrated design of a smart rotor

Modeling-Experiment

Aspects in modeling :

•Aerodynamics:

-unsteady airfoil aerodynamics + deformable shape (Theodorsen, Leishman, Gaunaa) – limitations?

-unsteady airfoil aerodynamics + BL control (?)

•Actuation devices

-smart actuators mechanical models

-smart materials in composite structures structural models

•Full rotor

-BEM

-unsteady airfoil aerodynamics

-necessary dynamics

-controller for aerodynamic devices

-how important are 3d effects?

Aspects in experiments:

•Fine tuning of models

•On-hands application

(actuators, sensors, cables etc)

•Active control (real time control hardware)

Target: Integrate available models for full smart rotor simulation + validate with experiment

Smart Rotor Blades and Rotor Control

UpWind DUWIND TUDelft

Experimental approach

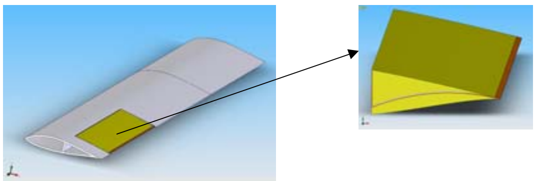
3 Series of experiments:

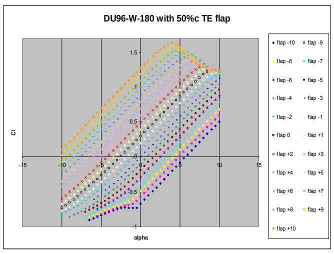
- 2d (+ control surfaces – flaps) in unsteady conditions (InWind) → Test unsteady aerodynamic models
- Non rotating blade with active control of smart devices (UpWind+STW) →
  - Apply active control on smart devices
  - Potential for load reduction
- Rotating case: 2-bladed wind turbine with integrated smart control devices in OJF of TUDelft (UpWind) →
  - Smart rotor behavior
  - Validate design tools

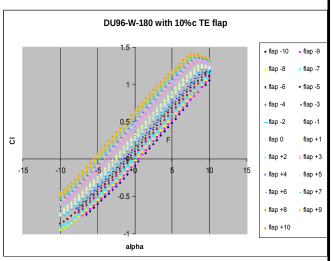
UpWind DUWIND TUDelft

Ongoing work

- Non-rotating experiment
  - -PZT based flexible flap
  - -Unsteady disturbances
  - -Dynamics tailored structure
  - -Real time controller
  - -Steady and Unsteady aerodynamics modeling (2D)
  - -Actuator measurements
  - -Better model for flexible flaps







Target: apply active smart control

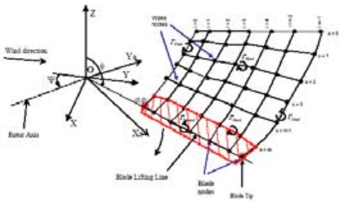
Smart Rotor Blades and Rotor Control

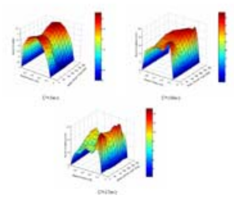
UpWind DUWIND TUDelft

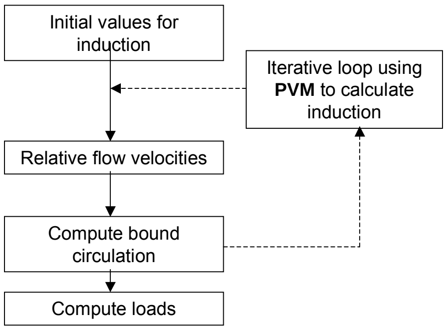
Future work

Need for reliable full smart rotor model:

- Traditional BEM based
- BEM+ Prescribed Vortex Model







UpWind DUWIND TUDelft

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

UpWind DUWIND TUDelft

Active Control Devices for Wind Turbine Blades

Paul Veers
-for-
Dale Berg and Jose Zayas
Wind Energy Technology Dept.
Sandia National Laboratories
www.sandia.gov/wind

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

Wind Energy Research: Sandia National Laboratories

Sandia

Multi-program
Federal Research Facility

Wind Energy Group

Began in 1970's

Currently Focused on Blades, Manufacturing and Reliability

- Design Analysis
- Manufacturing
- Lab Testing
- Field Testing

Then…

… and now.

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

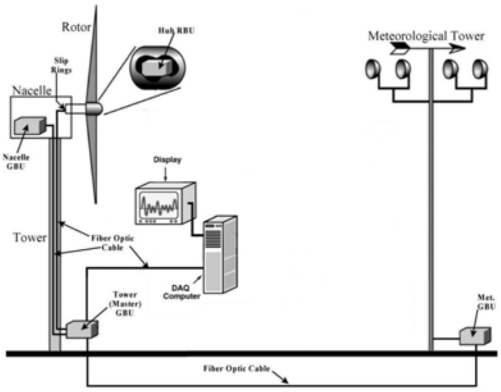
Sandia Wind Energy Department

- Partnership with NREL in an integrated DOE wind program
- Partnerships with industry to solve problems and develop new technology
- Partnership with other Sandia Departments to use their expertise (especially structural dynamics and aerodynamics)
- 11 Full time equivalents (includes matrix)

NREL/Sandia/GE cooperative test in Lamar, Colorado

Field Testing Capabilities

Data Acquisition

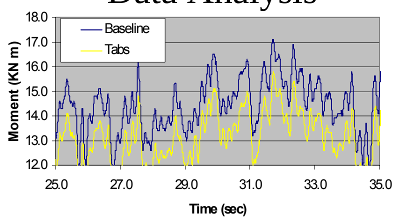


SNL-developed ATLAS system
Continuous Data Acquisition
GPS Synchronization
Lightning Protection on all Channels

Subscale Blade Testing

USDA-ARS Test Site
Bushland, TX

Data Analysis



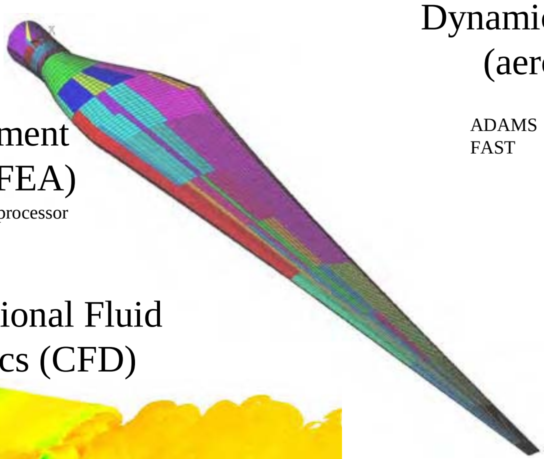
Blade Analysis Capabilities

Dynamic Simulation (aeroelastic)

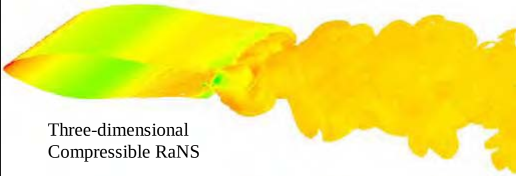
ADAMS
FAST

Finite Element Analysis (FEA)

NuMAD preprocessor
ANSYS



Computational Fluid Dynamics (CFD)



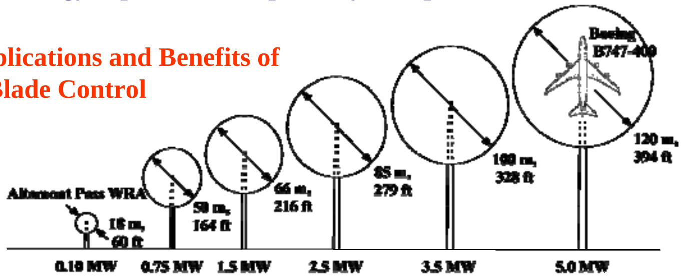
Three-dimensional
Compressible RaNS

Smart Structures: Problem Statement & Goal

- **Can the Rotor Weight be Reduced by Adding Active Devices?**
- **Can active control be used to reduce fatigue loads?**
- **Can energy capture in low wind conditions be improved?**
- **Can active devices reduce acoustic emissions – allow higher tip speeds?**
- **Systems Approach: Can a greater area be swept with the same blade weight to increase energy capture and improve system performance?**

Research Goal:

Understand the Implications and Benefits of Embedded Active Blade Control



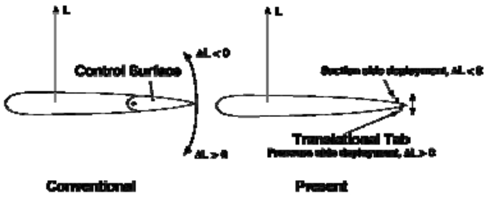
Aerodynamic Control

- **Active Load Control**
  - Blade incidence angle (pitch)
  - Flow velocity (modification in RPM)
  - Blade length
  - Blade aerodynamic characteristics through:
    - Changes in section shape (aileron, smart materials, microtab)
    - Surface blowing/suction
    - Other flow control techniques (VG's, surface heating, plasma)

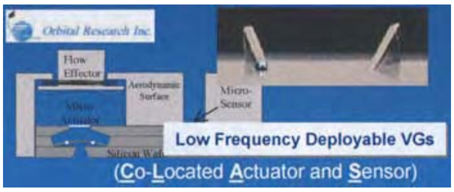
Current Technology:
Variable Speed, Variable Pitch

Examples of Active Flow/Load Control

Active Aileron on a Zond 750 Blade



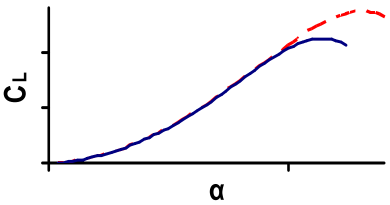
Microtab Concepts

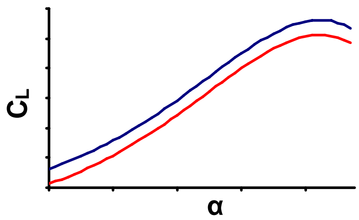


Active Vortex Generators

Adaptive Airfoils

Aerodynamic Effect of Active Control





- Plasma
- Active VG's
- Surface Blowing/Suction
- Surface Heating
- Synthetic Jets

- Flaps
- Ailerons
- Spoilers
- Microtabs
- Airfoil Morphing

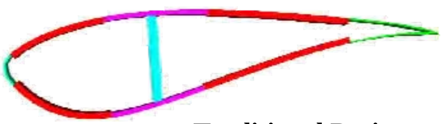
Ranking Criteria for Active Devices

Factors to Consider

- Cost
  - Materials
  - Repair or replace
  - Manufacturing
  - Installation

  } Sub-Factors
- Life Expectancy of the Device
- Weight
- Actuation

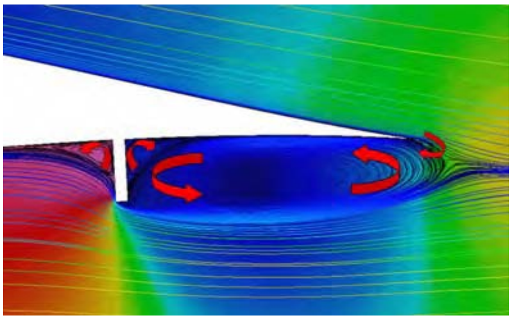
- Complexity
- Manufacturability
- Maintainability
- Noise
- Environmental Effects (Ice & Dust)
- Performance



Traditional Design

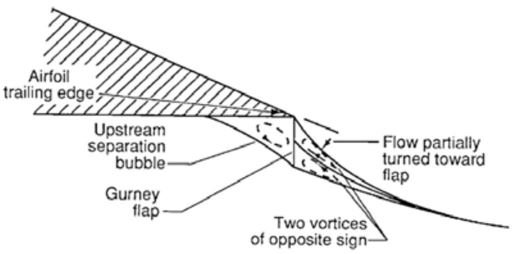
Potential Future Design

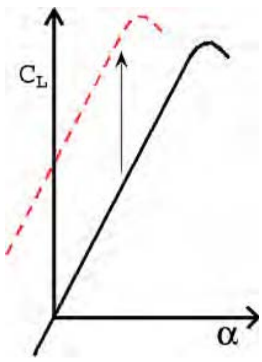
Microtab Example



Gurney Flap (Passive)

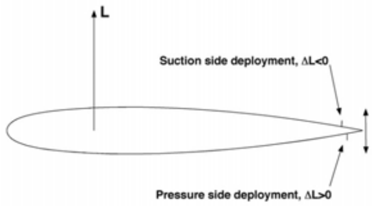
- **Gurney Flap (Liebeck, 1978)**
  - **Significant increases in C_L**
  - **Relatively small increases in C_D**
  - **Properly sized Gurney flaps ⇨ increases in L/D**

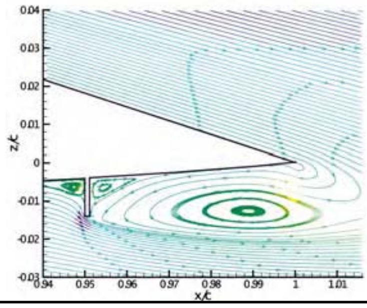


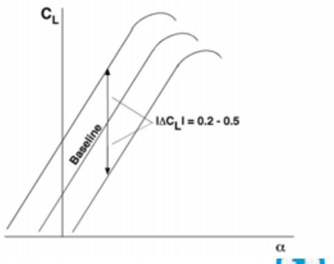


Microtab Concept

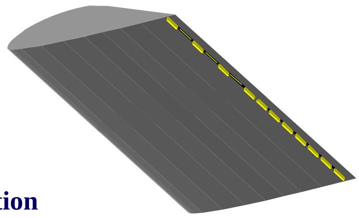
- Evolutionary Development of Gurney Flap
- Tab Near Trailing Edge Deploys Normal to Surface
- Deployment Height on the Order of the Boundary Layer Thickness
- Effectively Changes Sectional Camber and Modifies Trailing Edge Flow Development (the Kutta condition)





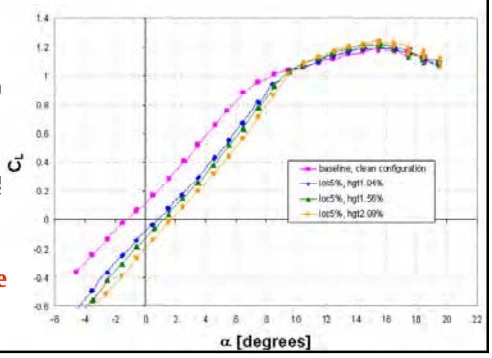


Microtab Concept



- Small, Simple, Fast Response
- Retractable and Controllable
- Lightweight, Inexpensive
- Two-Position "ON-OFF" Actuation
- Low Power Consumption
- No Hinge Moments
- Expansion Possibilities (scalability)
- Do Not Require Significant Changes to Conventional Lifting Surface Design (i.e., manufacturing or materials)

Tabs Deployed on the Upper Surface
Heights 1-2%



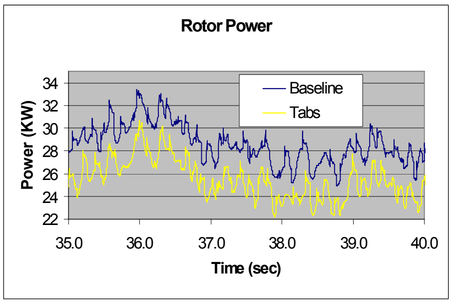
Full System Modeling

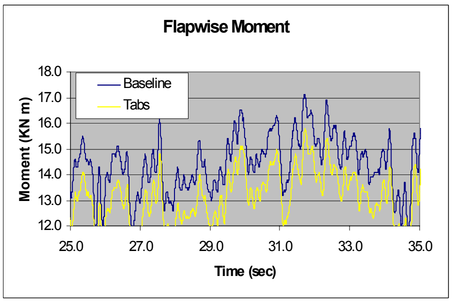
- **Wind Turbine Model**
  - **Micon 65 Stall Regulated**
  - **3-bladed upwind**
  - **Model results have been verified with field data**
- **Dynamic Simulation Tools**
  - **FAST (Fatigue, Aerodynamics, Structures, and Turbulence)**
    - **Modal representation**
    - **Limited degrees of freedom**
    - **Used as a preprocessor to ADAMS**
  - **ADAMS (Automatic Dynamic Analysis of Mechanical Systems)**
    - **Commercial multi body dynamic simulation software**
    - **Virtually unlimited degrees of freedom**

Micon 65 – ADAMS Model

Dynamic Effect of Microtabs
(no control)

10-12% Difference





Microtabs Deployed for the Entire Simulation

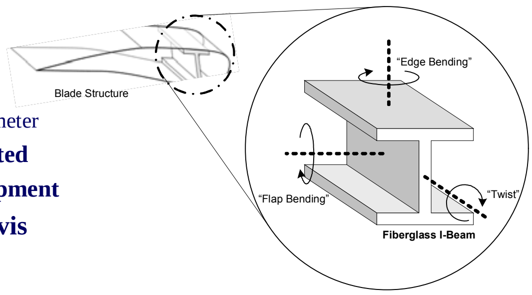
Sensor Research

- **Focus on Cost Effective Sensors (for lab and field environments)**
  - **Strain sensors**
  - **Embedded composite pressure sensors for airflow measurements**
  - **Fiber optic sensors**
  - **Piezo-ceramic**
  - **Displacement and proximity (blade tip deflection)**
- **Sensor Networks**
  - **Control inputs**
  - **Damage detection and health monitoring**
- **Embedded Sensors**
  - **Composite structures**
  - **Exploring possibilities of collaborating with SNL MEMS facility**
  - **Exploring potential benefit of PZT's with NASA**

Redundant Sensors are Needed to Ensure Reliability

Fiber Optics Research

- **Goal:** **Develop New Fiber Optic Interrogating Method to Reduce System Cost**
  - **Use Fiber Optics to measure flap and edge bending, as well as twist**
  - **Relies on using tunable filter and superluminescent diode**
    - Eliminates costly interferometer
  - **Temperature compensated**
  - **Currently under development**
- **Partnership with UC Davis**



Conclusions

- There appears to be a great deal of value in integrated aeroelastic sensing and control
- Preliminary investigations (CFD and wind tunnel) indicate some promise with a Microtab approach
- There is a long ways to go before any of these devices can be reliably integrated into commercial wind turbine systems

RISØ

LOAD ALLEVIATION ON WIND TURBINE BLADES USING VARIABLE AIRFOIL GEOMETRY

Thomas Buhl, Christian Bak, Mac Gaunaa and Peter Bjørn Andersen

www.risoe.dk

RISØ

Outline

- Motivation for the present work
- 2D computations
  - Tools
  - Main Results
- 3D computations
  - Tools
  - Main Results
- Wind tunnel testing
  - The model
  - Preliminary results
- Conclusions
- Future work

Motivation for the work

- State of the art active load reduction employs pitching of whole wing
- Reductions of fatigue loads of up to 28% have been predicted
- But… Very long flexible blades may keep us from pitching fast enough to further reduce fatigue loads

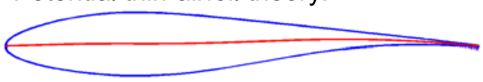
- What if much faster load control could be possible?
- What if local load control on the blade could be possible?

- Inspiration: Mother nature

- Idea: Use adaptive trailing edge geometry

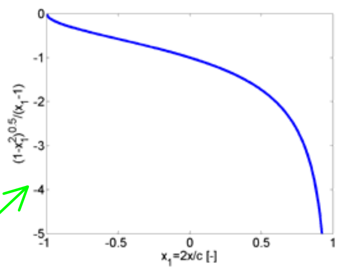
But why at the trailing edge?

- Potential thin-airfoil theory:

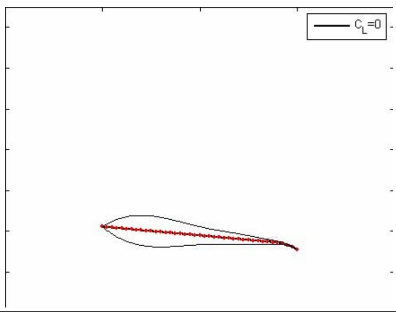


#1: Maximize bang for bucks

$$C_L = 2\int_{-1}^{1} \frac{\partial y}{\partial x}(x_1)\frac{\sqrt{1-x_1^2}}{x_1-1}dx_1$$



#2: Low loads at TE…
Both steady and unsteady.



Why not just a rigid flap?

- Surface discontinuity triggers stall

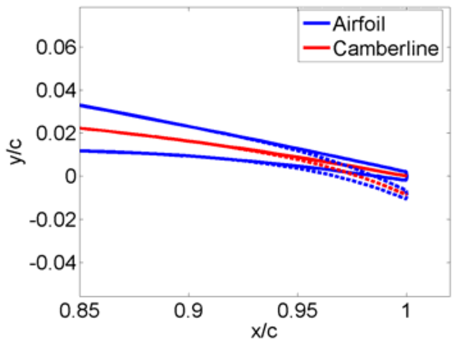
  ⇓

- Noise issues
- Bad L/D leading to loss in power production
- Flap losing it's potential load reduction effect

  ⇓

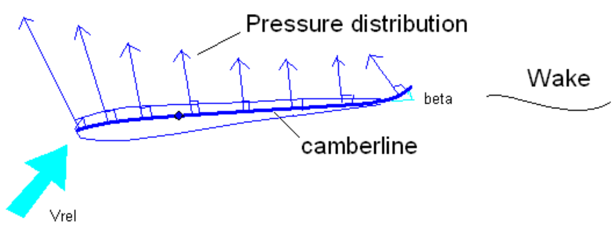
- Go for the continuously deforming one!

  For everything shown here a 10% flap with limits: -5°>β>5° was used



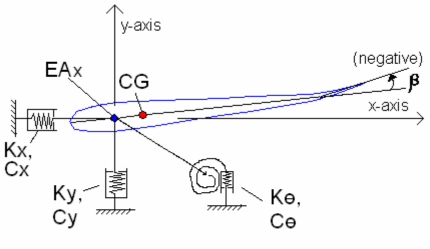
2D: The tools

- **Aerodynamics**: Unsteady thin airfoil theory (potential flow) developed
  - Modal expansion of the airfoil deflections
  - Unsteady terms associated with wake modelled by the computationally efficient indicial method
  - Model capable of predicting integral as well as local aerodynamic forces
  - Good agreement with attached flow CFD



2D: The tools

- Structural model:
  Solid body
  + forces from TE
  deformation



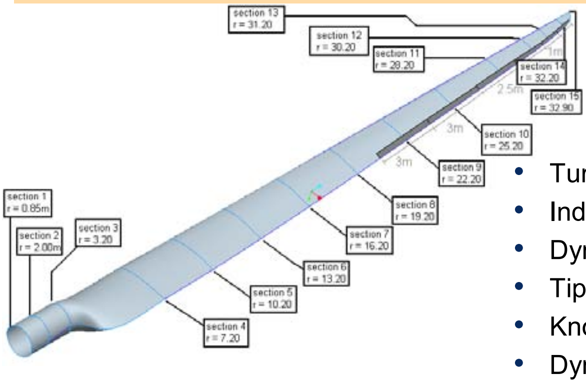
- Control: Simple PID control using flapwise deflection as input

2D: Main results

- Huge potential fatigue load reduction (~80% reduction of std(N))
- Low time lag essential
- Fast actuation velocity essential
- Trade-off to pitch DOF: Higher fatigue load in torsional direction.

3D model

RISØ



AERODYNAMIC

- Turbulent wind series (Veers)
- Induced velocity (Bramwell)
- Dynamic inflow model (TUDk)
- Tip-loss factor (Prandtl)
- Known static lift and drag
- Dynamic flow (Gaunaa)

STRUCTURAL

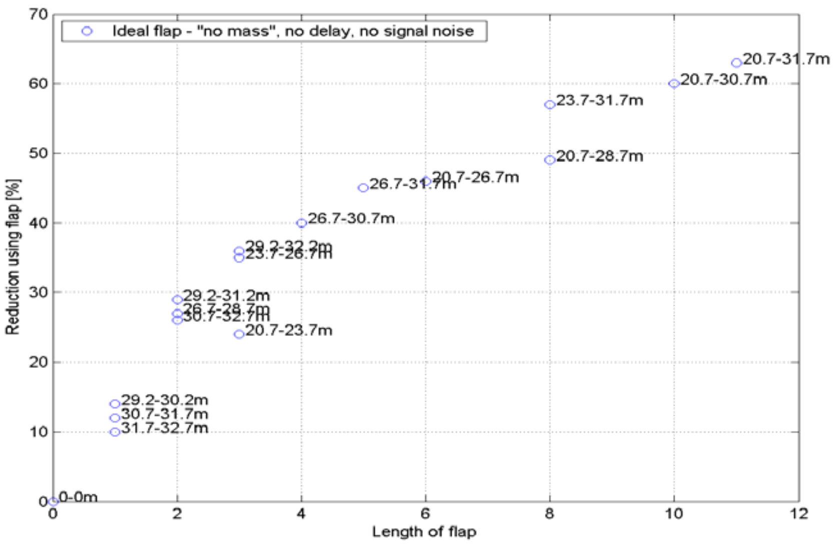
- Slender cantilever beam theory
- Blade length 33m
- Known structural data
- Mode shapes and eigenfreq. 1f,2f,3f,4f,1e,2e,1Θ,2Θ

CONTROL

- Local PID's on flapwise deflection
- Parameters determined using optimization. min(eq. flapw. root mom.)

3D Results (1)

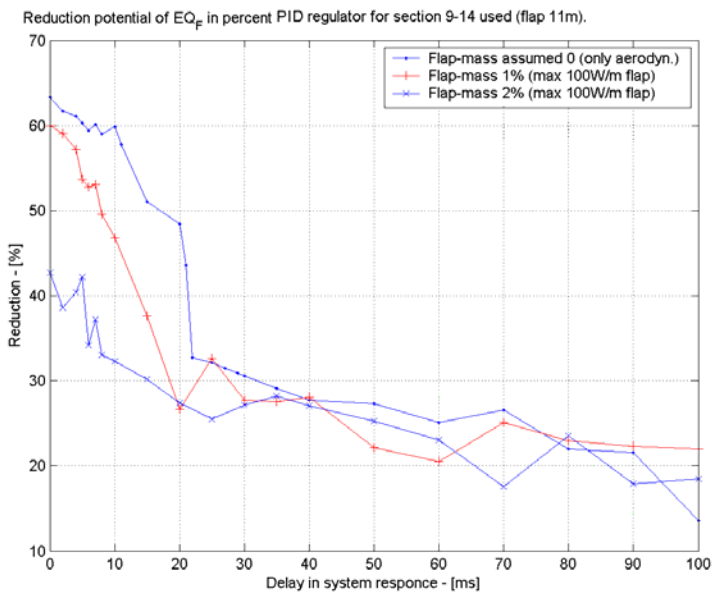
RISØ



3D results (2)

given flap	best radial location of given flap	flapwise root moment - maximum reduction potential – fatigue
one meter flap available	29-30m	14%
four meters flap available	24-27m 31-32m	50%
seven meters of flap available	21-24m 27-30m 32-33m	62%
eleven meters of flap available	22-33m	65%

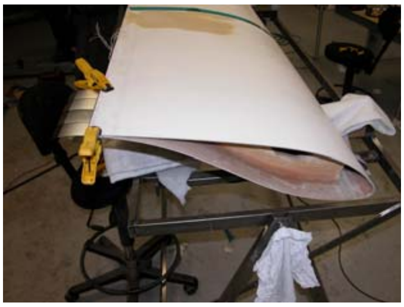
3D results (3)



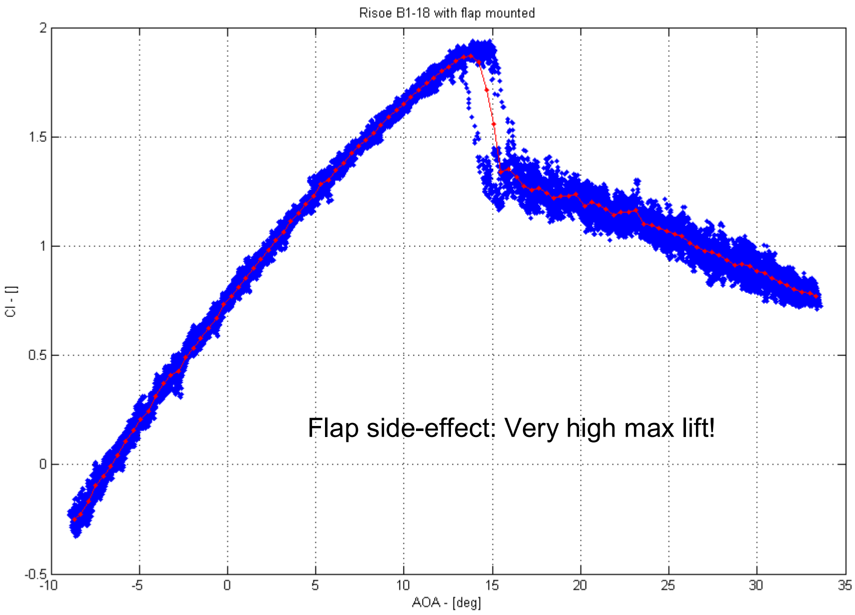
Wind Tunnel Testing

- The Actuator (piezo-electric)

- The Airfoil (Risø B1-18)

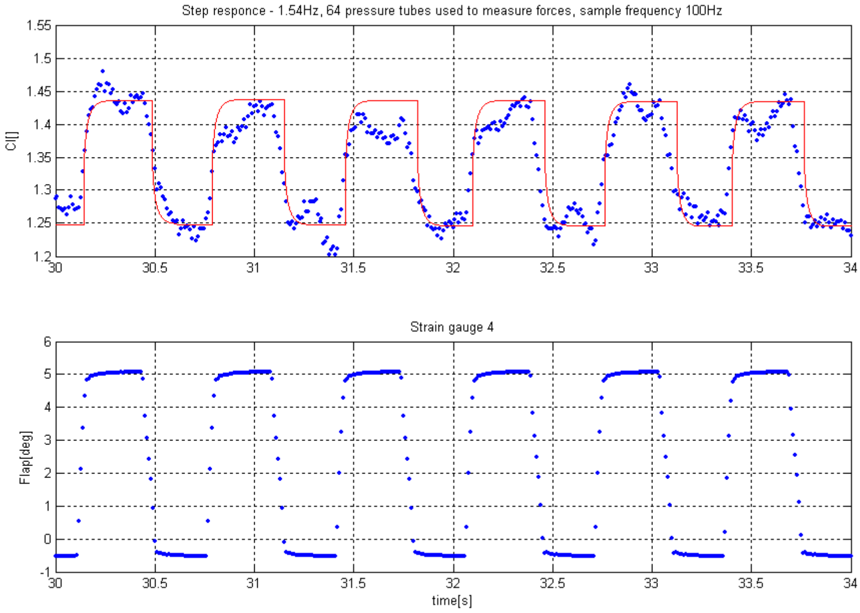


Preliminary result (steady)



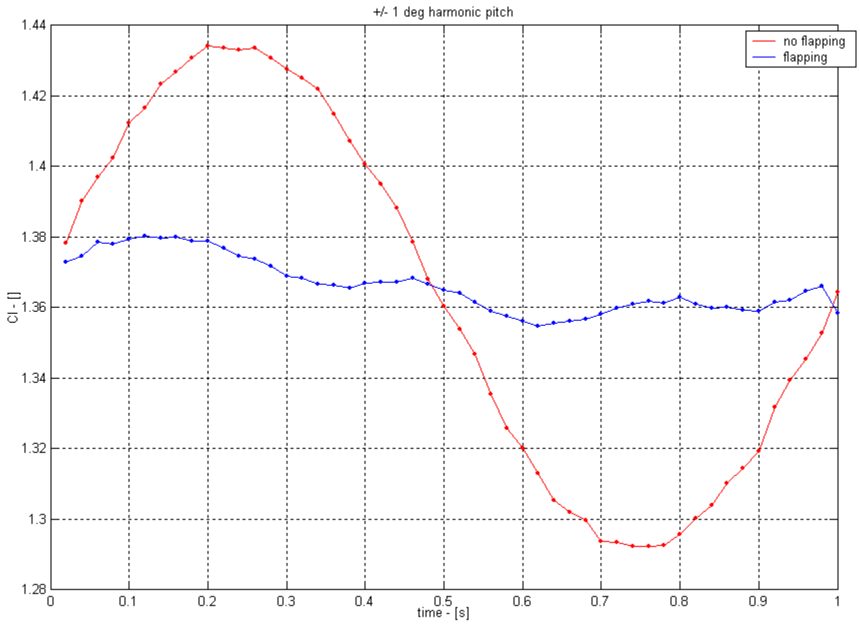
Preliminary result (step flap)

RISØ



Preliminary result (pitch + flap)

RISØ



Conclusions

- Big (huge?) load reduction potential
- Time-delays in the system should be avoided at all costs
- Fast actuation velocity important
- Preliminary wind tunnel results look very promising: TE could cancel out lift variations from +-1° pitch motion

Future (and present) work

- Sensoring technique (how to determine the state of the wing dynamically)
- Combined pitch and flap control
- Model aerodynamic dynamic stall effects
- Implement into HAWC2
- What are the implications of this stuff on dynamic stability
- More wind tunnel testing
- More realistic situations (whole span same flap control etc.)

Blank page

A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy.

NREL National Renewable Energy Laboratory

Innovation for Our Energy Future

Aeroelastic Modeling for Smart Rotors: Issues

Gunjit Bir
National renewable Energy Laboratory, CO, USA

Topical Expert Meeting on Smart Structures
Delft University, Netherlands
December 11-12, 2006

NREL is operated by Midwest Research Institute • Battelle

Smart Structures Application to Rotor
Issues

- Issue 1: Identifying most promising smart technologies for
  - Vibration & loads reduction, transients damping
  - Stability augmentation (e.g., active flutter suppression)
  - Performance improvement
  - Improved stability (especially for offshore turbines)
  - Noise suppression (BV interaction, acoustic and rotor/drivetrain)
  - Health monitoring (automated diagnostics of impact, creep, fatigue, crack)
  - Maintenance cost reduction (preventive maintenance, e.g., self-healing)
  - Improved structural integrity and weight reduction

IEA Topical Experts Meeting, Dec 11-12, 2007 2 NREL National Renewable Energy Laboratory

Examples of Promising Technologies

- Actuators (PZTs, electrostrictors, magnetosrictors, SMAs, magneto- and electro-rheological fluids)
- Sensors (optical fibers and the above bi-functional materials)
- Active aerodynamics (being researched at Sandia)
  - Airfoil morphing
  - Active twist
  - Active circulation control
  - Smart flaps and microtabs
- Novel controls (dense arrays of sensors & actuators, fault-tolerant, inter-linked)

Promising Technologies
Selection considerations

- Actuators & Sensors
  - Environment: corrosive, thermal, magnetic, electrical?
  - Driving energy: electrical, magnetic, thermal?
  - Dissipation requirements
  - Interfacing: geometry, size, properties matching
  - Capabilities: displacement, force, hysteresis, drift, sensitivity, response time, BW
- Controls
  - Optimal location of sensors & actuators
  - Control energy efficiency
  - Nonlinear adaptive controls using dense arrays
  - Faster sampling
  - Mode selection
- Other considerations: material cost, ease of fabrication, complexity, maintenance, reliability

Smart Structures Application to Rotor
Issues (cont'd)

- Issue 2: Acquiring/building data base for promising smart materials
- Issue 3: Performing basic research in specific areas:
  - Large-blade-suitable actuators & sensors (sizing, shaping)
  - Feedback electronics and processors
  - Automated diagnostics and parameter identification for AHM
  - Hardware & control requirements for AVC, ANC, and ASC
- Issue 4: Extending existing aeroelastic codes based on results/data from basic research

  Examples of aeroelastic codes used at NREL are FAST and ADAMS.

Aeroelastic Codes
Used at NREL

FAST

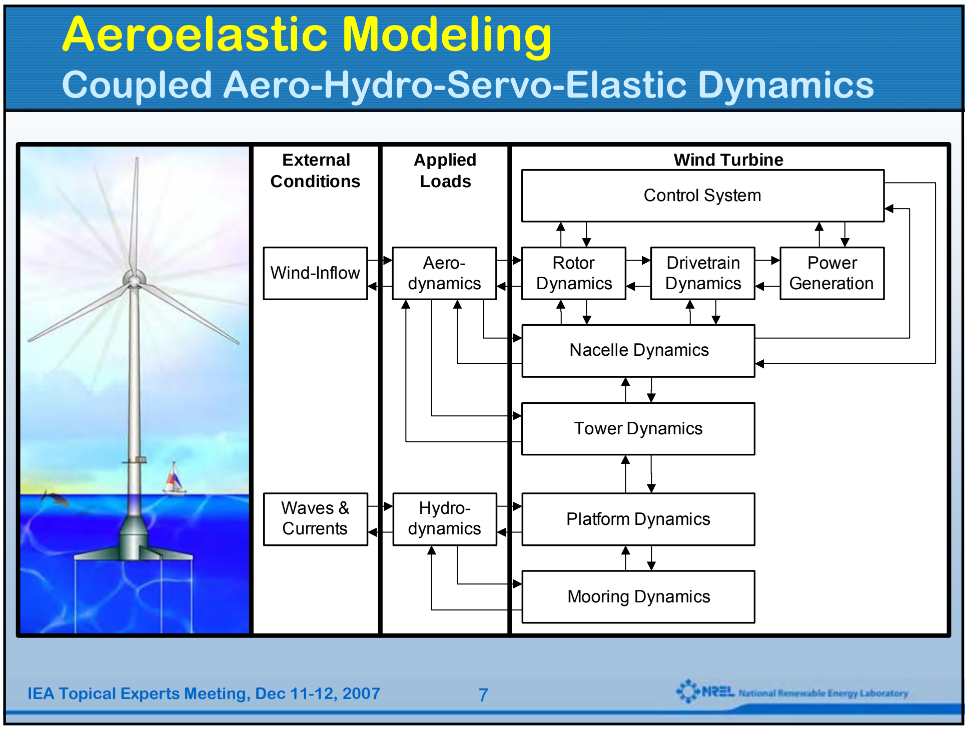
- Fatigue, Aerodynamics, Structures, and Turbulence
- Developed by NREL/NWTC
  - Originated from Oregon State University
- Wind turbine specific (HAWT)
- Structural dynamics and controls
- Combined modal & multibody rep. (modal for blades and tower)
- Up to 24 structural DOFs

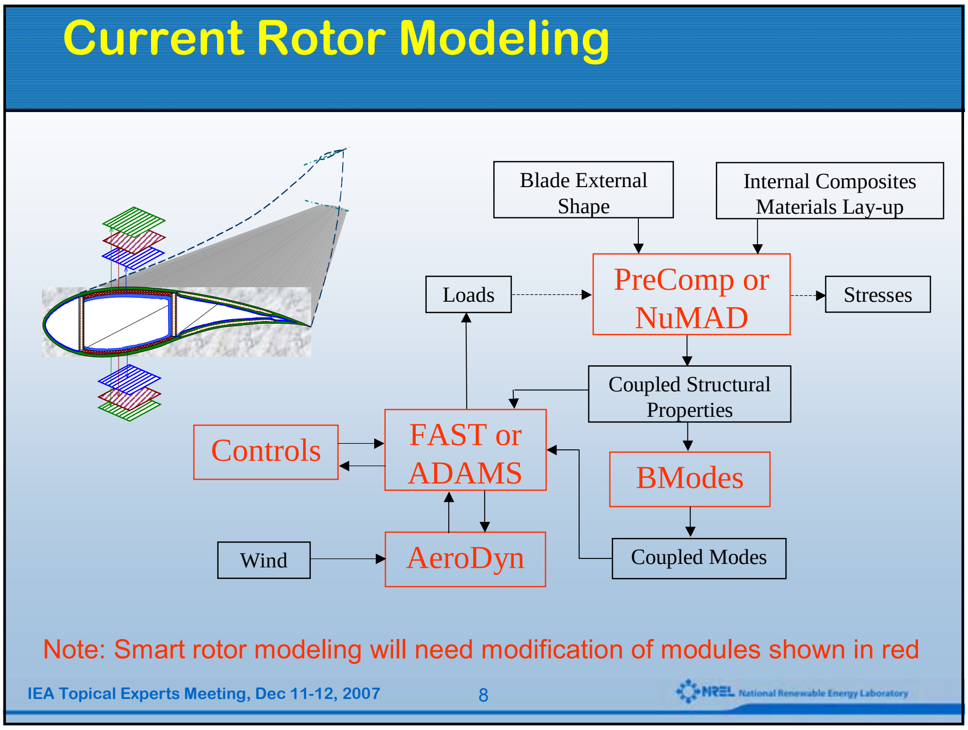
MSC.ADAMS®

- Automatic Dynamic Analysis of Mechanical Systems
- Commercial
  (MSC.Software Corporation)
- General purpose
- Structural dynamics and controls
- Multibody dynamics
- Virtually unlimited structural DOFs
- Datasets created by FAST

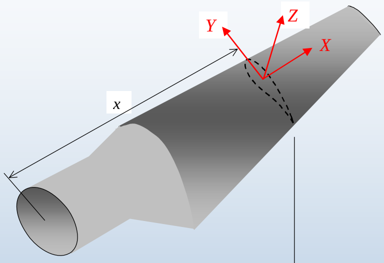
*Both use **AeroDyn** aerodynamics*

- Equilibrium inflow or generalized dynamic wake
- Steady or unsteady aerodynamics
- Aeroelastic interaction with structural DOFs

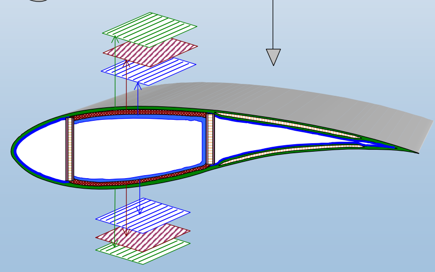

Aeroelastic Modeling
Coupled Aero-Hydro-Servo-Elastic Dynamics
External Conditions
Applied Loads
Wind Turbine
Control System
Wind-Inflow
Aero-dynamics
Rotor Dynamics
Drivetrain Dynamics
Power Generation
Nacelle Dynamics
Tower Dynamics
Waves & Currents
Hydro-dynamics
Platform Dynamics
Mooring Dynamics
IEA Topical Experts Meeting, Dec 11-12, 2007
7
NREL National Renewable Energy Laboratory

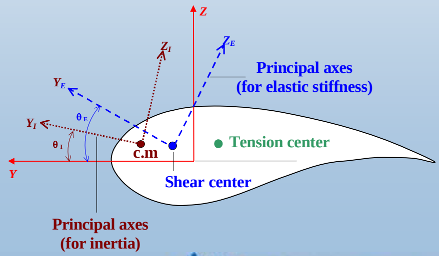

Current Rotor Modeling
Blade External Shape
Internal Composites Materials Lay-up
Loads
PreComp or NuMAD
Stresses
Coupled Structural Properties
Controls
FAST or ADAMS
BModes
Wind
AeroDyn
Coupled Modes
Note: Smart rotor modeling will need modification of modules shown in red
IEA Topical Experts Meeting, Dec 11-12, 2007
8
NREL National Renewable Energy Laboratory

PreComp:
Blade Structural Characterization



$$\begin{Bmatrix} F_X \\ M_Y \\ M_Z \\ T_X \end{Bmatrix} = \underbrace{\begin{bmatrix} \overline{EA} & S_{af} & S_{al} & S_{at} \\ S_{af} & \overline{EI}_{flap} & S_{fl} & S_{ft} \\ S_{al} & S_{fl} & \overline{EI}_{lag} & S_{lt} \\ S_{at} & S_{ft} & S_{lt} & \overline{GJ} \end{bmatrix}}_{\text{Section stiffness matrix}} \begin{Bmatrix} u_e' \\ w'' \\ v'' \\ \theta' \end{Bmatrix}$$





Aeroelastic Code Extensions
Required for Smart Rotors

- Extend PreComp to provide distributed blade structural characteristics using composites with embedded smart materials (structural characterization → relate loading & actuator states to displacement & sensor states)
- Extend AeroDyn (active variation of aero coefficients)
- Interfacing dynamics codes with CFD
- Extend control schemes (nonlinear, adaptive, fault-tolerant)
- Extend FAST equations to include actuator & sensor states and generalized smart-structure properties (UMARC approach?)
- Modify FAST/ADAMS interfaces with PreComp, AeroDyn, and controls

Extended Aeroelastic Code
Applications

- Try different smart structures and techniques
- Perform multi-disciplinary analyses
- Select smart designs which
  - Minimize vibration & loads
  - Enhance performance
  - Improve stability
  - Minimize noise suppression (acoustic and structure-borne)
  - Improve structural integrity and reduce weight/cost
  - Allow improved health monitoring (distributed, inter-linked, real-time, and low-maintenance)

Expectations from this Meeting

- Discussion of promising wind-specific smart technologies
- Public-domain sources for smart materials and properties (e.g., electro-mechanical constituent relations)
- Areas for further research in smart structures and experts in those areas
- Feedback on aeroelastic modeling
- Collaborative programs and research required for a smart rotor development

National Renewable Energy Laboratory

A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

Innovation for Our Energy Future

Turbine Blade Flow Fields and Active Aerodynamic Control

Scott Schreck
NREL's National Wind Technology Center
1617 Cole Boulevard
Golden, CO 80401
scott_schreck@nrel.gov

NREL is operated by Midwest Research Institute • Battelle

Blade Flow Field States

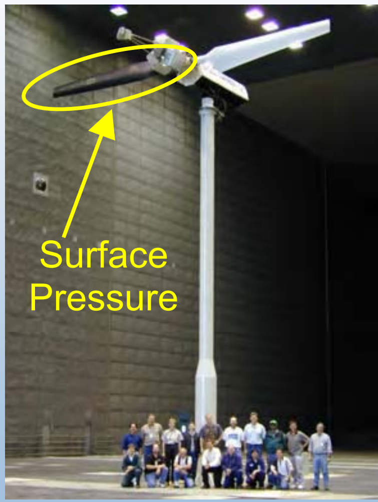
- Relatively benign
  - Zero to low yaw
  - Low angle of attack
- Rotational augmentation
  - Zero to low yaw
  - Moderate to high angle of attack
- Dynamic stall
  - Yaw or spatial wind speed gradients
  - Moderate to high mean angle of attack

National Renewable Energy Laboratory

NREL UAE Data

- NFAC 80' x 120'
- Two blade rotor
- Upwind of tower
- Rigid hub
- Zero cone
- Constant speed

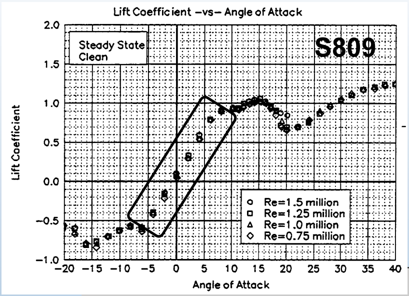
Greatly simplified --- complex flows



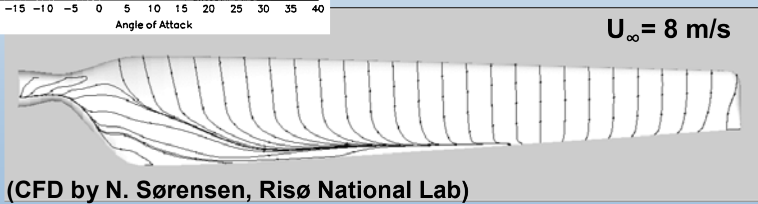
Relatively Benign

(Steady, Attached, Two-Dimensional)

Relatively Benign Flow State



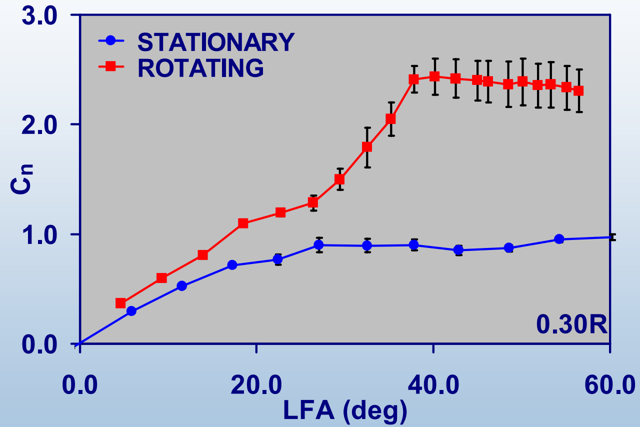
- Linear region of lift curve
- Limited separation extent
- 2-D flow topology



Rotational Augmentation

(Axisymmetric Operation)

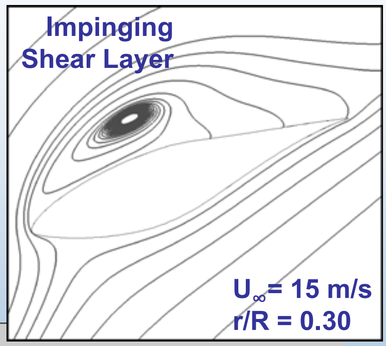
Rotationally Augmented Aero Loads

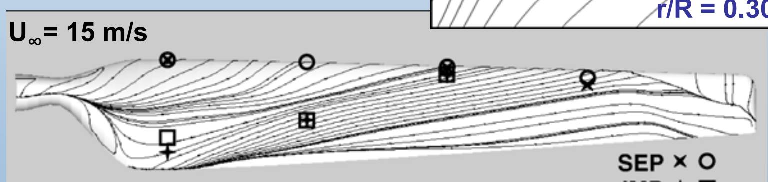


- Rotation augments mean aero loads across span
- Temporal load variations significant, 1 – 10 Hz
- Augmentation dominates broad LFA/α range

Rotationally Augmented Flow Field

- Distinct flow fields
  - Separating B. L.
  - Impinging S. L.
- Flow field evolution
- Abrupt switching
- Load amplification



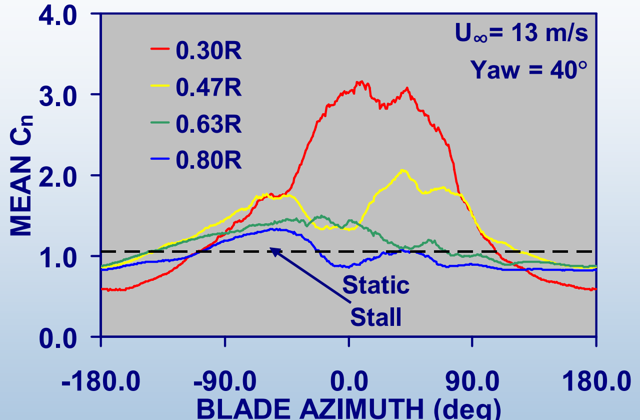


(CFD by N. Sørensen, Risø National Lab)

Dynamic Stall

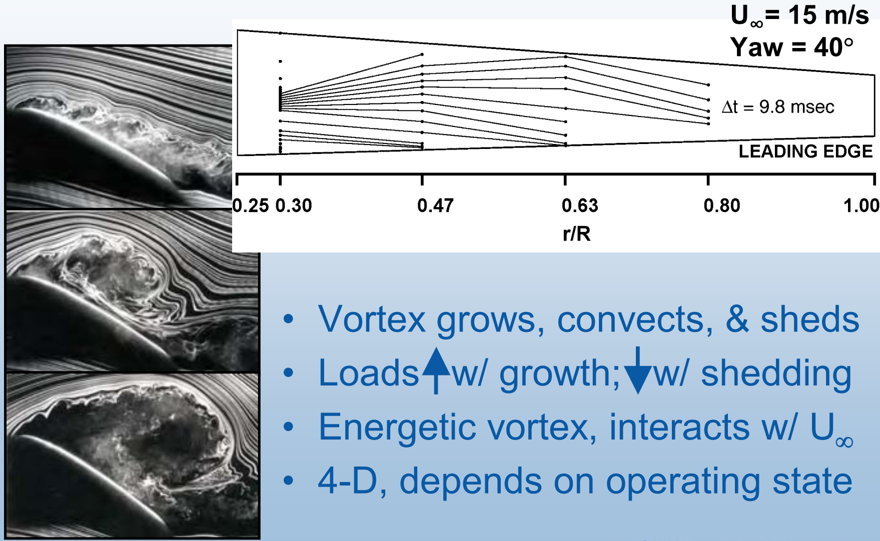
(Yawed Operation)

Dynamic Stall Aero Loads



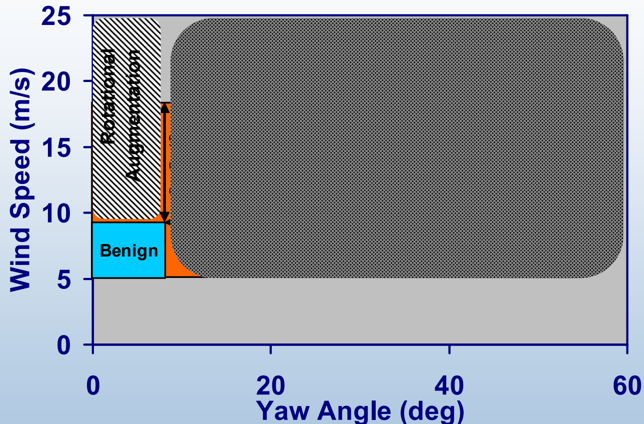
- Mean C_n maxima = 1.5X - 3X static stall levels
- High cycle-to-cycle repeatability
- Rise times = 0.1 - 0.2 sec (1/8 - 1/4 cycle)

Dynamic Stall Flow Field



- Vortex grows, convects, & sheds
- Loads ↑ w/ growth; ↓ w/ shedding
- Energetic vortex, interacts w/ U_∞
- 4-D, depends on operating state

Complex Flow States Prevail



- GL IV-Part 1, Section 2 B External Conditions
- Benign state is small subspace of operating envelope
- Gusts, direction changes drive departure from benign

Summary

- Different blade flow field states
  - Relatively benign
  - Rotationally augmented
  - Dynamically stalled
- Flow field state transition
  - Occurs readily in response to inflow
  - Complex, energetic states favored
- Flow field temporal/spatial scales
  - 0.1c – 1.0c
  - 1 Hz – 10 Hz

NREL National Renewable Energy Laboratory

Implications for Aero Control

- Some pertinent questions
  - Control rotational augmentation, dynamic stall?
  - If yes, are the necessary elements feasible?
  - If no, collateral effects hinder other controls?
- Some initial considerations
  - Actuator selection and placement
  - Sensor selection and placement
  - Controller design and implementation
- Computation and experiments valuable
- Turbine testing will be final determinant

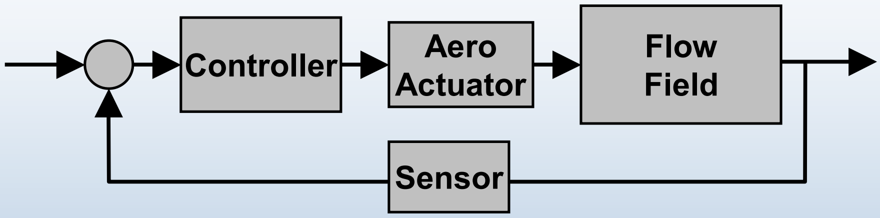
NREL National Renewable Energy Laboratory

Questions or Comments?

Turbine Aerodynamic Load Control

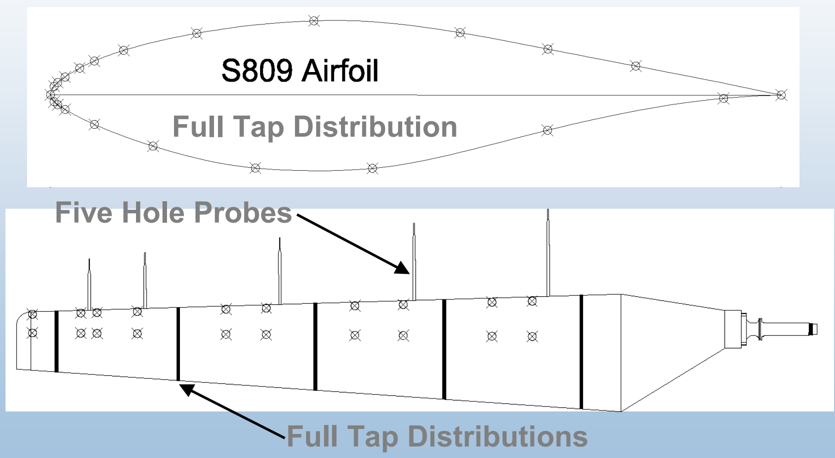
- Evolved design
  - Airfoils, blades
- Passive control
  - Free yaw, teeter
  - Sweep-twist, bend-twist
- Active control
  - Yaw, pitch, rotor (generator) speed
  - Variable diameter rotor
  - Blade flow field control

Active Aero Control Elements

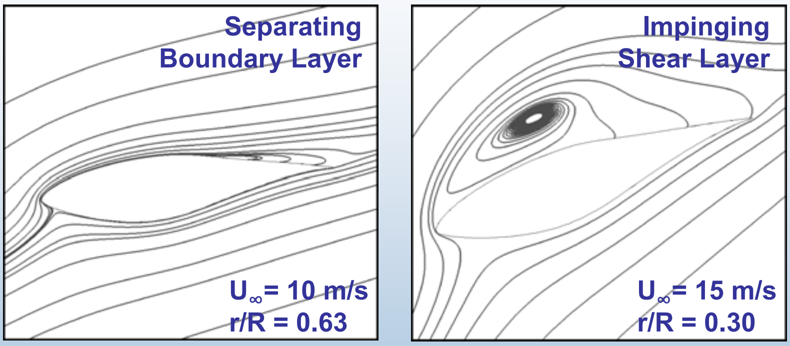


- Inputs/outputs, objective function (loads/AEP)
- Flow field system model (accurate, robust, efficient)
- Aerodynamic actuators (speed, power, size, location)
- Sensors (BW, sensitivity, robustness, placement)
- Controller (linear/nonlinear, single/multiple)

Aerodynamic Data Acquisition



Structures Responsible for Loads

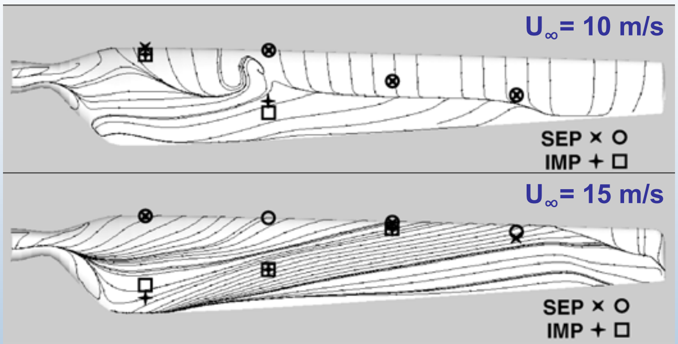


(CFD courtesy of N. Sørensen, Risø National Laboratory)

- Separating boundary layer outboard, lower α
- Impinging shear layer inboard, elevated α
- Disparate flow field modes, abrupt switching
- Vortical structure is large and energetic

NREL National Renewable Energy Laboratory

Flow Field Topology

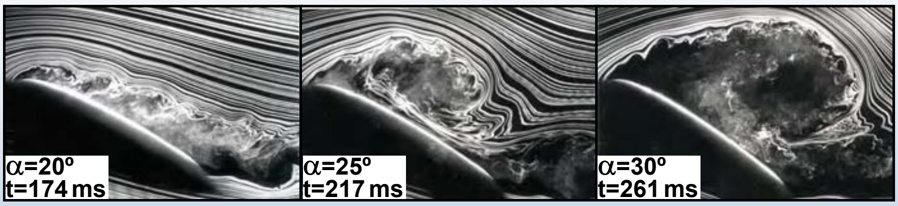


(CFD courtesy of N. Sørensen, Risø National Laboratory)

- Separation and impingement coexist, unsteady state
- Topology highly responsive to operating condition
- Above surface structures correspondingly complex

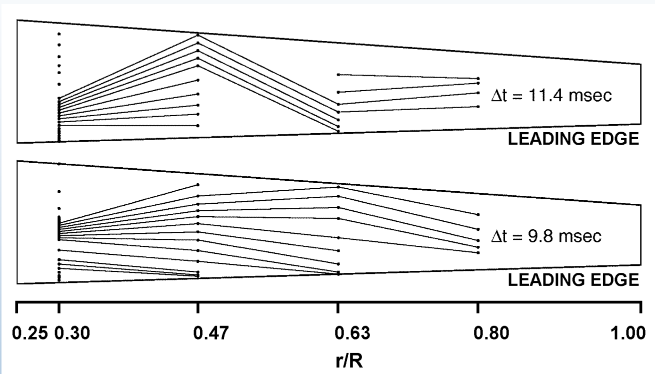
NREL National Renewable Energy Laboratory

Dynamic Stall Flow Field Development



- At nonzero yaw, blade α dynamically rises as rotor turns
- α exceeds static stall threshold, vortex initiates near LE
- Vortex grows, convects aft toward TE, sheds into wake
- Aero loads rise as vortex initiates and grows; fall as it sheds
- Vortex is energetic and interacts strongly with freestream

Flow Field Topology



U_∞ = 13 m/s
Yaw = 30°

U_∞ = 15 m/s
Yaw = 40°

- Dynamic stall vortex convects rapidly from LE to TE
- Vortex convection accompanied by 3-D deformation
- 3-D deformation sensitive to operating condition

Blank page

Collocated Damping of Rotating Wind Turbine Blade

Jan R. Høgsberg & Steen Krenk

Department of Mechanical Engineering
Technical University of Denmark

- Equation of motion in rotating coordinate system
- Beam with geometric stiffness
- System reduction technique for damped system
- Optimal damper properties and attainable damping
- Modal properties of wind turbine blade
- Possible damping devices
- 'Optimal' damping of wind turbine blade
- Control law for adaptive tuning

Agenda

Optimal tuning of damper $\Leftrightarrow$ *Maximum modal damping ratio.*

Wind Turbine Blades

- Flexible structure
- Band limited response
- Damping $=$ modal damping ratio

Dampers

- Passive, active or semi-active dampers
- Collocated configuration
- Viscous damper frequency dependent
- Hysteretic damper amplitude dependent

Equation of motion

Displacement described by shape functions:

$$\mathbf{x} = \mathbf{N}(\mathbf{x}_0 + \mathbf{u})$$

Velocity in rotating co-ordinate system:

$$\mathbf{v} = \mathbf{N}\dot{\mathbf{u}} + \hat{\boldsymbol{\omega}}\mathbf{N}\mathbf{u} + \hat{\boldsymbol{\omega}}\mathbf{N}\mathbf{x}_0$$

Lagrange's equations:

$$\mathbf{M}\ddot{\mathbf{u}} + 2\mathbf{G}_y\dot{\mathbf{u}} + \left(\mathbf{K}_u + \dot{\mathbf{G}}_y - \mathbf{C}_f\right)\mathbf{u} = -\left(\dot{\mathbf{G}}_y - \mathbf{C}_f\right)\mathbf{x}_0$$

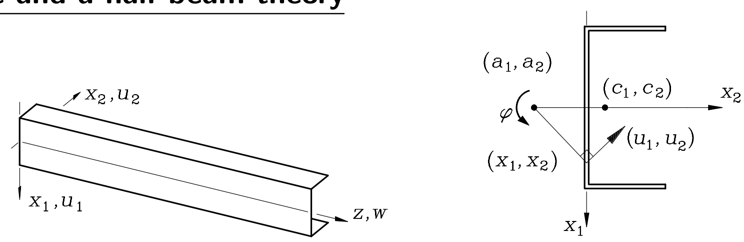
Centrifugal stiffening governed by:

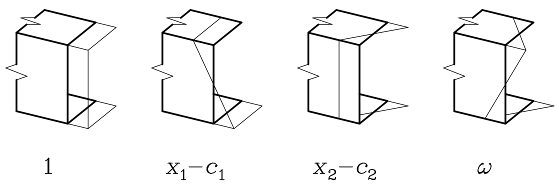
$$\mathbf{K}_u = \mathbf{K}_c + \mathbf{K}_g \qquad , \qquad \left(\dot{\mathbf{G}}_y - \mathbf{C}_f\right)\mathbf{x}_0$$

Centrifugal and gyroscopic matrix:

$$\mathbf{C}_f = \int_{V_0} (\hat{\boldsymbol{\omega}}\mathbf{N})^T \hat{\boldsymbol{\omega}}\mathbf{N}\rho \,\mathrm{d}V \qquad , \qquad \mathbf{G}_y = \int_{V_0} \mathbf{N}^T \hat{\boldsymbol{\omega}}\mathbf{N}\rho \,\mathrm{d}V$$

One-and-a-half beam theory



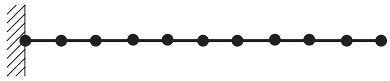


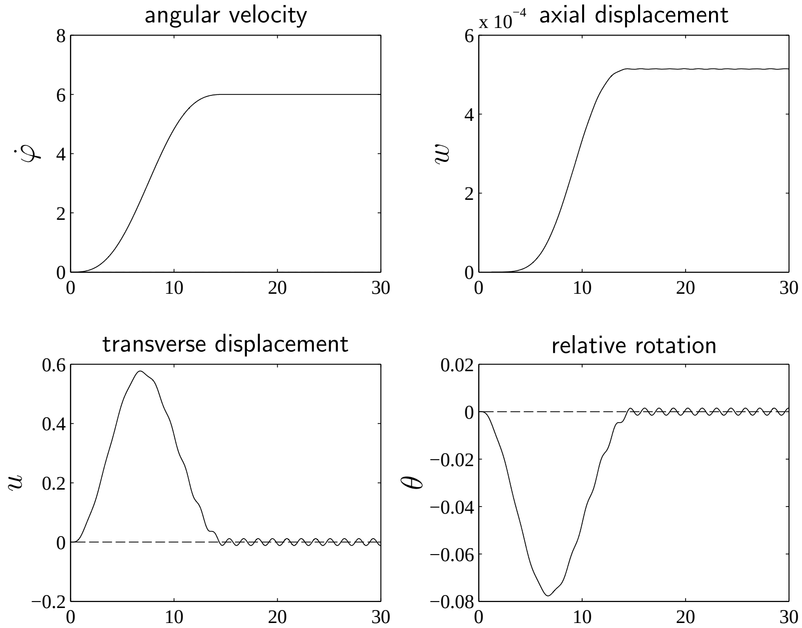
Stiffness matrix with bending-torsion coupling:

$$\mathbf{K} = \mathbf{K}^c + \mathbf{K}^g = \begin{bmatrix} \mathbf{K}^c_\zeta & & & \\ & \mathbf{K}^c_{11} & \mathbf{K}^c_{12} & \\ & \mathbf{K}^c_{21} & \mathbf{K}^c_{22} & \\ & & & \mathbf{K}^c_\varphi \end{bmatrix} + \begin{bmatrix} \mathbf{K}^g_{11} & & \mathbf{K}^g_{1\varphi} \\ & \mathbf{K}^g_{22} & \mathbf{K}^g_{2\varphi} \\ (\mathbf{K}^g_{1\varphi})^T & (\mathbf{K}^g_{2\varphi})^T & \mathbf{K}^g_\varphi \end{bmatrix}$$

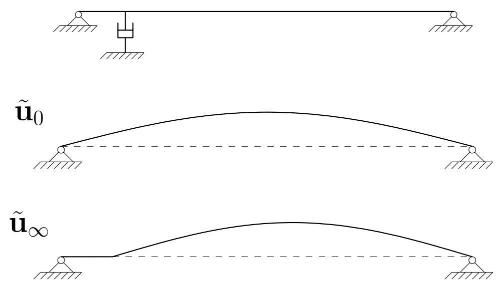
NB: Warping omitted in present formulation.

Kane's driver





System reduction



Two-component representation by *Main & Krenk (2005)*:

$$\mathbf{u}(t) \;=\; \tilde{\mathbf{u}}_0\, r_0(t) \,+\, \tilde{\mathbf{u}}_\infty\, r_\infty(t)$$

– Accurate for: $\Delta\tilde{\mathbf{u}}_\infty^T \mathbf{M} \Delta\tilde{\mathbf{u}}_\infty \ll 1$

– Collocated damper.

– Explicit solution for natural frequency and damping ratio.

– Theory includes several dampers.

Free vibration solution

– Projection on to reduced sub-space.

– Frequency solution: $r(t) = \tilde{r}\exp(i\omega t)$.

– Characteristic equation in complex-valued ω.

Single viscous damper = direct velocity feedback:

$$\mathbf{f}_d \;=\; c_d\,\mathbf{w}\,\dot{u}_d \;=\; c_d\,\mathbf{w}\mathbf{w}^T\dot{\mathbf{u}}$$

Approximate frequency solution from system reduction:

$$\frac{\Delta\omega}{\Delta\omega_\infty} \simeq \frac{i\eta}{1+i\eta} \qquad , \qquad \eta \;=\; c_d\,\frac{(\mathbf{w}^T\mathbf{u}_0)^2}{2\Delta\omega_\infty}$$

Damping ratio:

$$\zeta \;=\; \frac{\mathrm{Im}[\Delta\omega]}{|\omega|} \;\simeq\; \frac{\Delta\omega_\infty}{\omega_0}\,\frac{\eta}{1+\eta^2}$$

Maximum damping for $\eta = 1$:

$$c_d^{opt} \;=\; \frac{2\Delta\omega_\infty}{(\mathbf{w}^T\mathbf{u}_0)^2} \qquad , \qquad \zeta^{max} \;\simeq\; \frac{1}{2}\,\frac{\Delta\omega_\infty}{\omega_0}$$

Limiting modal solutions

– Constant angular velocity: $\hat{\boldsymbol{\omega}} = const.$.

– Neglecting 'gyroscopic' damping.

Deformation from centrifugal effect by quasi-static equation:

$$\mathbf{u}_* \;=\; \big(\,\mathbf{K}_u \;-\; \mathbf{C}_f\,\big)^{-1}\mathbf{C}_f\mathbf{x}_0$$

Stiffening effect into geometric stiffness matrix

$$\mathbf{K}_g \;=\; \mathbf{K}_g(\mathbf{u}_*)$$

Natural frequency given by generalized eigenvalue problem:

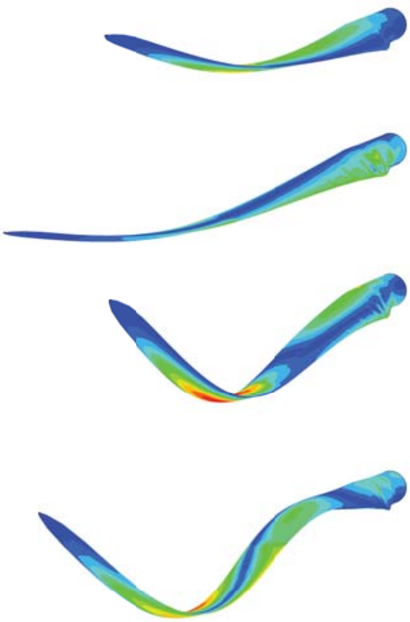
$$\big(\mathbf{K}_c \;+\; \mathbf{K}_g \;-\; \mathbf{C}_f \;-\; \omega^2\mathbf{M}\big)\tilde{\mathbf{u}} \;=\; \mathbf{0}$$

Solution gives limiting mode shapes and frequencies:

$$\big(\,\tilde{\mathbf{u}}_0\,,\,\omega_0\,\big) \qquad , \qquad \big(\,\tilde{\mathbf{u}}_\infty\,,\,\omega_\infty\,\big)$$

NB: Locked solution may be obtained by damper support in $\mathbf{K}_c$.

Natural frequencies and vibration modes



$\omega_1 = 4.60$ rad/s

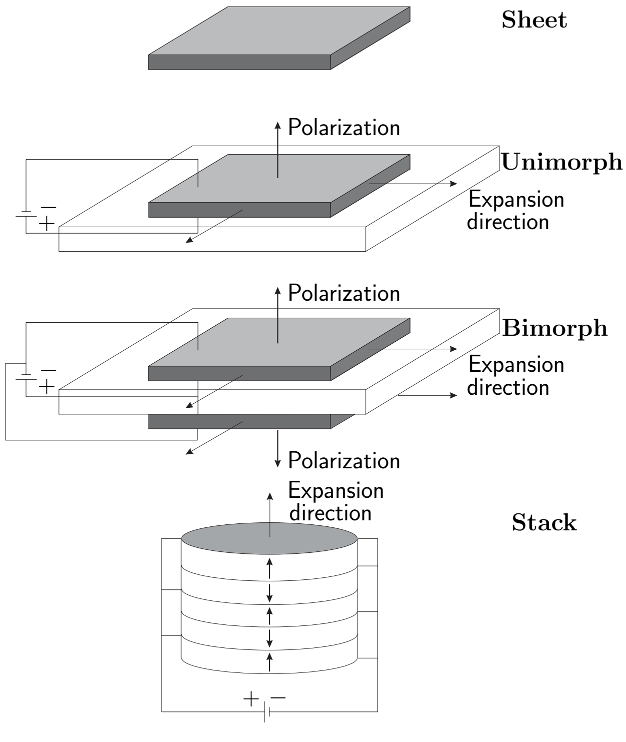
$\omega_2 = 9.37$ rad/s

$\omega_3 = 13.64$ rad/s

$\omega_4 = 29.19$ rad/s

Holm-Jørgensen & Jørgensen (2004), Aalborg University

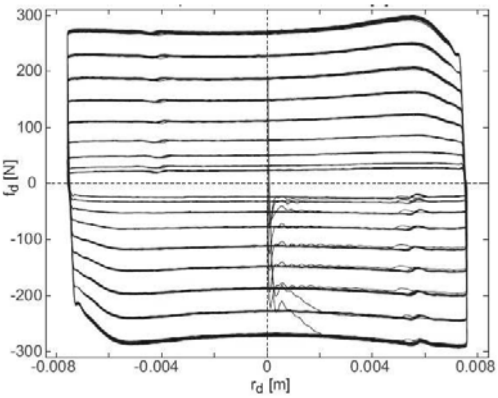
Piezoelectric strips and stacks



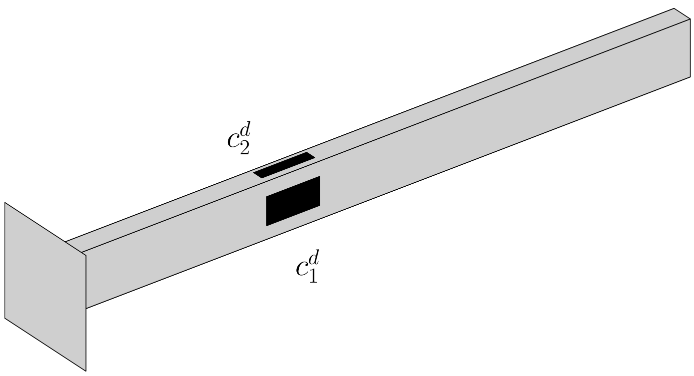
Holm-Jørgensen & Jørgensen (2004), Aalborg University

MR dampers

Magneto-rheological dampers are produced by:
Maurer Söhne Gmbh & Co. KG
and tested and installed in collaboration with Dr. Felix Weber from *EMPA, Zürich*
See *Weber et al. (2005)*



Tuning of piezo-strips with viscous feedback



Rectangular strip $\Rightarrow$ Local bending moment.

Direct velocity feedback:

$$M_d = c_d \, \Delta\dot{\theta} = c_d \, \mathbf{w}^T \dot{\mathbf{u}}$$

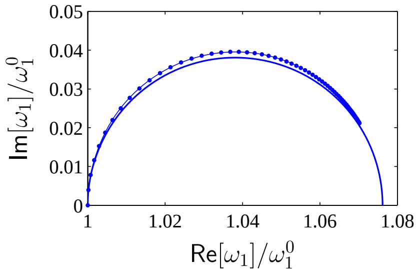
Operational conditions

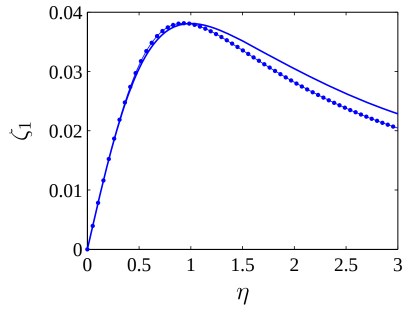
Rotational velocity:

$$\dot{\varphi} = 1.6\,\mathrm{rad/s}$$

Optimal viscous gain and maximum damping:

$$c_d^{opt} = \begin{cases} 9.22 \cdot 10^7 \\ 1.36 \cdot 10^7 \end{cases} \qquad , \qquad \zeta^{max} = 0.038$$





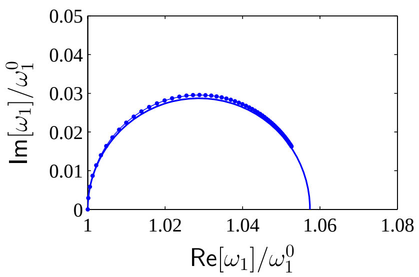
Extreme conditions

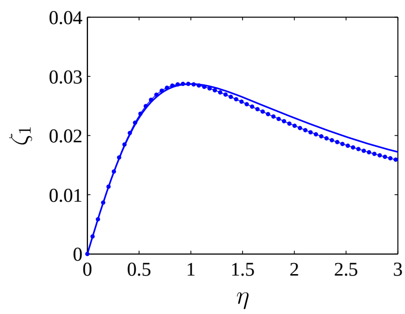
Rotational velocity:

$$\dot{\varphi} = 3.0\,\mathrm{rad/s}$$

Optimal viscous gain:

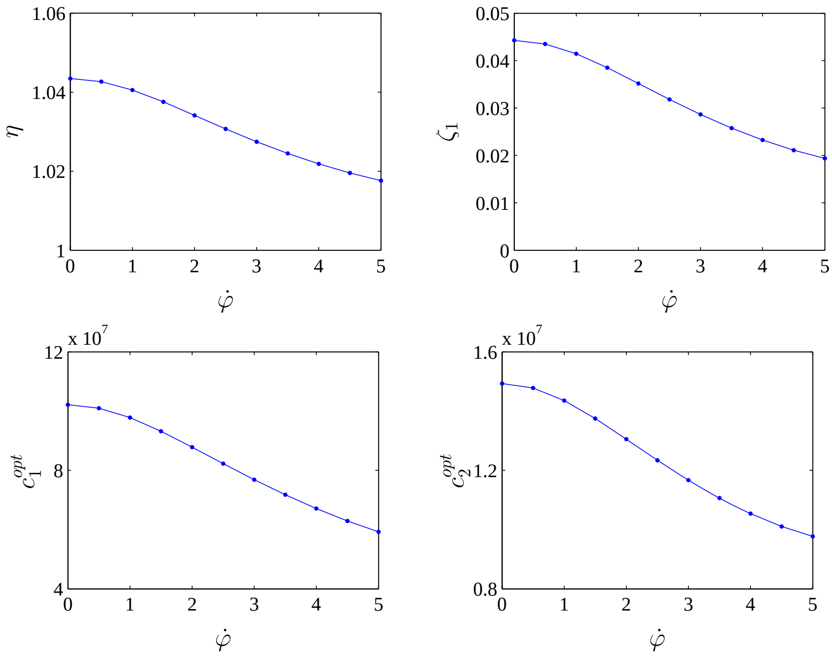
$$c_d^{opt} = \begin{cases} 7.68 \cdot 10^7 \\ 1.17 \cdot 10^7 \end{cases} \qquad , \qquad \zeta^{max} = 0.029$$





Adaptive tuning

... with respect to rotational velocity.



Summary

– Equation of motion

Centrifugal stiffening into geometric stiffness

– Two-component system reduction

Solution for optimal tuning and maximum damping

– Adaptive tuning

Viscous gain with respect to rotational velocity.

Discussion

– Additional damping:

Active damping or nonlinear semi-active damping

Apparent negative stiffness

– Several vibration modes:

Hysteretic dampers: MR or friction dampers

– Stability and energy spill-over

References

[1] J.A. Main, S. Krenk, Efficiency and tuning of viscous dampers on discrete systems, *Journal of Sound and Vibration* 286 (2005) 97–122.

[2] K. Holm-Jørgensen, M. Jørgensen, *Modelling of generator failure of a wind turbine and active control of blade vibrations using smart materials*, Msc thesis, Aalborg University (2004).

[3] F. Weber, G. Feltrin, M. Motavalli, Passive damping of cables with MR dampers, *Materials and Structures* 38 (2005) 568–577.

Blank page

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 actuator choice and modeling

Ben Marrant

PhD Researcher

DUWIND TU Delft

Introduction

Smart rotor concepts:

- Trailing-edge/leading-edge flaps
- MEM tabs
- Active twist
- Inflatable structures
- Part-span/full-span pitch
- Variable camber
- Synthetic jets
- Boundary layer suction
- Aeroelastic tailoring
- Constrained layer damping
- Discrete dampers

Criteria:

- (Aerodynamic) efficiency
- Bandwidth
- Constructability
- Reliability
- Applicability
- Maintainability
- Measurability

DUWIND TU Delft

Smart rotor concepts

Mechanical devices have influence in in-plane direction:

- Discrete dampers

Aerodynamic devices have influence in out-of-plane direction or indirectly in in-plane direction through use of coupling effects

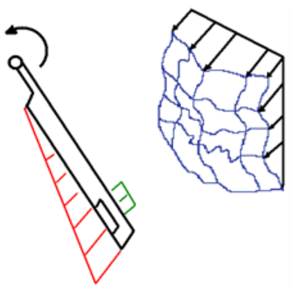
- TE-flaps
- MEM-tabs
- Active twist

Comparison of smart rotor concepts

Wind input: → Variation in aerodynamic moment

•Turbulence

•Wind shear



↓

Smart rotor concept reduces variations

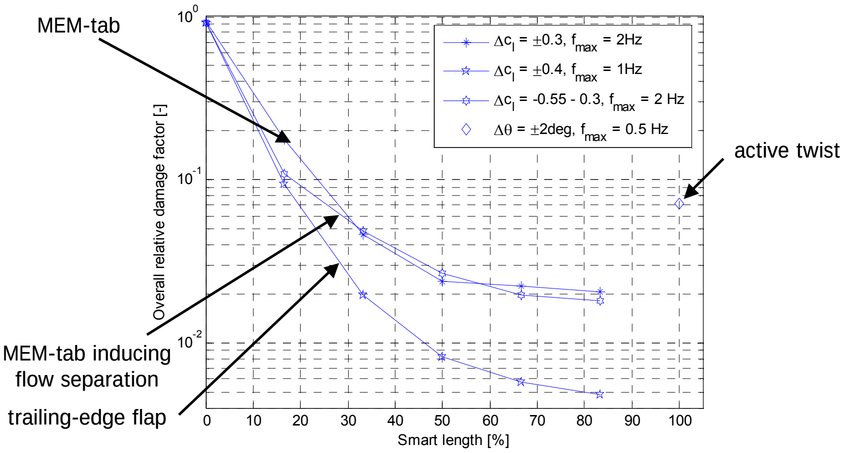
↓

Determination of fatigue damage with rainflow counting

↓

Comparison of concepts

Comparison of smart rotor concepts



DUWIND TU Delft

Modeling

Smart structure models:

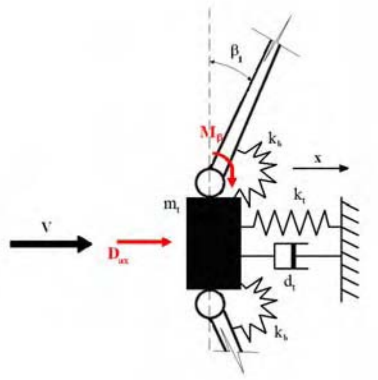
- Simple linear smart wind turbine models
- Non-linear smart blade models

DUWIND TU Delft

Linear smart wind turbine model

Dynamics:

- •Flapping degree of freedom for every blade
- •Torsional degree of freedom for the shaft
- •Translational degree of freedom for the tower

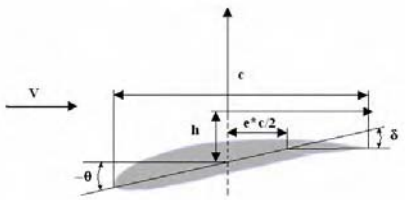


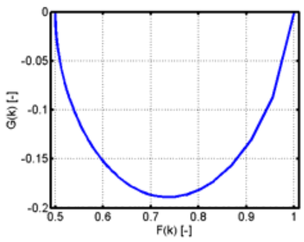
DUWIND TUDelft

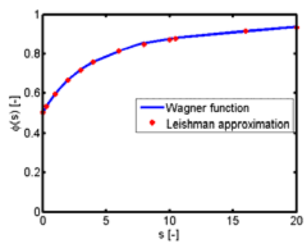
Linear smart wind turbine model

Aerodynamics:

- •Unsteady airfoil models:
  - •Theodorsen model



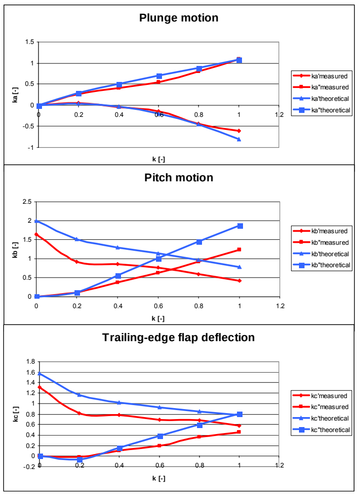




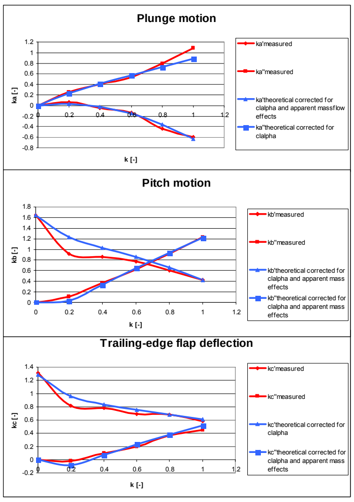
  - •Wagner and Küssner functions
- •Dynamic inflow: quasi-steady

DUWIND TUDelft

Linear smart wind turbine model



Linear smart wind turbine model

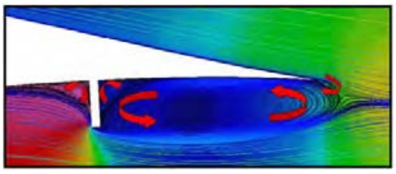


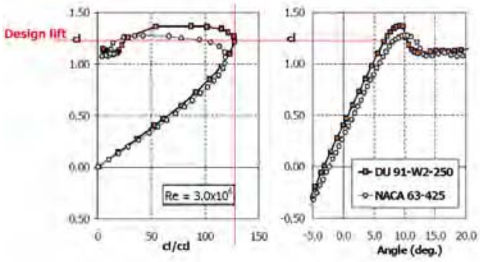
Future work

•Aerodynamic modeling of MEM-tabs in similar way as T.E.-flaps

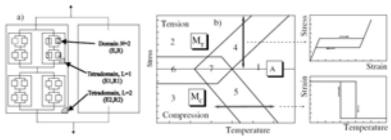
•Comparison of T.E. flaps and MEM-tabs

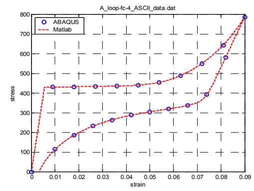
•Unsteady T.E. flap model in the stall region





Questions?

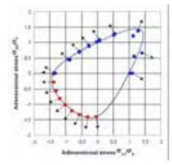


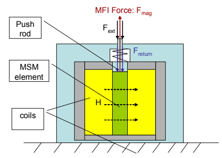


MAFESMA

(Material Algorithms Finite Elements Shape Memory Actuators)

Tools for modeling, design and control of
smart structural systems based on
shape memory alloys (SMA):
Material algorithms,
Finite Element methods, Experiments





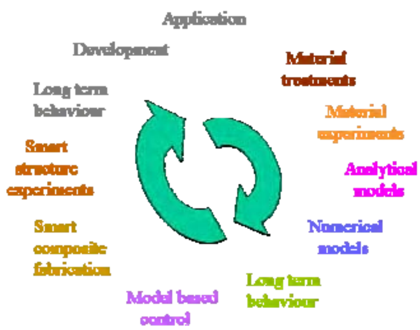
MAFESMA

Collaboration of research groups from four European countries, including some of the top research groups of ordinary SMAs and magnetic shape memory (MSM) alloys

AIM

Bridging the gap between
extending **material knowledge** and the
design of active machines and structures

- Tools for modeling the functional behaviour of SMA/MSM-devices
- Controlling the long term behaviour of SMA/MSM actuators
- Development and control of SMA actuated smart structures, especially smart Fiber Reinforced Polymer composite structures



Background

Embedded structural intelligence

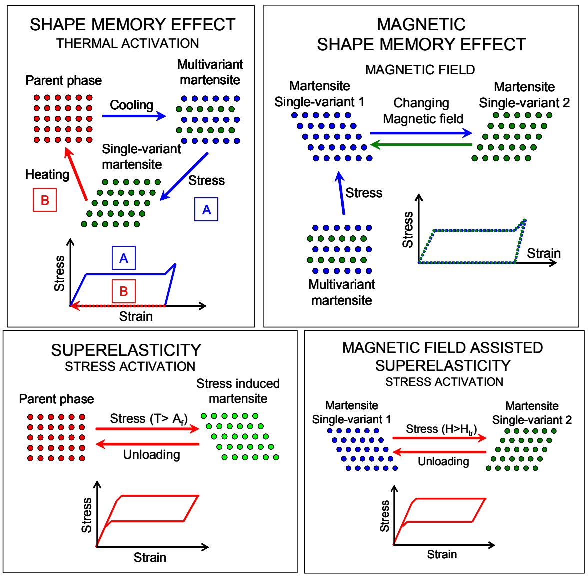
Sensing, decision making, active reaction, communication

↓

Optimum performance, new product concepts, minimized lifecycle costs, adaptation to all operational conditions

SHAPE MEMORY ALLOYS

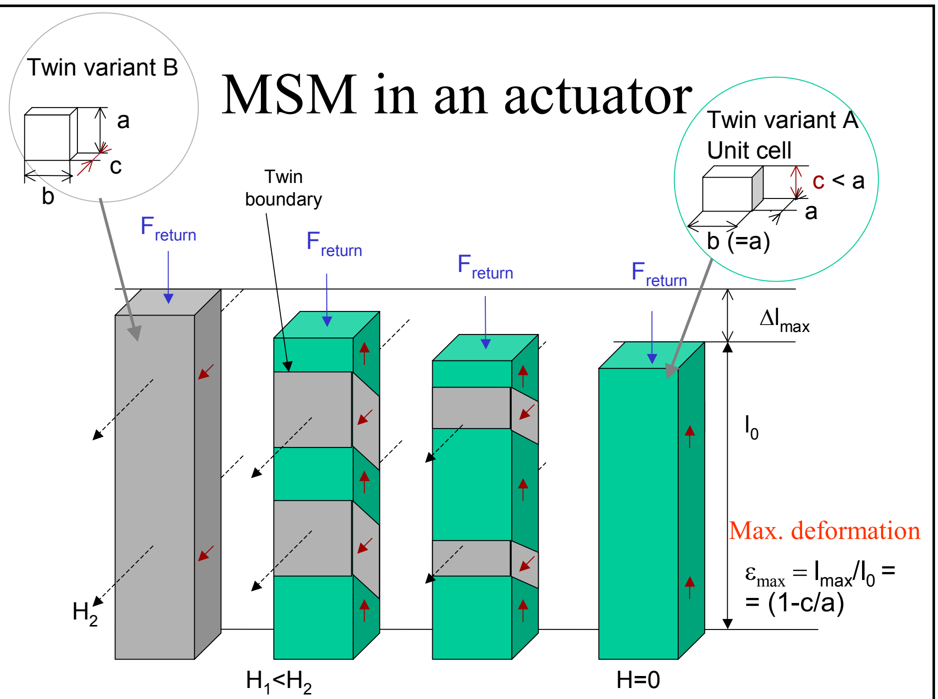
- Metallic alloys that react to changes of temperature or magnetic field by changing their shape - even against considerable force
- Often used as passive or on/off devices, but can also be used as actively controlled actuators or sensors
- MAFESMA project focuses on SMAs as actuators in active devices, especially for shape control and semiactive vibration control



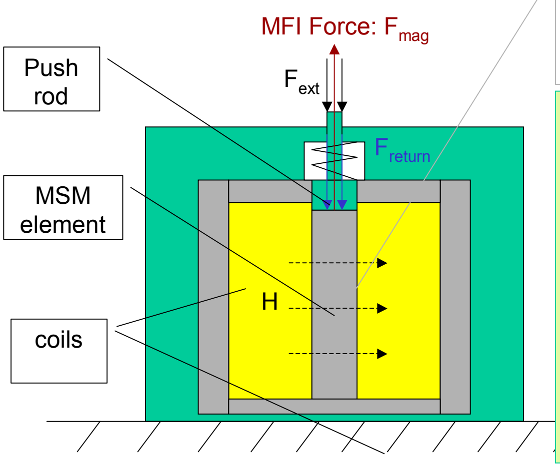
Background - continued

Ordinary Shape Memory Alloys (SMA)	Magnetic Shape Memory alloys (MSM)
Actuation by heating and cooling	Actuation by external magnetic field
Resistive heating needs wiring in the actuator	No wiring needed in the actuation element
most used NiTi, NiTiCu, CuZnAl, CuAlNi	most used Ni-Mn-Ga, also Fe-Pt, Fe-Pd, Co-Ni-Ga
shape memory effect (deformation by detwinning of the martensite, heating to austenite structure for the recovery) or stress induced martensitic phase transformation of the austenitic structure and its recovery (superelasticity)	rearrangement of the twin variants in the martensitic structure in alternating magnetic field; also springlike behaviour in the martensitic structure under constant magnetic field; in some alloys stress induced martensitic phase transformation of the austenitic structure by the magnetic field
actuator usually in tension	actuator usually in compression
NiTi max deformation 8 % practical range < 5 %	Ni-Mn-Ga max deformation 6-10 % practical range < 4 %
max superelastic recoverable strain 15 %	
max stress 800 MPa practical range < 200-300 MPa	max stress < 3 MPa practical range about 1-2 MPa, depending on twinning stress
rather slow (max 5 Hz) (R-phase transformation in thin coatings 100Hz)	rather fast (max 380-500 Hz)
biocompatible	not biocompatible

MSM in an actuator



MSM actuator operation (schematic)



"Twinning stress", σ_{tw}, resists the twin boundary motion

Output

$\sigma_{mech} = \sigma_{mag} - \sigma_{tw}$,

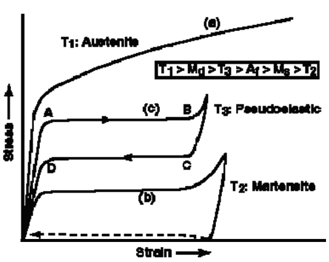
where

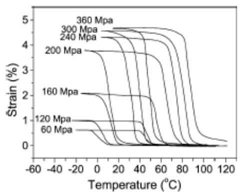
σ_{tw} = twinning stress.,
σ_{mag} = magnetic-field-induced (MFI) stress,
σ_{mech} = opposing external stress (working stress) + returning spring stress.

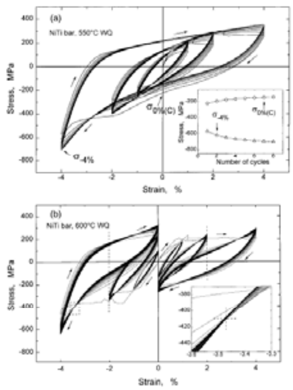
(Likhachev et al. 1999, Heczko et al. 2003)

SMAs - continued

About thermally activated (especially NiTi based) SMAs:
- The deformation of stabilized SMA is a hysteretic function of temperature and stress.
- SMAs behave differently in tension and compression.
- Under cyclic loading stabilized SMA follows a repetitive T,σ,ε path.
- In tension-compression cycling of SMA the dislocations created in compression affect the behaviour in tension.







MAFESMA

Research groups from four European countries, including some of the top research groups of ordinary SMAs and magnetic shape memory (MSM) alloys

Each participating group has co-operation links to many other countries through bilateral or European projects.

The participating groups have several other smart materials and structures related projects belonging to a long term research strategy.

Tasks

Developing tools for modeling the actuation cycles (heating and cooling / magnetic) of stabilized SMA (NiTi based wire and MSM) actuators.

Developing model based control systems for SMA / MSM actuators.

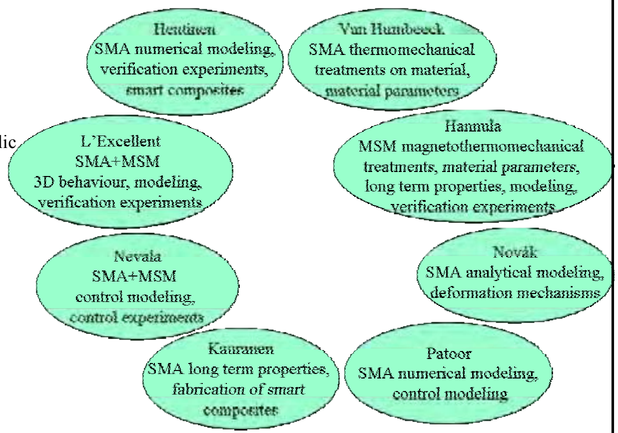
Tools for controlling and modeling the long term behaviour of SMA /MSM actuators.

Developing tools for modeling the time dependent behaviour of SMA actuators and SMA actuated FRP composite structures.

Appropriate experiments to control and sustain the models.

Work breakdown

Project Leader:
Professor Jan Van Humbeeck,
KULeuven, Belgium
Principal Investigators:
Dr Václav Novák
Academy of Sciences of the Czech Republic
Professor Christian L'Excellent
Univ. of Franche-Comte, France
Professor Etienne Patoor
ENSAM, Metz, France
Professor Simo-Pekka Hannula
Helsinki Univ. of Technology
Professor Kalervo Nevala
University of Oulu
Dr Pertti Kauranen
VTT Technical research centre of Finland
Markku Hentinen
VTT Technical research centre of Finland



CONCLUSIONS

- SMAs have much potential that has not been utilized so far
- Most commercial applications are passive or on/off devices
- SMAs are suitable for actively controlled use, especially in shape control and semiactive vibration control
- This project **tackles the bottlenecks** that hinder the design and development of SMA actuated **active** devices, machines and structures

REFERENCES

- Sapozhnikov K., Golyandin S., Kustov S., Schaller R. and **Van Humbeeck J.**, Anelasticity of B19′ martensitic phase in NiTi and NiTiCu alloys, Materials Science and Engineering: A, In Press, Corrected Proof, Available online 24 July 2006.
- **Van Humbeeck J**., Non-medical applications of shape memory alloys, Materials Science and Engineering A, Volumes 273-275 (1999) 134-148.
- Liu Y., Xie Z., **Van Humbeeck J**., Delaey L.: Asymmetry of stress-strain curves under tension and compression for NiTi shape memory alloys, Acta Materialia, Vol 46, No 12, pp. 4325-4338, 1998
- Peultier B., Ben Zineb T., **Patoor E**.: Macroscopic constitutive law of shape memory alloy thermomechanical behaviour, Application to structure computation by FEM, Mechanics of Materials, Vol 38, 2006, pp. 510-524
- **Patoor E.**, Lagoudas D.C., Entchev P.B., Brinson L.C. and Gao X.J., Shape memory alloys, Part I: General properties and modeling of single crystals, Mechanics of Materials 38 (2006) 391-429.
- Calloch S., Taillard K., Arbab Chirani S., **Lexcellent C**. and **Patoor E.**, Relation between the martensite volume fraction and the equivalent transformation strain in shape memory alloys Materials Science and Engineering: A, In Press, Corrected Proof, Available online 30 June 2006.

REFERENCES - continued

- Hirsinger L., Creton N. and **Lexcellent C.,** Stress-induced phase transformations in Ni–Mn–Ga alloys: experiments and modelling, Materials Science and Engineering A 378 (2004) 365-369.
- Taillard K., Calloch S., Bouvet C., **Lexcellent C**.: Determination of phase transformation yield surface of anisotropic shape memory alloys, www.lmt.ens-cachan.fr/PDFs/Taillard.2004.2.pdf
- **Sittner P**., Stalmans R., Tokuda M.: An algorithm for prediction of the hysteretic responses of shape memory alloys, Smart Materials and Structures, Vol 9, 2000, pp. 452-465
- **Novak V., Sittner P**.: A network micromechanics model of thermomechanical behaviors of SMA polycrystals, Scripta Materialia, Vol 50, 2004, pp. 199-206
- **Šittner P.**, **Landa M.**, Lukáš P. and **Novák V.**: R-phase transformation phenomena in thermomechanically loaded NiTi polycrystals, Mechanics of Materials 38 (2006) 475-492
- L. Straka, O. Heczko, and **S-P. Hannula**, Temperature Dependence of Reversible Field-Induced Strain in Ni-Mn-Ga Single Crystals, Scripta Materialia 54 (2006) 1497-1500.

REFERENCES -continued

- I. Aaltio, J. Tellinen, K. Ullakko, **S.-P. Hannula**, Deformation Properties of Magnetic Shape Memory Materials used in Actuators, H. Borgmann (Ed.), Proc. ACTUATOR 2006 pp. 402-405.
- O. Söderberg, Y. Ge, A. Sozinov, **S.–P. Hannula** and V. K. Lindroos, Recent Breakthrough Development of the MSM Effect in Ni-Mn-Ga Alloys, Smart Mater. and Struct. 14 (2005) S223-S235.
- Y. Ge, O. Heczko, O. Söderberg and **S-P Hannula**, Direct optical observation of magnetic domains in Ni- Mn-Ga martensite, Applied Physics Letters 89 (2006) 082502.
- Liedes, T.; Kantola, L.; **Nevala**, **K.**; Klinge, P.; Vessonen, I.: Smart vibration isolation devices, Proceedings of the Smart systems 2005. Seinäjoki, 3 - 4 May 2005. Seinäjoki Technology Centre Ltd., (2005), 1 - 7
- Liedes, T., **Nevala, K.**, 2004. Vibration damping devices using smart materials. Second Artic-Mediterranean Post Graduate Workshop on Intelligent Machines and Transport Systems, March 13 – 21, 2004, Oulu, Finland-Kiiruna, Sweden-Narvik, Norway. Proceedings. 6 p.

REFERENCES - continued

- Virtanen, J., Malila, M., Louhisalmi, Y., Hyvärinen, P., **Nevala, K.**, 2004. Machine vision based fiber optic joint sensor for MR-compatible robot. Proceedings of the 18th International Congress and Exhibition (CARS2004). International Congress Series No. 1268, ISBN:0444517316. Pp. 555 – 560.
- **Sippola M**.: Modelling of GFRP laminate beams with SMA actuators, Research Report BTUO36:051352, 2005, VTT, Espoo, Finland
- Kantola L., Söderstrom P., **Sippola M**.: Increasing the stiffness of a light weight laminate structure utilising Shape Memory Alloy actuators, Nordic Vibration Research Conference, KTH, Stockholm, June 3-4, 2004
- **Some images were taken from:**
- Hodgson D.E., Wu M.H., Biermann R.J.: Shape Memory Alloys, Johnson Matthey, http://www.jmmedical.com/html/_shape_memory_alloys_.html
- Wu X.D., Sun G.J., Wu J.S.: The nonlinear relationship between transformation strain and applied stress for nitinol, Materials Letters, Vol 57, 2003, pp. 1334-1338

Smart Rotor for Wind Turbine Blades - Materials and Structure -

ir. Teun Hulskamp
dr.ir. H.E.N. Bersee

Design and Production of Composite Structures
Faculty of Aerospace Engineering

Introduction
Materials
Wind tunnel
blade design
Conclusions

Introduction

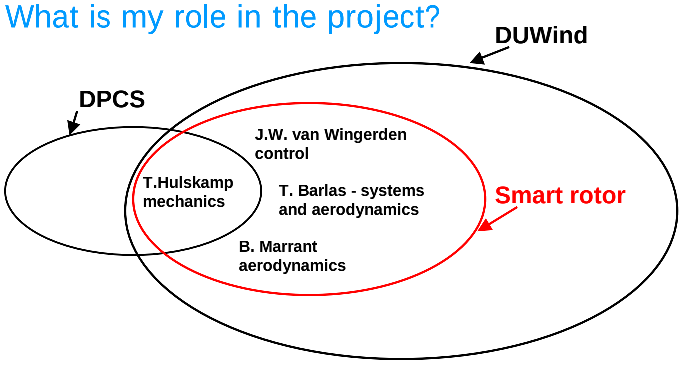
Presentation layout:

- Introduction
- Materials research
  - adaptive materials
  - design lay-out
- Wind tunnel model
- Conclusions

Introduction
Materials
Wind tunnel
blade design
Conclusions

Introduction

What is my role in the project?

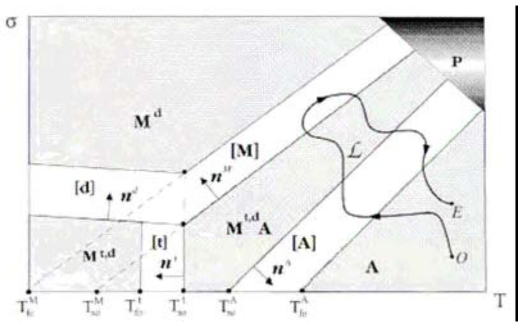


UpWind DUWIND TUDelft

Introduction
Materials
Wind tunnel
blade design
Conclusions

Materials - SMA

Implementing the Brinson model (with "switching points"):

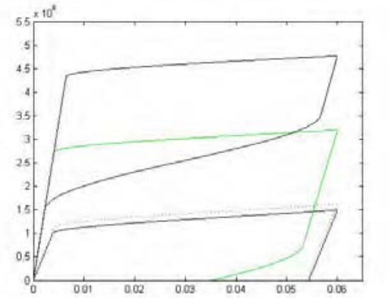


$$\sigma = E(\xi)(\varepsilon - \xi_s \varepsilon_L)$$

UpWind DUWIND TUDelft

Introduction
Materials
Wind tunnel
blade design
Conclusions

Materials - SMA



Problem: stress-controlled

Working on trajectory control

UpWind DUWIND TUDelft

Introduction
Materials
Wind tunnel
blade design
Conclusions

Materials – Piezo benders

We're looking into:
- **Bi-morphs**
- **PBP's**
- **Thunders**
- **LiPCA's**

For Now:
- **Models based on CLPT**
- **Application in wind tunnel experiment model**

UpWind DUWIND TUDelft

Introduction

Materials

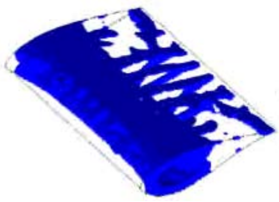
Wind tunnel
blade design

Conclusions

Materials – Lay out

Previous work of Kjelt van Rijswijk and Simon Joncas at our group showed:

- Possibility of thermoplastic composite blades
- Possibility of rib-spar-like construction



Options for load paths and deformable surfaces

UpWind DUWIND TUDelft

Introduction

Materials

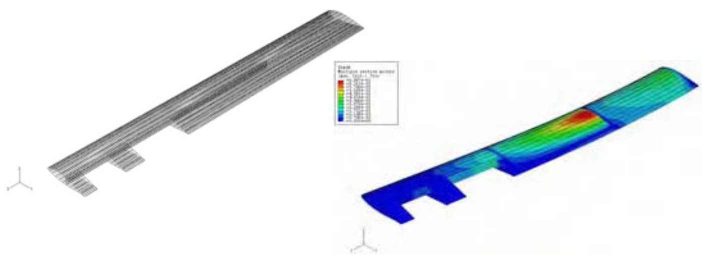
Wind tunnel
blade design

Conclusions

Wind Tunnel Blade Design

Mechanics:

- High strength
- Matching dynamics
- Actuator design and manufacturing
- Manufacturing the blade

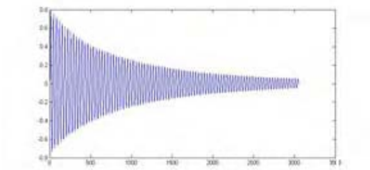


UpWind DUWIND TUDelft

Wind Tunnel Blade Design

Material testing:

- Three point bending to verify glass-epoxy properties
- Vibration testing for dynamic properties



$$\zeta \cong \frac{1}{2\pi j} \ln\left(\frac{x_1}{x_{j+1}}\right)$$

Stiffness proportional damping in FE:

$$\sigma_d = \beta \cdot D_{el} \cdot \dot{\varepsilon}$$

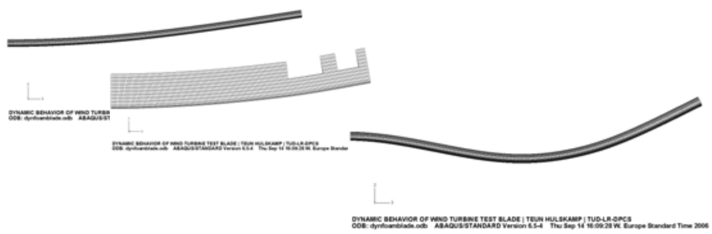
$$\beta = \frac{2\zeta}{\omega_n}$$

UpWind DUWIND TUDelft

Wind Tunnel Blade Design

Matching dynamics: required first eigenfrequency of 10-25Hz.

Both Modal and Direct-solution steady-state dynamic analysis



Calculated first eigenfrequency: 23Hz

UpWind DUWIND TUDelft

Introduction

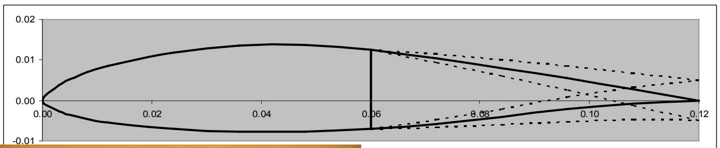
Materials

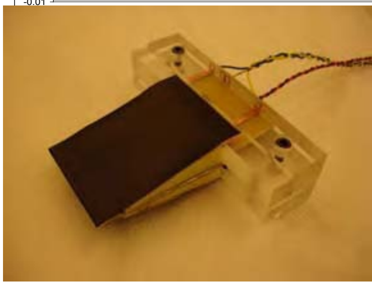
Wind tunnel
blade design

Conclusions

Wind Tunnel Blade Design

Actuator design:





Introduction

Materials

Wind tunnel
blade design

Conclusions

Conclusions

Results:

- Preliminary material models
- Ideas for structural lay out
- Work on wind tunnel test model

Thank you for your attention, and…

?

Questions?

Blank page

An example for adaptive technology

Andreas Knauer, IFE
December 2006

IFE

Transonic airfoils

Transonic airfoils on civil airplanes are subjected to considerable changes in operational conditions. During the flight are varied height, mass and speed. On airfoil sections, this is variation of:

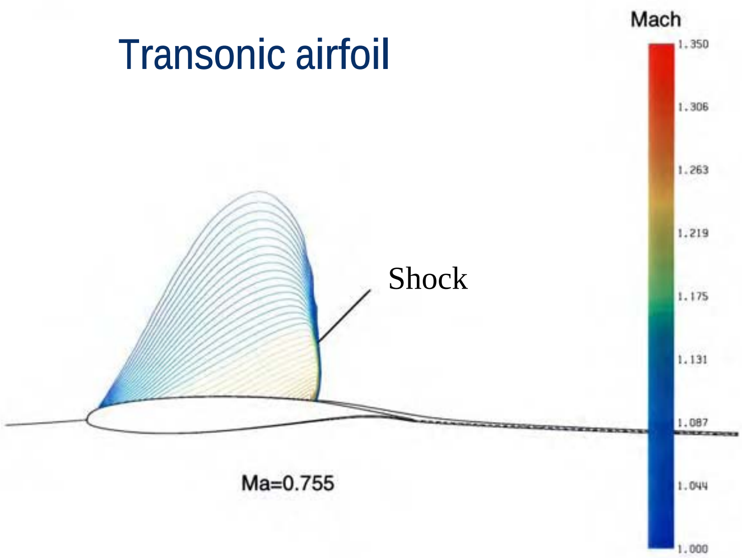
- Reynolds number
- Mach number
- Lift coefficient

Aim of the following investigation was the optimisation of the aerodynamic performance from cruise speed to slight off-design points.

The work was carried out at DLR Göttingen, as part of the ADIF project.

IFE

Transonic airfoil

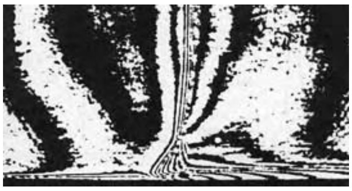


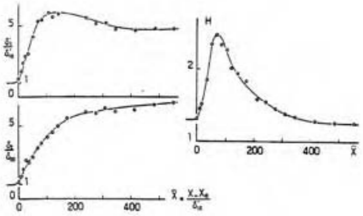
Shock/Boundary-layer interaction

The boundary layer is altered:

- Displacement thickness
- Impulse thickness
- Form parameter H

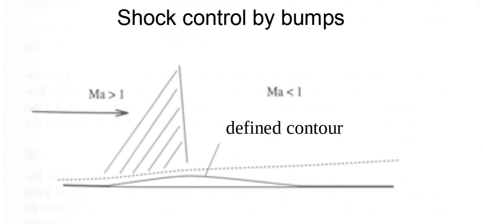
increase considerable.

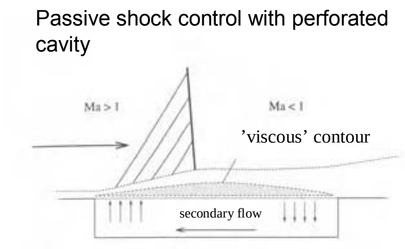




Two methods for shock control:

- Contour bumps
- Viscous bumps



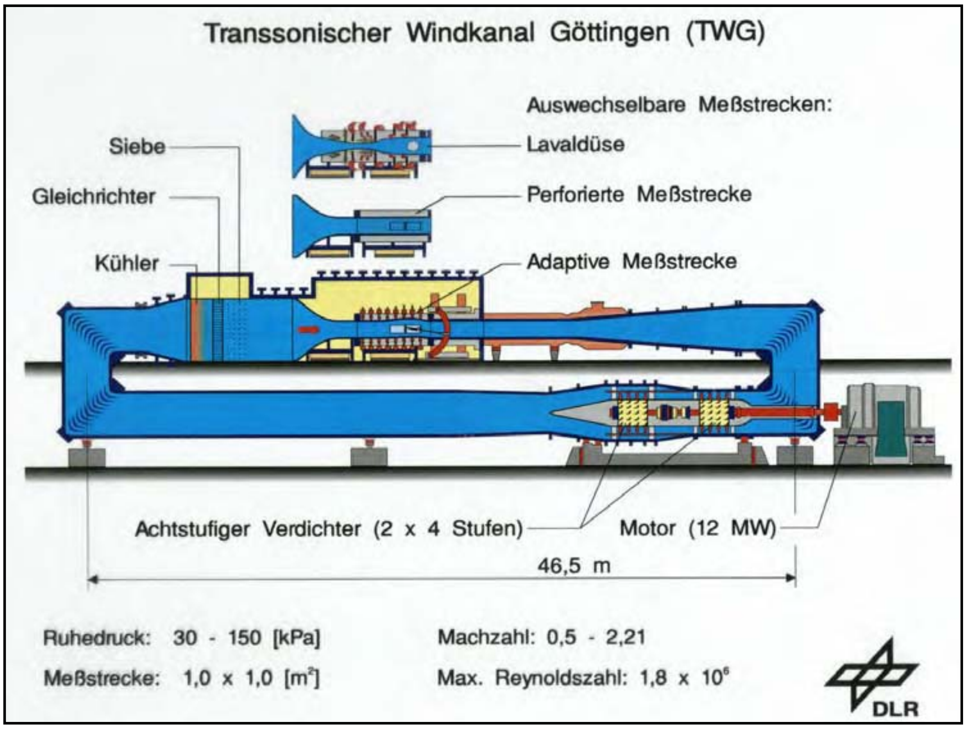


Activities

Part 1: Experimental investigation of passive shock control (with existing model VA-2).

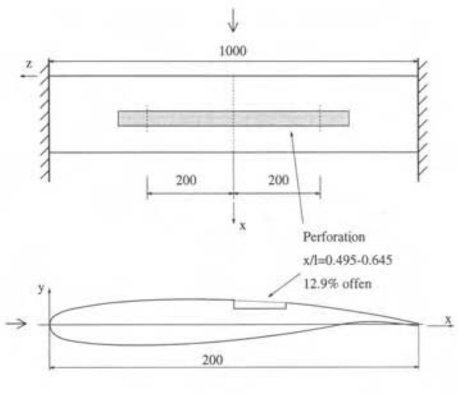
Part 2: Numerical design of contour bumps with MSES code on ADIF profile (Airbus A340).

Part 3: Experimental investigation of contour bumps on ADIF profile.

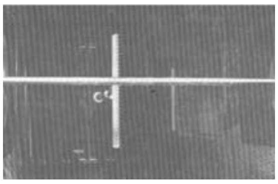


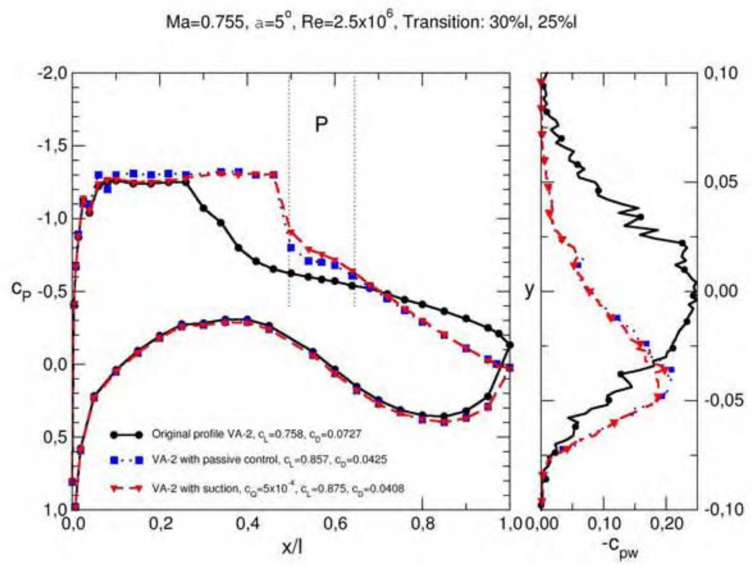
Transsonischer Windkanal Göttingen (TWG)
Auswechselbare Meßstrecken:
Lavaldüse
Perforierte Meßstrecke
Adaptive Meßstrecke
Siebe
Gleichrichter
Kühler
Achtstufiger Verdichter (2 x 4 Stufen)
Motor (12 MW)
46,5 m
Ruhedruck: 30 - 150 [kPa]
Meßstrecke: 1,0 x 1,0 [m²]
Machzahl: 0,5 - 2,21
Max. Reynoldszahl: 1,8 x 10⁶
DLR

Model VA-2



1000
z
200
200
x
Perforation
x/l=0.495-0.645
12.9% offen
y
x
200





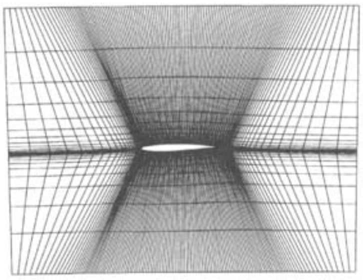
Conclusion: Passive control

Passive control increases the airfoil's performance by delaying stall and amplifying maximum lift.

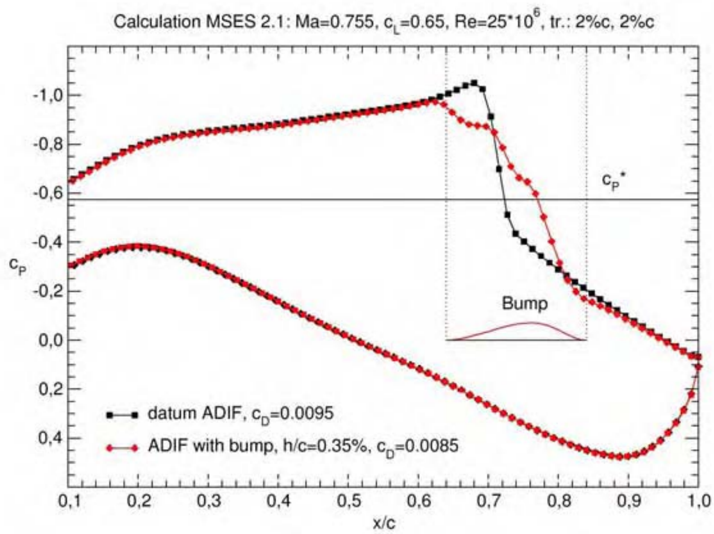
Drag reductions were not observed.

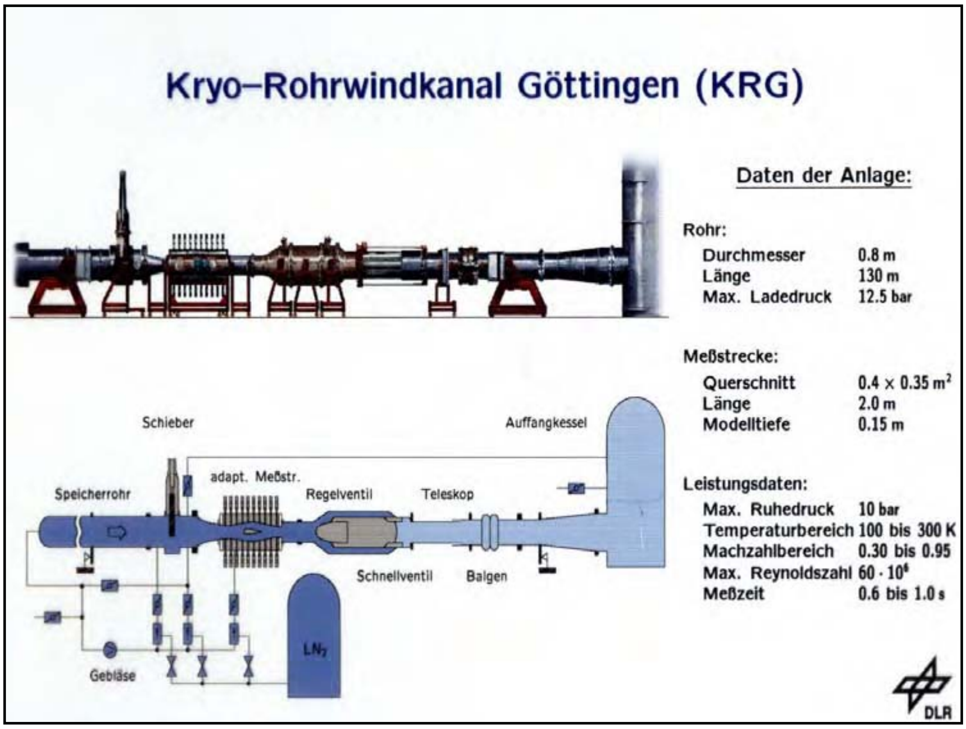
The maximum lift/drag ratio is not increased by passive control.

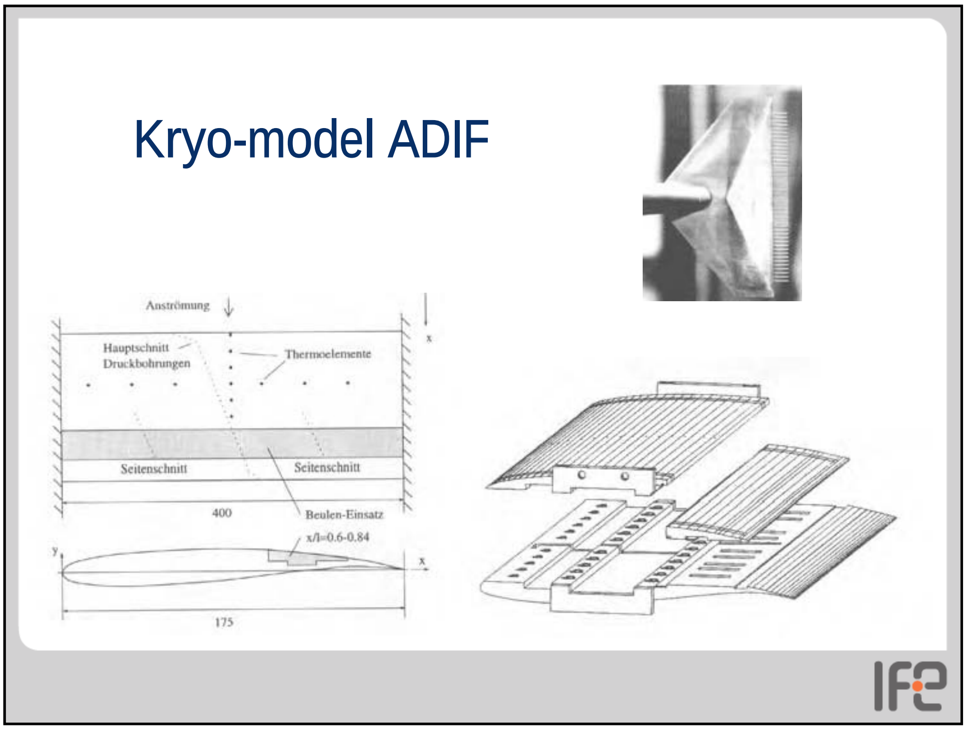
Numerical investigations: ADIF profile / MSES code

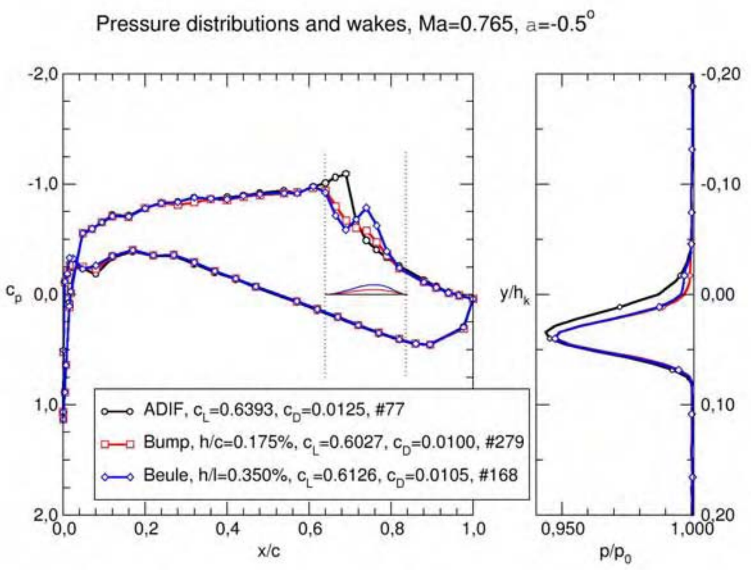


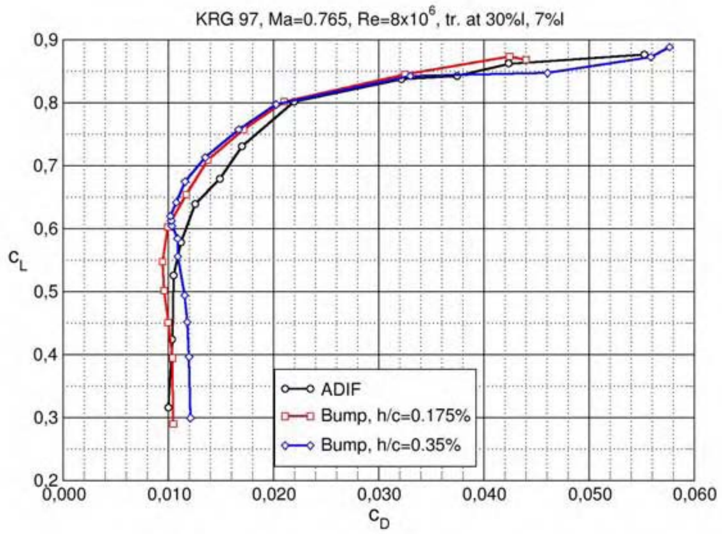
Ma(2D)	CL(2D)	Note
0.735	0.7	Design (wave drag < 0.0001)
0.735	0.8	Drag rise (wave drag > 0.0010)
0.755		Off-design
0.775		Off-design




Kryo–Rohrwindkanal Göttingen (KRG)
Daten der Anlage:
Rohr:
Durchmesser 0.8 m
Länge 130 m
Max. Ladedruck 12.5 bar
Meßstrecke:
Querschnitt 0.4 × 0.35 m²
Länge 2.0 m
Modelltiefe 0.15 m
Leistungsdaten:
Max. Ruhedruck 10 bar
Temperaturbereich 100 bis 300 K
Machzahlbereich 0.30 bis 0.95
Max. Reynoldszahl 60 · 10⁶
Meßzeit 0.6 bis 1.0 s
Schieber
Auffangkessel
adapt. Meßstr.
Speicherrohr
Regelventil
Teleskop
Schnellventil
Balgen
LN₂
Gebläse
DLR

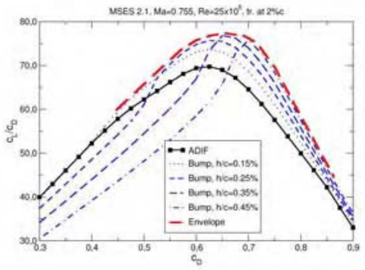

Kryo-model ADIF
Anströmung
Hauptschnitt
Druckbohrungen
Thermoelemente
Seitenschnitt
Seitenschnitt
400
Beulen-Einsatz
x/l=0.6-0.84
175

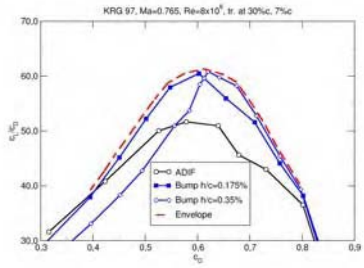

Pressure distributions and wakes, Ma=0.765, a=-0.5°
c_p
x/c
y/h_k
p/p_0
ADIF, c_L=0.6393, c_D=0.0125, #77
Bump, h/c=0.175%, c_L=0.6027, c_D=0.0100, #279
Beule, h/l=0.350%, c_L=0.6126, c_D=0.0105, #168


KRG 97, Ma=0.765, Re=8x10^6, tr. at 30%l, 7%l
c_L
c_D
ADIF
Bump, h/c=0.175%
Bump, h/c=0.35%

Conclusion Bumps

- Optimised 'Bumps' increase the performance, drag reductions of up to 25% were measured.
- Aerodynamic performance can be enhanced in a broad operation range.
- For adaptive solutions, envelopes appear at polars and L/D-ratios.





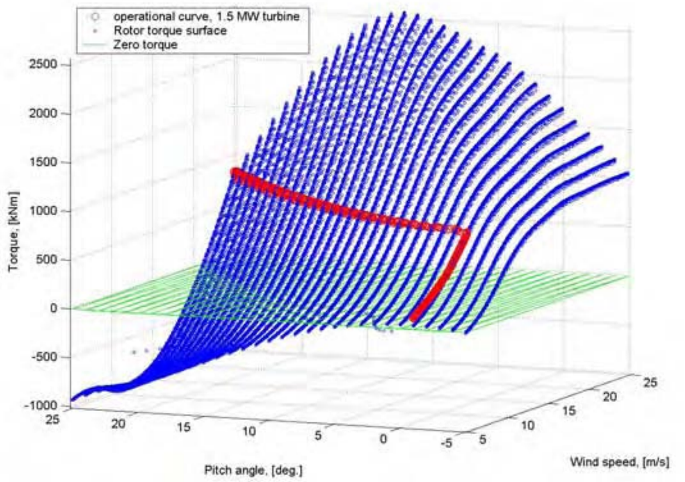
Wind turbine technology

Rotorblades

- 'Clean' blade structure
- Add-ons
- Winglets

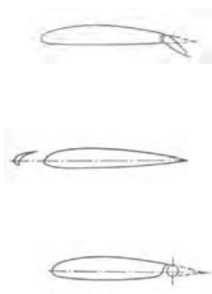
Smart structures to be tested…

Torque generation of a 1.5 MW turbine



Methods for lift modifications

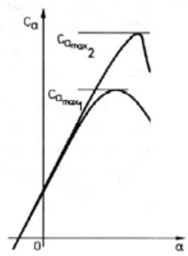
- Blade pitching (individual blade mass: 5 – xx tons)
- Flaps (structure modifications, reliability)
- Slots (structure modifications, reliability)
- Add-ons (small masses, BL modification)
- Ventilation (BL-modification)



Vortex generators

VG's give a delay of separation.

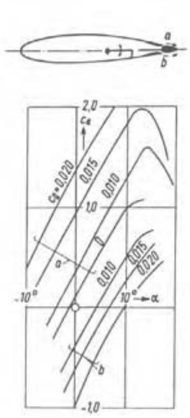
This results in the elongation of the linear part of the lift curve until the VG location has separated flow.

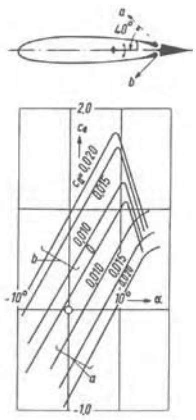


Lift amplification

Blow-out

- Thin slot at trailing edge 'energizes' BL
- Cq > 0.001 effective
- Pressure side slot might simulate flap





Outlook

For modification of the aerodynamic characteristics of rotorblades, methods focusing on boundary layer manipulation should be regarded too.

Add-ons: Masses of smart add-ons (VGs, Gurney flaps) are some magnitudes less than rotorblade mass, effect on lift can be considerable.

BL- ventilation: No moving masses, but large compressor necessary, effect on lift can be considerable.

Techniques might be used to adapt the blade to different operational conditions and to decrease loads.

Modeling of a 'Smart' rotor from the control point of view

Expert-meeting:
Jan-Willem van Wingerden
Michel Verhaegen

With input from:

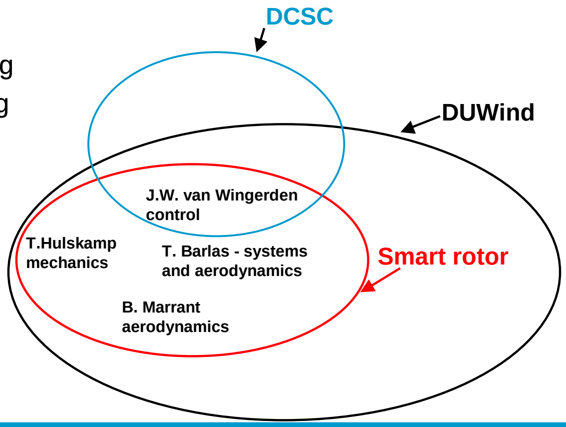
Teun Hulskamp
Gijs Hulscher
Ivo Houtzager

Delft Center for Systems and Control

Delft University of Technology

Outline

- Introduction
- First principal modeling
- Experimental modeling
- Wrap-up



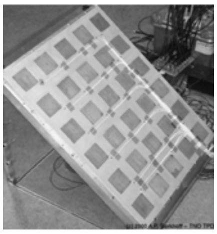
Introduction

When is a structure 'Smart'?

'Smart' rotor control of large offshore wind turbines

Introduction

'Smart' panel



- Actuator
- Sensor
- Feedback Controller
- Other Hardware

} 'Smart' structure

Wafer stage

Introduction

When is a structure 'Smart'?

'Smart' rotor control of large offshore wind turbines

What do we need for control?

What is control?

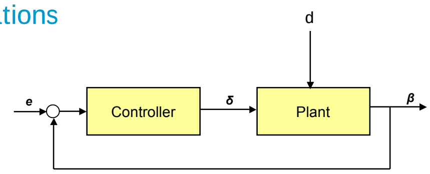
Introduction: Control

What is control: Prescribe the dynamic behavior of the system

Smart Rotor: No vibrations

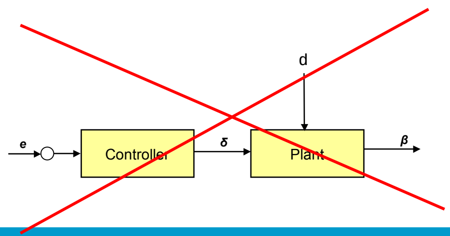
How to do this:

- Feedback control



- Feedforward control

Smart Rotor:



Introduction: Control

How to design a feedback controller:

- A number of design methodologies are available
- Most of them require: mathematical model

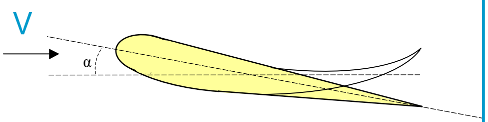
Mathematical model:

- Most dominant dynamics in the input-output behavior
- Certain framework: LTI, LPV, Bilinear

The focus of the rest of the presentation is on the modeling for control

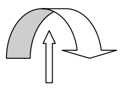
First Principle modeling

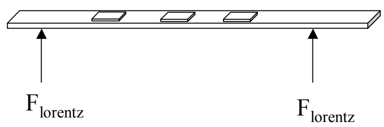
2D-airfoil (model RISØ)



- 2D airfoil with piezo flap
- Objective: Reduction of the vibrations
- Requires: -Aerodynamics -Mechanics -Electronics

Beam with piezo's

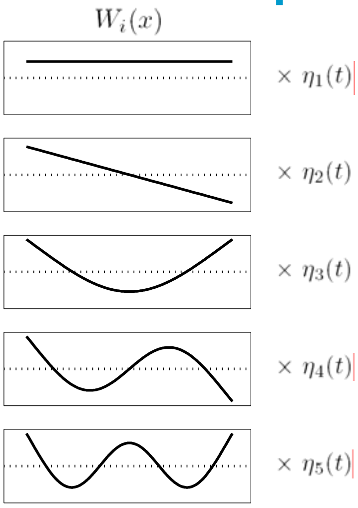




- 2 dof motion system
- Objective: Positioning and reduction of the vibrations
- Requires: - Mechanics - Electronics

Typical Response of a badly damped system

First Principle modeling: Mechanics



Modal approach:

- Linear combination of modes

$$w(x,t) = \sum_{i=0}^{\infty} W_i(x)\eta_i(t)$$

- Coupling with the forces:

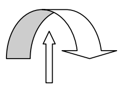
$$N_i = \int_x W_i \mathcal{F} dx$$

- Complete dynamics

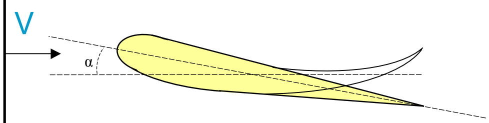
$$\frac{d}{dt}\begin{pmatrix}\eta \\ \dot{\eta}\end{pmatrix} = \begin{pmatrix}0 & I \\ -\omega^2 & -2\zeta\omega\end{pmatrix}\begin{pmatrix}\eta \\ \dot{\eta}\end{pmatrix} + \begin{pmatrix}0 \\ N\end{pmatrix} u$$

$$y = \begin{pmatrix} Q & 0 \end{pmatrix}\begin{pmatrix}\eta \\ \dot{\eta}\end{pmatrix}$$

First Principle modeling



2D-airfoil (model RISØ)

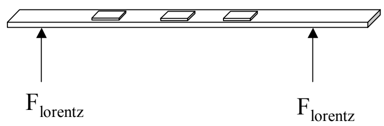


- Coupling with the aerodynamics
- Linear Parameter Varying (LPV)

$$\begin{aligned}\dot{x} &= (A_0 + A_1 \otimes V + A_2 \otimes V^2)\,x + BV_{piezo} \\ y &= Cx\end{aligned}$$

- Non-Minimum Phase
- A large number of assumptions made

Beam with piezo's



- Multiple Input Multiple Output (MIMO)
- Linear Time Invariant (LTI)

$$\begin{aligned}\dot{x} &= Ax + B\begin{pmatrix}V_{piezo,1} \\ \vdots \\ V_{piezo,n}\end{pmatrix} \\ y &= Cx + D\begin{pmatrix}V_{piezo,1} \\ \vdots \\ V_{piezo,n}\end{pmatrix}\end{aligned}$$

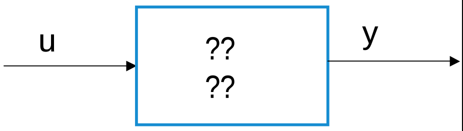
A number of design methodologies are available to design controllers for these kind of models. However, how accurate is your model?

Experimental modeling

Experimental modeling (system identification):
Given input output data reconstruct a mathematical model

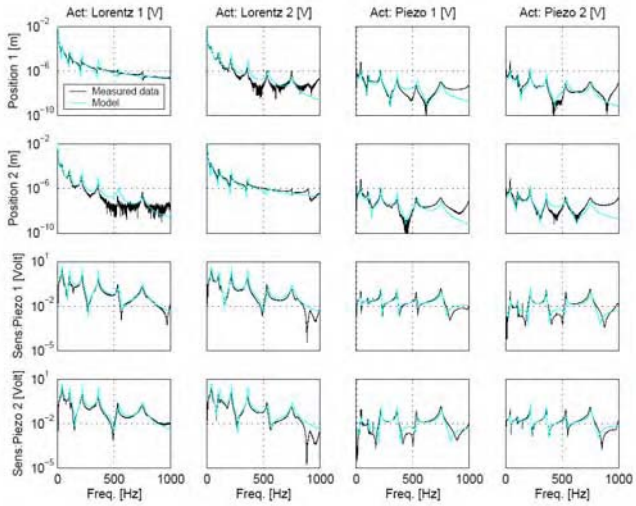
Reasons for doing experimental modeling
- Accurate
- Fast
- For validation or fine tuning of your dynamical model
- Only the most dominant dynamics is present
- Can directly be used for control

We use: Subspace identification
- Can handle MIMO system
- Numerically robust (LQR, SVD)
- No optimization



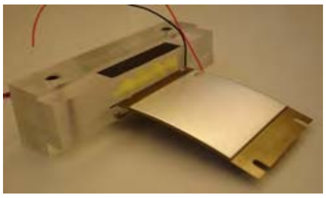
Experimental modeling

Experimental vs Analytical Modeling of 'Smart' beam

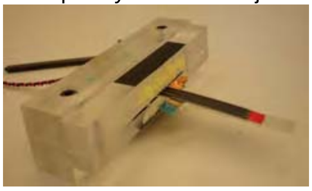


Experimental modeling: Piezo bender

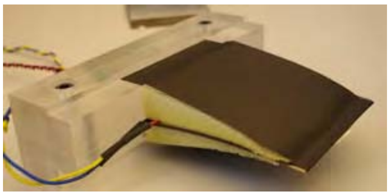
Developed by: Teun and Gijs



Thunder



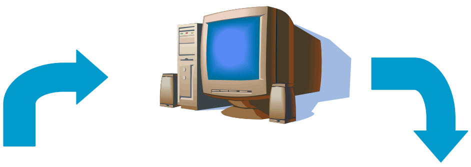
‘Lipca’ (first proto-type)

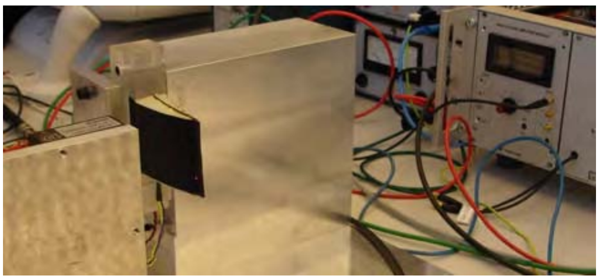


Thunder (with skin)

‘Piezo’ (first proto-type)

Experimental modeling: Real-time environment

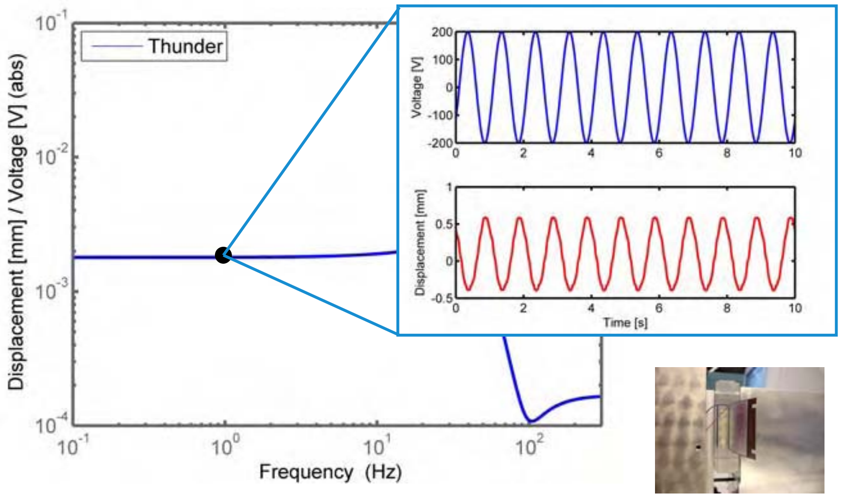




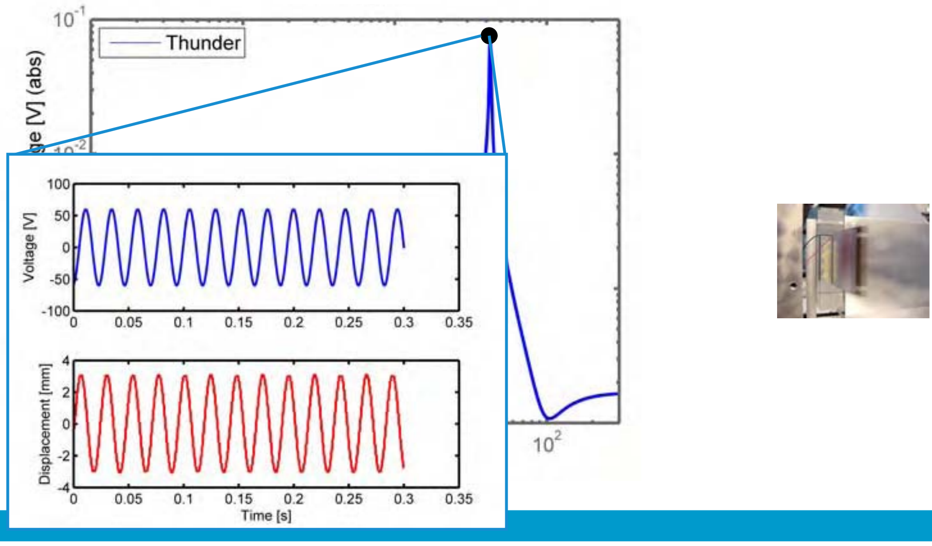
DSPACE

- Based on matlab simulink
- User friendly
- Fs > 100 kHz
- Hard real-time control (no buffers)

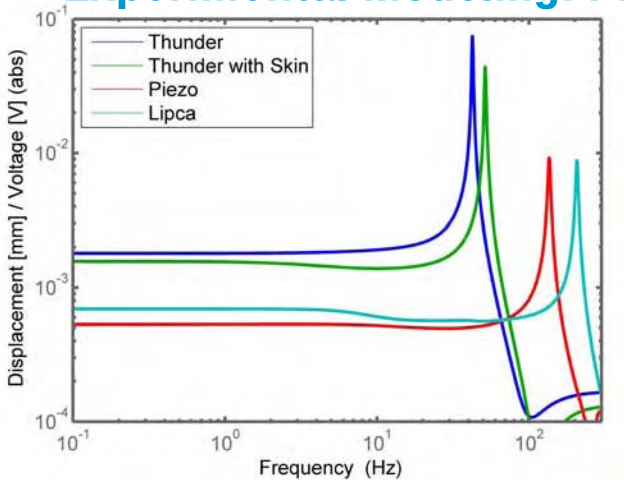
Experimental modeling: Piezo bender



Experimental modeling: Piezo bender



Experimental modeling: Piezo bender



Wrap-up

For the ‘Smart’ rotor is holds that:

- An accurate dynamic model is required of the whole ‘Smart’ rotor
  (rotor, actuator, sensor, amplifier, etc.)
- Analytical modeling is required for dimensioning
  (but time and knowledge intensive)
- Experimental modeling is a necessary tool
  (generic and fast)
- For control a ‘good’ real time environment is required

Future work

<u>Fundamental:</u>
Extending LTI identification to LPV identification

<u>Practical:</u>
Control of a ‘Smart’ rotor blade

Adaptronics for Wind Energy Plants

IEA Meeting on Smart Structures

November 11 & 12, 2006

Delft

Thilo Bein

Fraunhofer-Institute Structural Durability & System Reliability LBF

Fraunhofer Institut Betriebsfestigkeit Systemzuverlässigkeit

Fraunhofer Center Windenergie und Meerestechnik

Outline

- Introduction
- What is Adaptronics?
  - Basics
  - Principles
  - Examples
- Application to Wind Energy
  - Aerodynamic Efficiency
  - Noise and Vibration
  - Structure Health Monitoring
- Summary / Conclusion

Fraunhofer Institut Betriebsfestigkeit Systemzuverlässigkeit

Fraunhofer Center Windenergie und Meerestechnik

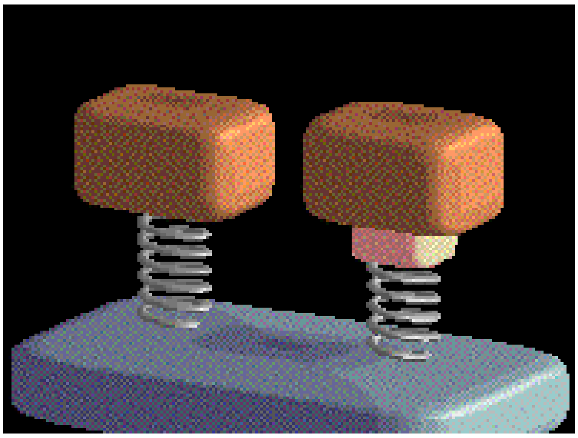
Quelle: DC

Goals

- Active vibration control
- Active structural acoustic control
- Active shape control
- Structural Health Monitoring

to

- optimize lightweight design / structural loading
- increase safety / comfort
- reduce maintenance
- increase functions



Application areas

Structure Optimization for

- **Automotive structures:** safer, less noisy, more comfortable, lighter, more reliable, ...
- **Machine tools:** more reliable, more precise, more flexible, higher speed, ...
- **Air- and Space technology, medical engineering, optics, defense, traffic engineering, ...**

current situation

✓ Potential for product optimization understood by commercial users

✓ Increasing market demand, feasibility limits been reached

Transducer Materials

Elektrics Field
Magnetic Field
Heat
Light

actuator

Piezo-Keramiken
Piezo-Polymere
Elektrostrikt. Keramiken
Elektroviskose Flüssigkeiten
Polymergele

Magnetostrikt. Legierungen
Magnetoviskose Flüssigkeiten

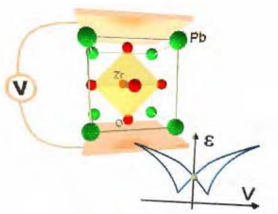
Gedächtnislegierungen
Gedächtnispolymere
Hybride Werkstoffsysteme
Polymergele

Polymergele
Elektrostriktive Materialien
Photomechanische Materialien
Optische Fasern

sensor

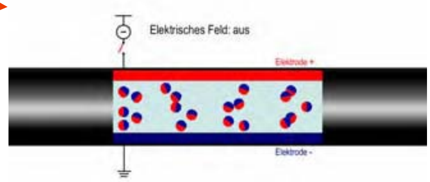
Current, Voltage
Resistance, Inductivity
Resistance
Intensity

Mechanical force, deformation, u.a.



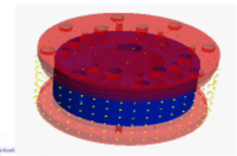
Piezo- ceramics, electrostrictives and ...

... ERF



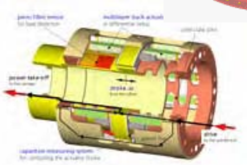
Quelle: LPA

Multifunctional Approach



←... modular, discrete Systems

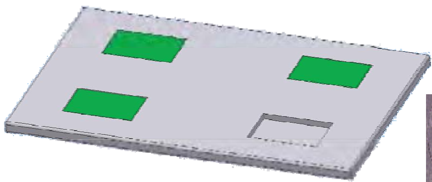
Structural integration of Transducer materials as ...

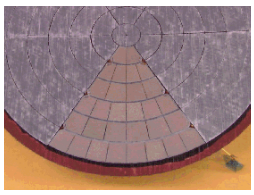


IWU

LBF

LBF

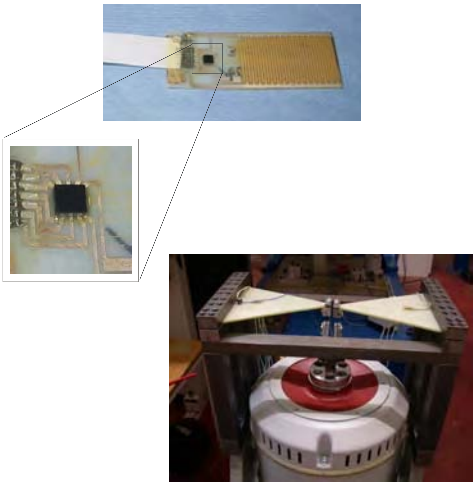




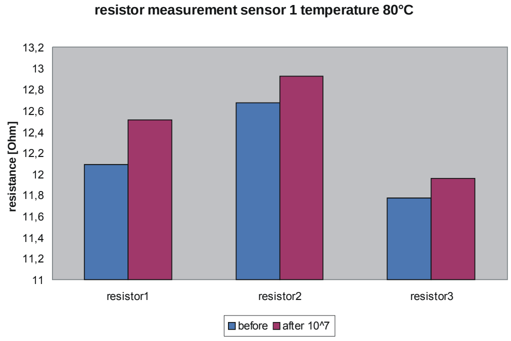
... integrated / applied systems →

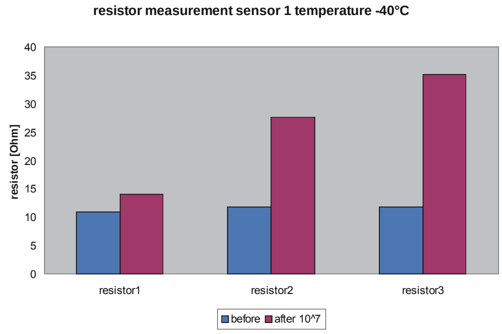
IKTS

System Reliability on Piezo Sensors with Integrated Electronics



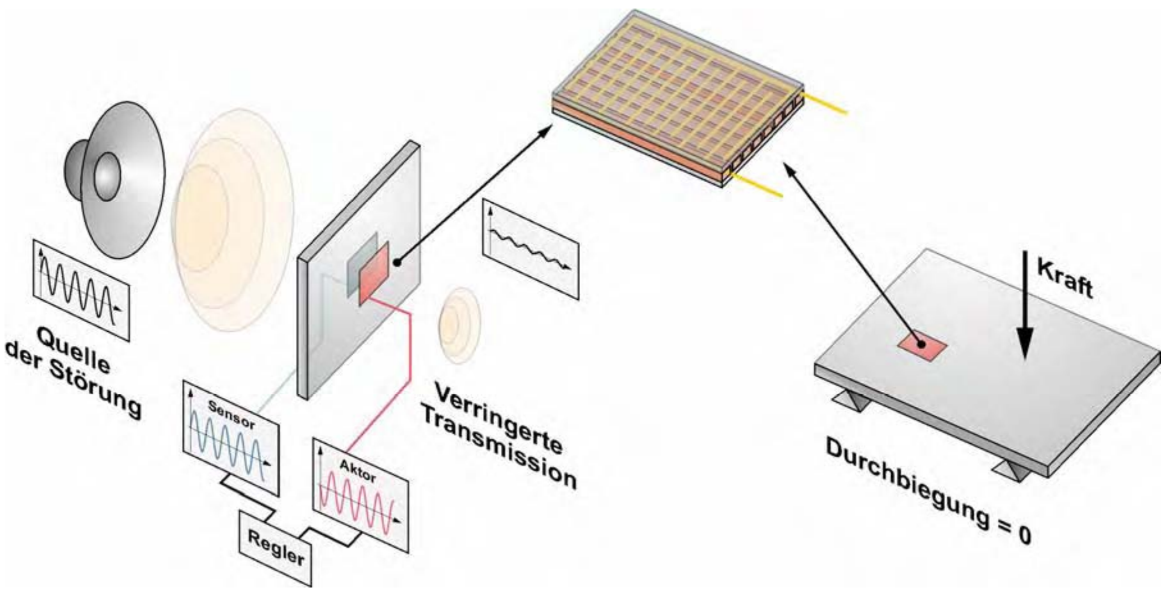
	MIN.	MAX.
strain	-0.3%	+0.3%
Max. cycle frequency @ 0.3% strain	30 Hz	
temperature range	-40°C	+80°C
humidity	5%	90%





Project: MaVo FASPAS

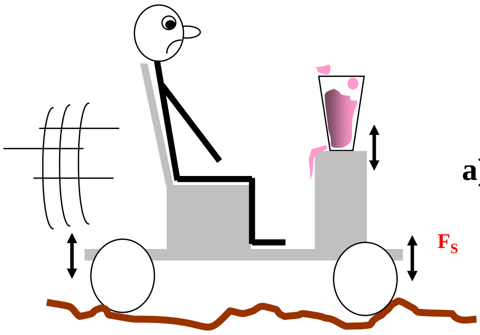
Principles of Applications



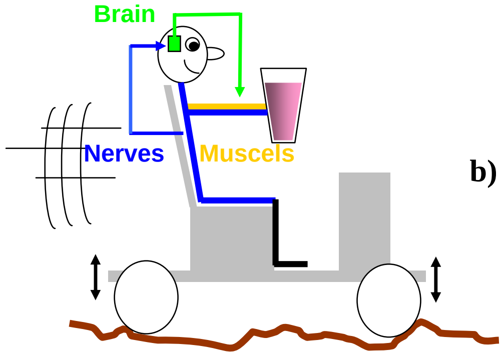
Active Noise and Vibration Control

Active Shape Control

Example: Active Vibration Control (I)

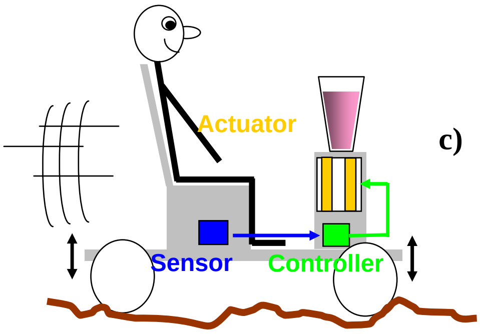


a)



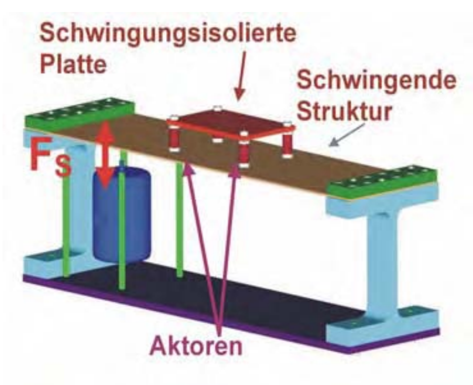
b)

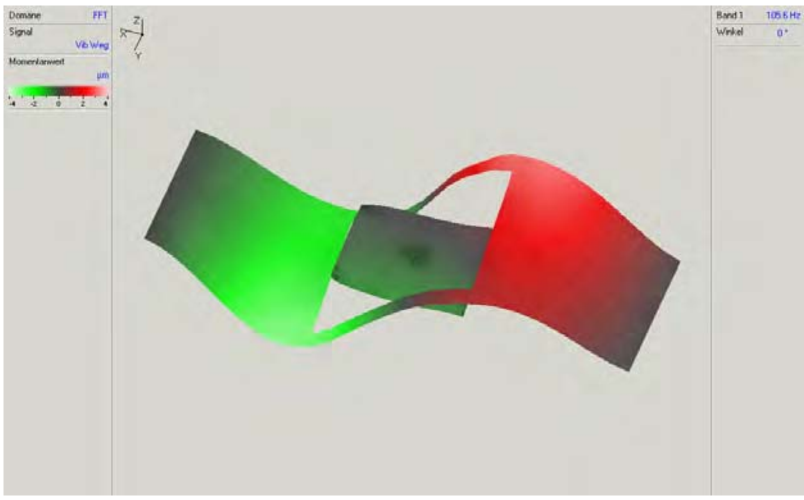
Control of the structure-borne sound path



c)

Example: Active Vibration Control (II)





Application of Adaptronics to Wind Energy

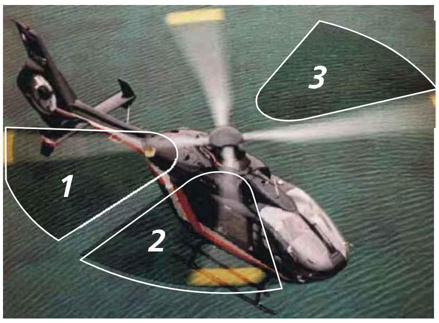
- Transfer of concepts from previous projects to wind energy-

Fraunhofer Institut Betriebsfestigkeit Systemzuverlässigkeit

Fraunhofer Center Windenergie und Meerestechnik

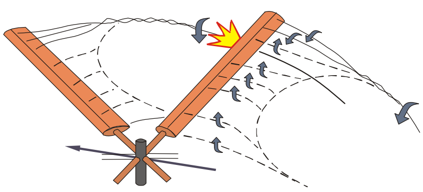
Aerodynamic Efficiency – Smart Wing and Smart Rotorblade

Noise and vibration sources at helicopters

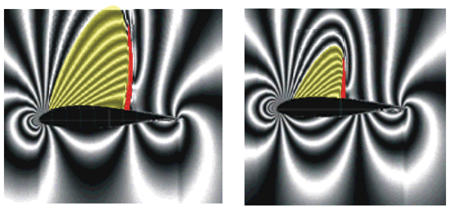


3 Vibration due to dynamic stall

1 Blade-Vortex-Interaction



2 Transsonic noise



DLR Institut für Strukturmechanik

Fraunhofer Institut Betriebsfestigkeit Systemzuverlässigkeit

Fraunhofer Center Windenergie und Meerestechnik

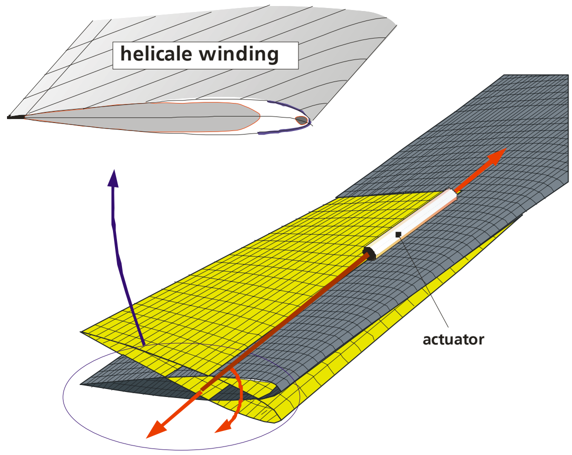
Aerodynamic Efficiency – Smart Wing and Smart Rotorblade

Suitable concepts
- flaps (already in flight tests)
- adaptive blade twist
- adaptive control of profil

advantage
- direct use of aerodynamic forces
- low structural loads

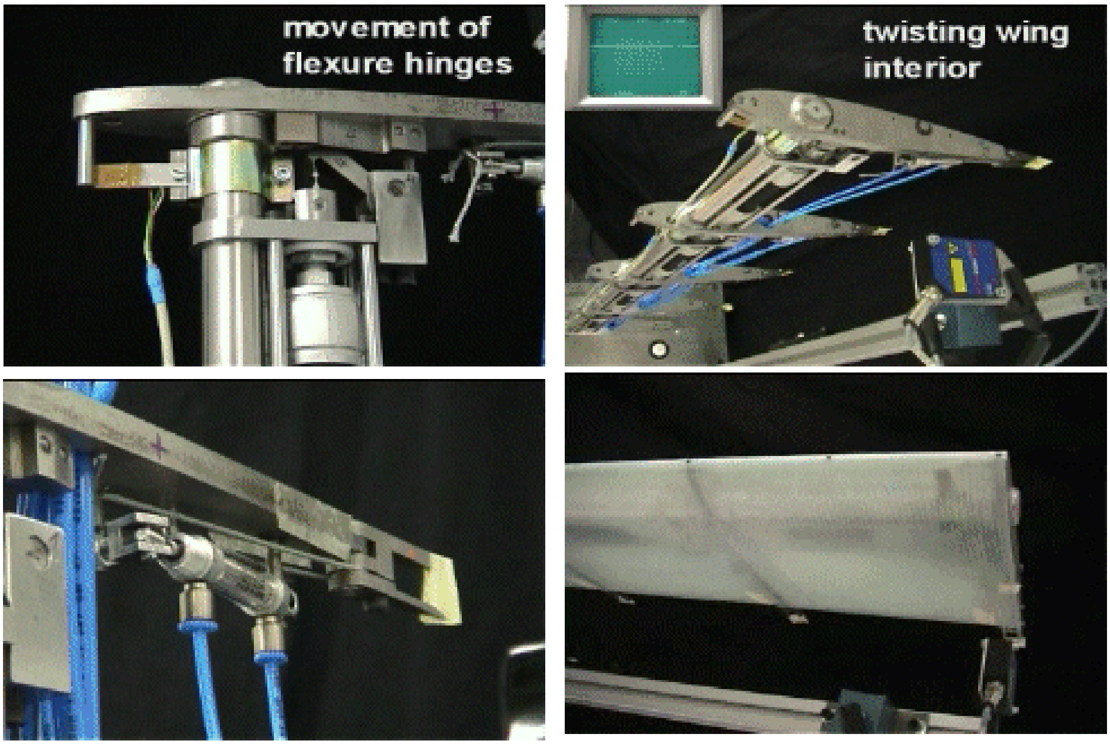
disadvantage
- long signal transfer path

Tension-Torsion Coupling



Fraunhofer Institut Betriebsfestigkeit Systemzuverlässigkeit
Fraunhofer Center Windenergie und Meerestechnik

Aerodynamic Efficiency – Morphing Blades



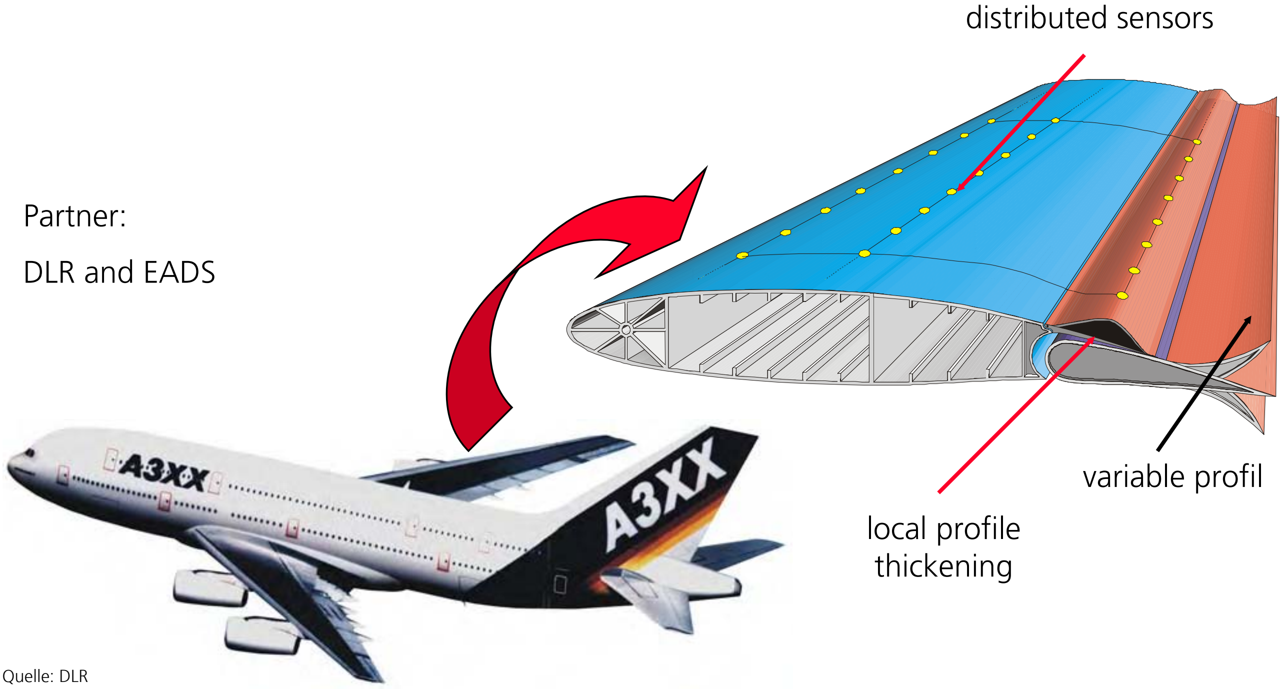
Fraunhofer Institut Betriebsfestigkeit Systemzuverlässigkeit
Fraunhofer Center Windenergie und Meerestechnik

Aerodynamic Efficiency – Morphing Blades

Aerodynamic Efficiency – Smart Wing and Smart Rotorblade

Partner:

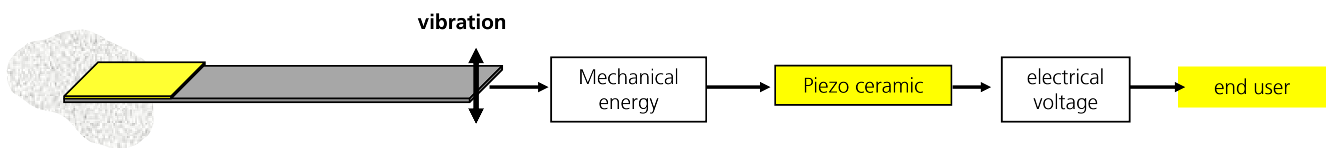
DLR and EADS



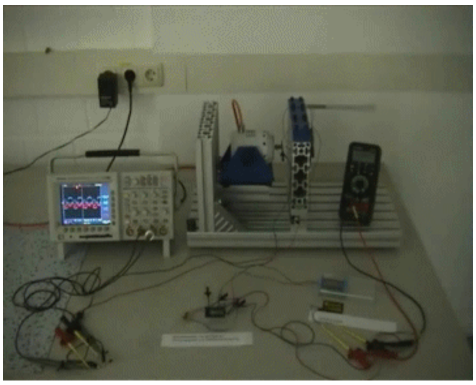
Quelle: DLR

Structure Health Control Based on Adaptronics

SHM – Autonomous sensor



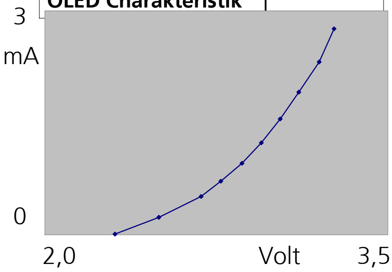
Example: thermometer, counter and OLED driven by energy harvesting



Energie Output (2 Piezo-Patches)

Power (max.)	0,8 mW
Load Resistance	38 kΩ
Bending Frequency of Beam	19 Hz

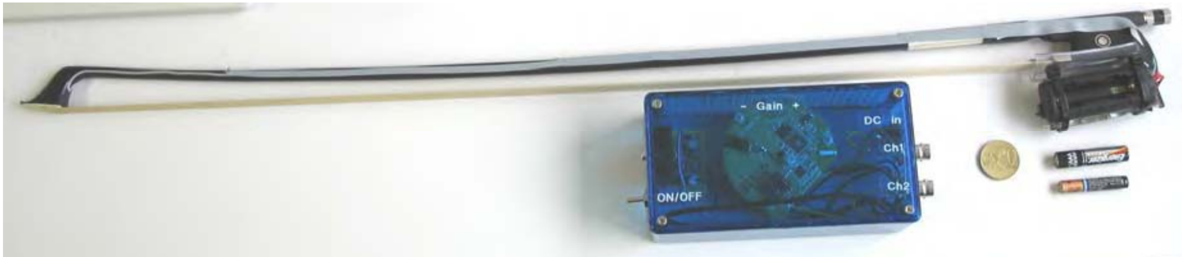
OLED Charakteristik



SHM – Wireless sensors

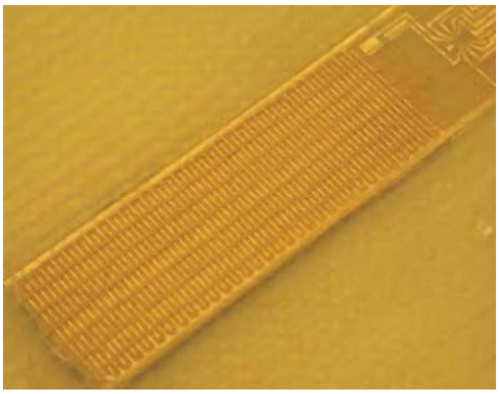
Violin bow

- Sensors: DMS and piezo ceramic
- Amplifier:
  Size: (25*45*4) mm, Weight: 8g
- Transmission:
  Bluetooth-Transmitter, 3 Hz bis 20 kHz
  Size: (25*67*17) mm, Weight: 9g
- Weight of electronics: <70g



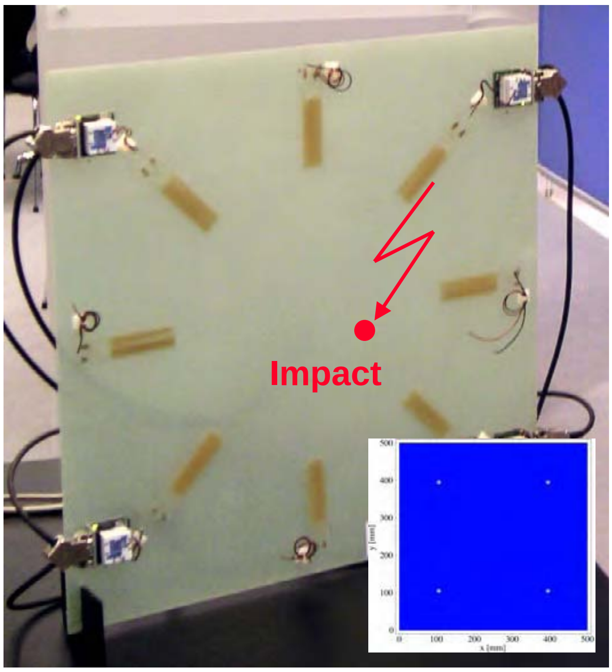
SHM – Concepts based on Surface Acoustic Waves / Lamb Waves

piezo fibre transducers



piezofibre transducer embedded in GFRP

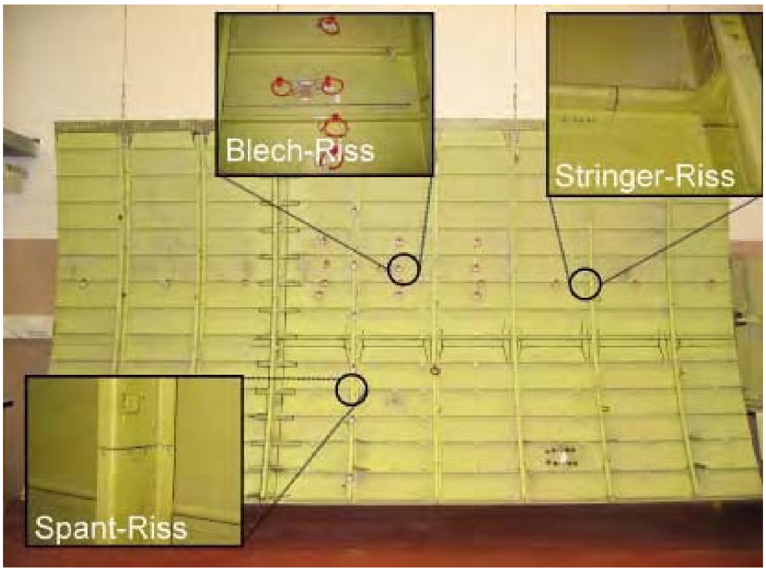
ISC



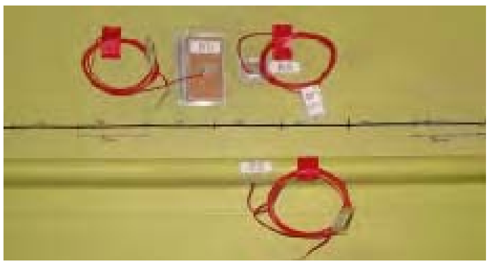
SHM – Concepts based on Surface Acoustic Waves / Lamb Waves

SHM – Concepts based on vibration methods

Detection of cracks on a fuselage structure



placing piezo-patches:



Summary / Conclusion

- **Adaptronics is an emerging technology dealing with**
  - active noise and vibration control
  - shape and position control
  - structural health monitoring and energy harvesting
- Adaptronics are well established in machine tool industry, in the transport sector and is ready to be applied also to wind energy
- **Adaptronics could provide solutions**
  - to improve the efficiency
    - adaptive flaps
    - variable profile
  - noise and vibration reduction in the drive train
  - load reduction
  - Structure Health Monitoring
    - blades
    - drive train
    - tower

Thank your very much for your attention

IPPT contribution to
IEA Meeting:

Smart interfaces between blades and hub

Arkadiusz Mroz

Motivation, concept demonstration development, further steps

December 11-12th 2006, Delft, the Netherlands

UpWind IP task 1B3.7 Main objectives

- semi-active devices to mitigate vibrations
  - Simulations and feasibility studies of systems with controllable stiffness and damping
  - Development of control strategies to optimise the damping effect
  - Hardware using MR fluid, piezo-valves or other
  - Sensor system allowing for real-time adaptation
- span wise distributed, active pitch control system
  - Local deformation of aerofoil, moveable surfaces or other means to control air flow locally
  - Control strategies to reduce aeroelastic forces
  - Sensor system allowing for real-time adaptation

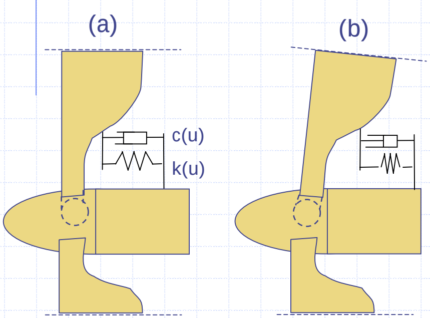
Motivation

- problem of strong wind gusts
  - big bending moments at blade-hub connection
  - up-scalling is likely to push the resulting stress beyond the safe limits for any materials

new materials | adaptive solutions

Adaptive solution – the concept

- two modes of work
  - stiff – during normal operation (a)
  - reduced stiffness – under extreme loading (b)



In the reduced stiffness mode displ. increase more rapidly, but in turn forces in the connection decrease, or increase much slower.

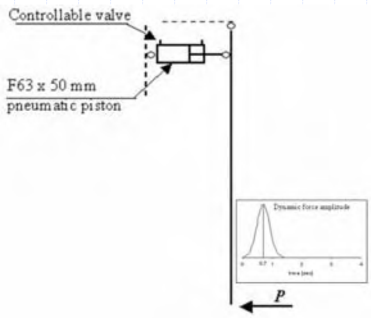
As the result blade – hub connection forces could be kept within the device safety limits.

Elastic element of the device should accumulate enough energy to draw the blade into the initial position after the gust has decayed (return phase).

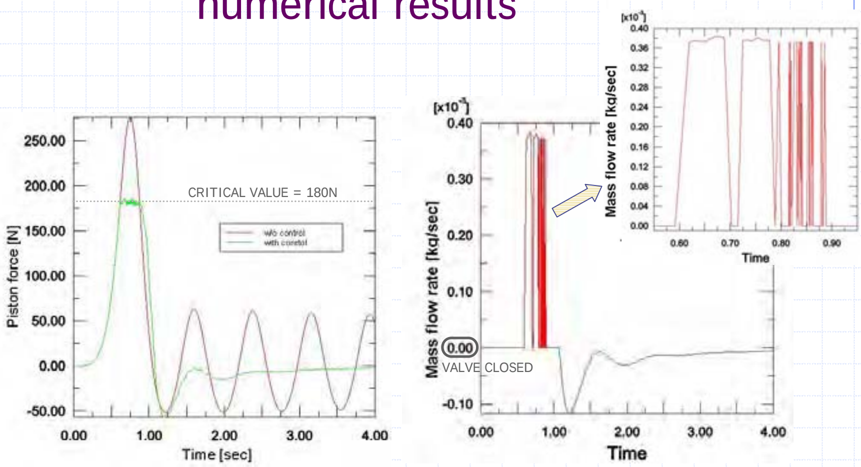
u – control variable, f.e. wind gust intensity

Proof-of-the-concept demonstrator

- **‘smart bond’** – adaptive interface between two substructures
  - pneumatic piston + controllable valve
- **control**: closed loop between valve opening and the dynamic force level
- **goal**: dynamic force in the piston cannot exceed a critical value

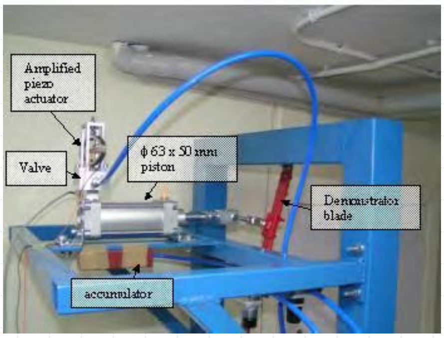


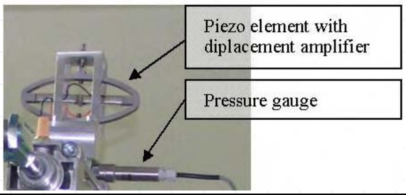
Demonstrator
numerical results



Demonstrator

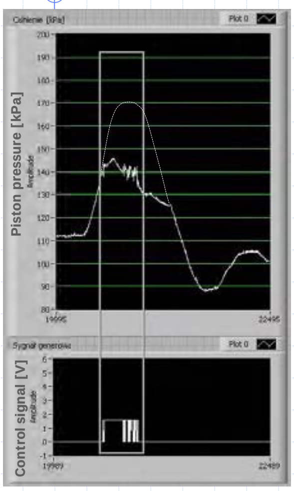
experimental set-up

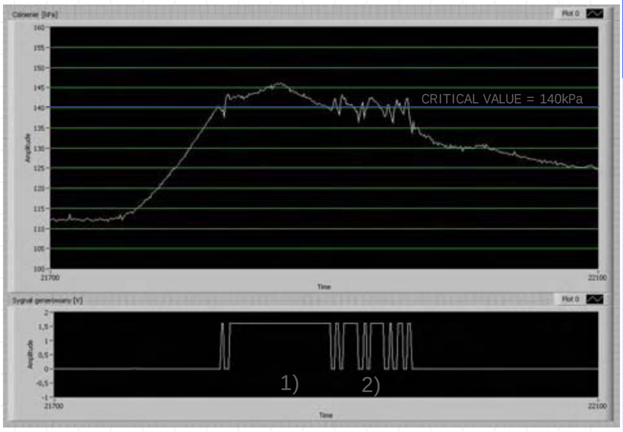




Experimental set – up

first results





1) valve open until the load reaches its peak and starts to decrease
2) series of opening and closing of the valve in order to save the stroke

Further steps

- use proportional control instead of two state (on/off) control
- repeat the numerical simulation for the wind turbine blade model (CFD)
- elaborate possible solutions for the actuator hardware

Blank page

The Application of Smart Structures for Large Wind Turbine Blades

December 11-12, 2006
Delft University of Technology
IEA Expert Meeting:
The Application of Smart Structures for Large Wind Turbine Blades
IEA RD&D Wind Annex XI

Mark Capellaro
Endowed Chair of Wind Energy at the Institute for Aircraft Design - University Stuttgart

'Almost Smart' Blades by Passive Control

'Almost Smart' Blades by Passive Control

Presentation

- SWE research and potential contributions to smart structures and Upwind
- Turbine and Blade Design
- ' Almost Smart' Blade Concepts
  - Bend twist coupled blades (composite material couplings)
  - Sweep twist coupled blades (geometric couplings)
  - Blunt Trailing Edge Airfoils
  - Extendable Blade turbine (Sectional blade)
- Future Research and Cooperation
- Conclusions

Endowed Chair of Wind Energy

- **Ongoing Research (<u>partial</u> listing of current Phd. research) at the SWE**
  - **Mitigation of Aerodynamically and Hydrodynamically induced Loads of Offshore Wind Turbines**
  - **Load Monitoring and Multivariable Control of Wind Turbines**
  - **Dynamic Loading of Wind Turbines in Wake Operation**
  - **Load measurement and power curve determination of the Multibrid M5000 prototype**
  - **On-line Load Monitoring and Performance Evaluation using Standard Wind Turbine Signals**
  - **Multibody Wind Turbine Simulation (SimPack)**
  - **Design Wind Turbine Dynamic Modeling Code Comparison**
  - **Blades and Composite Materials – (Passive Control)**

Turbine Design

Lowering the cost of energy is the goal.

Turbines need to produce more power for the same cost
or
Less expensive turbines need to be designed that produce the same power

Lower loads
→ Lower amount of material needed
→ Lower costs

'Smart Blades' will reduce peak loading or fatigue damage accumulation through smart design and controls.

Blade Design

Blade have to last 20 years (or more)

- **Flapwise the wind dominates the loading. Must add mass/stiffness to resist bending.**
- **Edgewise the rotor rotation drives the fatigue damage. Heavier blades means higher fatigue loads.**

Blades are robust and reliable and any changes must be as reliable

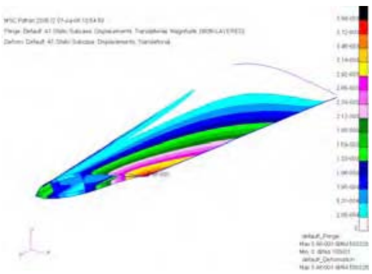
Blade must be stiff enough to avoid blade tower accidents

Blades are made from composite material to benefit from the high strength to weight ratios

Composite materials allow coupling options that should not be overlooked.

'Almost Smart' Blade Design Concepts: Bend Twist Coupling

- **Deflected blade forced, by material fiber geometry, to twist towards feather**
- **US simulation studies demostrated potential benefits (NREL, GE,...)**
- **Reduces loading through material coupling**
- **Studied in the USA and Denmark(!)**
- **Research in Denmark was part of a larger project to determine accurately the torsional stiffness of a blade**



‘Almost Smart‘ Blade Design Concepts: Bend Twist Coupling

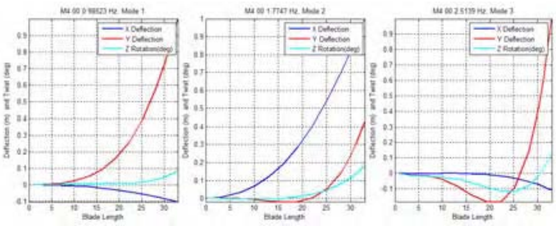
Research Reasons

- **Current finite element models of blades are unable to predict accurately the torsional stiffness or frequency of blades.**
- **Not a problem as long as torsional frequency is high enough to be ignored**
- **Larger blades means lower torsional frequency**

‘Almost Smart‘ Blade Design Concepts: Bend Twist Coupling

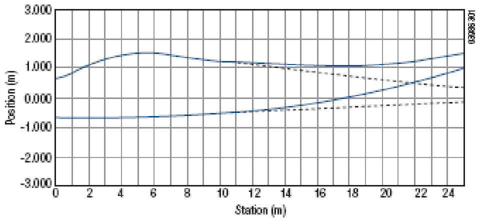
Some Findings

- **A FE code used to model helicopter rotor blades (VABS) was adapted to model wind turbine blades with some promising results**
- **Blades already have some naturally occuring twisting under deflection (the blade reduces loading due to geometry)**
- **Attempted to dynamically model a bend twist coupled blade turbine in a mode shape based simulation code**



Almost ‘Smart‘ Blade Design Concepts: Sweep Twist Blades

- **Sweep is in the rotor plane (instead of out of plane or upwind)**
- **Blade center of mass and Aerodynamic center are aft of blade root center**
- **Lift causes the blade to twist towards feather, reducing loads in gusts**



Planform of the sweep twist blade.

Source: US Dept of Energy Wind Energy Technology Program

Almost ‘Smart‘ Blade Design Concepts: Sweep Twist Blades

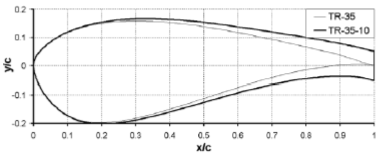
- **Concept was studied for a very small wind turbine, a 400W Southwest Windpower machine**
- **Research paper by Global Energy Concepts in Seattle demonstrated the concept (*but had trouble modeling the blade dynamically*)**
- **Wanted to lower loads (*same goal as the big guys*)**
- **A year after the research was published, a 3.7kW Southwest turbine is commercially available with a suspiciously similar blade design.**
- **A 29m blade is now in prototype phase**

Sources http://www.skystreamenergy.com/skystream/
Evaluation of Aeroelastically Tailored Small Wind Turbine Blades

‘Almost Smart‘ Blade Design Concepts: Blunt Trailing Edge Airfoils

FatBacks

- Increase thickness (up to 30%) on inboard sections
- Trailing edge does not contribute to support
- Reduces stresses if thicker sections are used
- May improve lift and has other aero benefits



Source: http://gcep.stanford.edu/pdfs/energy_workshops_04_04/wind_van_dam.pdf! Case van Dam (Delft – UC Davis)

- Noise Penalty
- Limited to non cambered sections

‘Almost Smart‘ Blade Design Concepts: Extendable Blades

Extendable blades

- Couple folks in the US modified a Bonus 120 turbine
- Same goals, lower loads and produce more power
- At lower wind speeds the blade extends

Essentially a sectional blade that extends

These ideas all assume blades are in front of the tower

Source: Variable Length Wind Turbine Blade, Dynamic Design Engineering, Inc., Knight and Carver Wind Blade Division

Future Research

Passive control of smart blades

Improved modelling of wind turbine blades (torsional behavior)

- Validation & comparison blade design tool
  - PreComp, NuMAD, FE shells vs. solid elements...

Large turbine blades will need more accurate torsional stiffness and frequency data

- Precondition for bend twist coupling (useful for smart blades)

Future Research

New structural blade design e.g. textile techniques

- IFB composite laboratory
  - Braiding machine
  - Stitching machine
  - Facilities for microwave hardening of composite material
  - Experienced researchers

By creating high quality composites, you get as close as you can to theoretical results

  - Control fiber angles
  - Optimize Fiber/Matrix ratios
  - Minimize voids...

The improved modeling of blades will be possible by having accurate test specimens!

Future Research

New structural blade design e.g. textile techniques

- Design of primary blade structure
- Design of laminates and materials
- Want to design, build and test scaled blades (up to 12 m)

Accurate dynamic simulation of wind turbines can only be accomplished with accurate modeling of wind turbine blades

Wind turbine design relies heavily on dynamic simulations

Cooperation with UpWind WP 1B3

- New aerodynamic/elastic rotor design models
- Complimentary technology
- Comparison of active and passive control on a wind tunnel model
- Different paths to same goal
  - Lower loads
  - Lower COE

‘Almost Smart‘ Blade Design Concepts:Conclusions

- All of these passive technologies are very hard to model in dynamic simulations
- None of these technologies are exclusive, they can be combined with Active Control Technologie
- None of these technologies can be used to replace current control mechanisms for large turbines
- Passive controls
  - cheaper?
  - reliable

And as with every researcher presenting any idea...

More research is necessary!

Blank page

VTT TECHNICAL RESEARCH CENTRE
OF FINLAND

The application of smart structures for large wind turbine rotor blades

Delft 11.-12.12.06

Tomi Lindroos & Merja Sippola

The application of smart structures for large wind turbine rotor blades
related topics at VTT

Background - Smart materials and structures research at VTT

Embedded structural intelligence

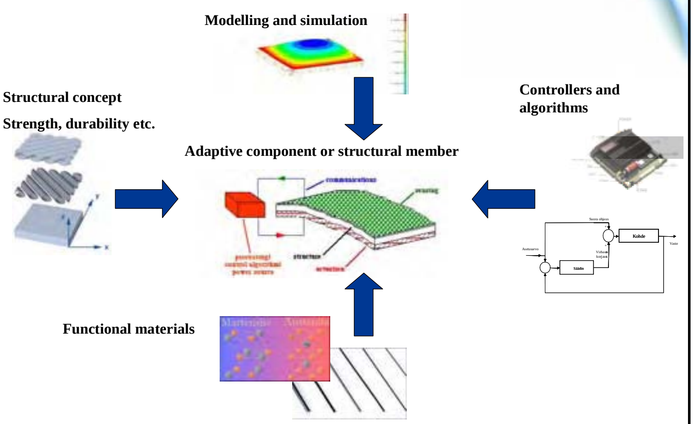
Development of adaptive wing profile

The application of smart structures for large wind turbine rotor blades related topics at VTT

Research of smart material and structures at VTT started at the beginning of 1990. Strong growth of research activities at the end of 1990

⇒ VTT technology theme

⇒ EMBEDDED STRUCTURAL INTELLIGENCE



- ***Research areas are covering the most of known smart material groups***
- ***Multidisciplinary approach: materials, processing, structures, control, application know-how***

VTT

The application of smart structures for large wind turbine rotor blades related topics at VTT

EMBEDDED STRUCTURAL INTELLIGENCE

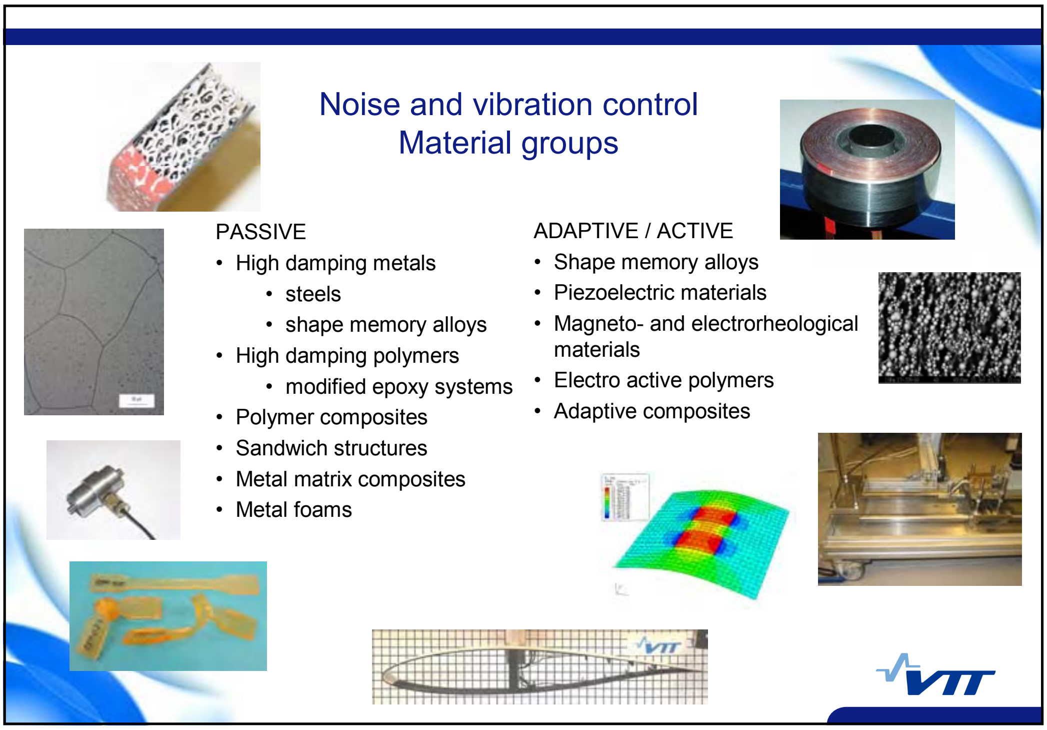
Focus areas

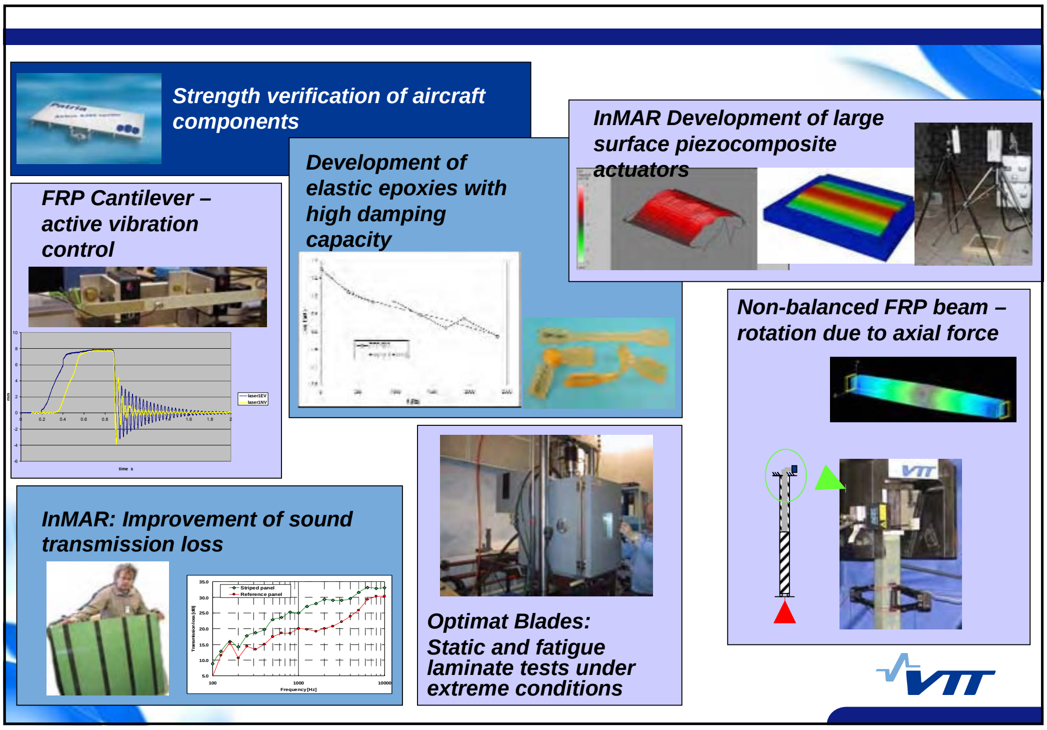
- Noise and vibration control
  - Passive
  - Adaptive
  - Active
- Shape control
  - Adaptive
  - Active

At the first stage wind turbine was chosen to be common application platform

- ***Tower***
- ***Blades***

VTT


Noise and vibration control
Material groups
PASSIVE
• High damping metals
• steels
• shape memory alloys
• High damping polymers
• modified epoxy systems
• Polymer composites
• Sandwich structures
• Metal matrix composites
• Metal foams
ADAPTIVE / ACTIVE
• Shape memory alloys
• Piezoelectric materials
• Magneto- and electrorheological materials
• Electro active polymers
• Adaptive composites
VTT


Strength verification of aircraft components
FRP Cantilever – active vibration control
Development of elastic epoxies with high damping capacity
InMAR Development of large surface piezocomposite actuators
Non-balanced FRP beam – rotation due to axial force
InMAR: Improvement of sound transmission loss
Optimat Blades: Static and fatigue laminate tests under extreme conditions
VTT

CASE – *Adaptive wing profile*

Shape memory alloy composites

Adaptive wing profile

Modeling

Manufacturing

Control and Measurement

Challenges

Next steps

CASE – *Adaptive wing profile*

Background – *Shape memory alloys composites*

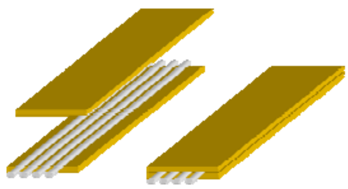
1988 Rogers *et al.* reported about composites where shape memory alloys were utilized

After that research of smart composites has been come one of the hot topics in the field of smart structures:

- More than 1700 scientific reports were published since

Three main directions of use of SMA's can be seen:

- Improve the strength of the structure against shock loads,
- Control the shape of the structure and
- Control the stiffness of the structure for vibration control.



CASE – *Adaptive wing profile*

Founding: because of the multidisciplinarity of the development work is done in group of sub-projects with national and EU funding

Main partners

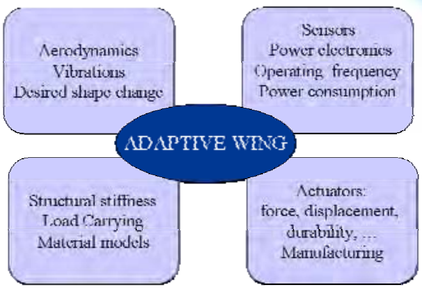
- VTT Technical Research Centre of Finland
  - Modeling tools for smart structures
  - Smart materials and manufacturing technologies for smart structures
- Helsinki University of Technology
  - Fiber optics
- University of Oulu
  - Control systems for smart structures

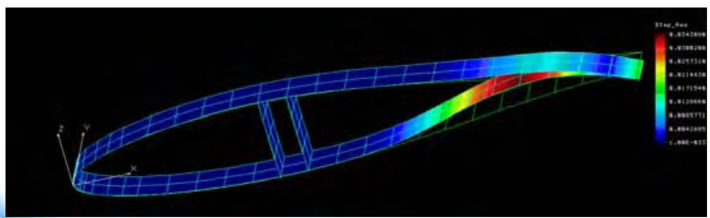
VTT

CASE – *Adaptive wing profile*

Modeling

- Structural optimization
  - Fiber angles and layers
  - Position and amount of shape memory actuators
- Material model of the shape memory alloys: implementation of Sittner's model to ABAQUS
- FE-modeling of the smart structure





VTT

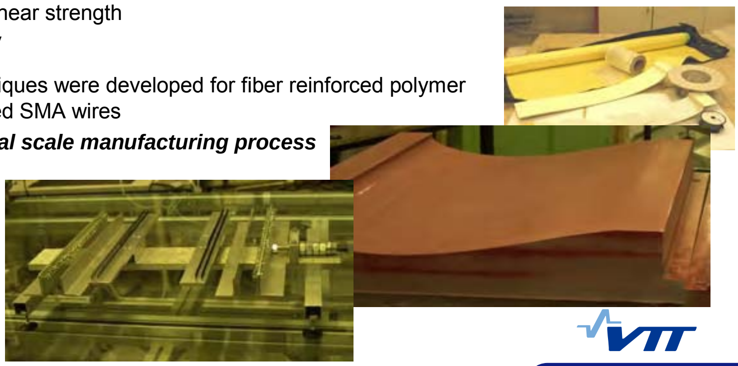
CASE – *Adaptive wing profile*

Development of manufacturing technologies

- Embedding SMA wires into composite structure
    - Positioning of wires
    - Double-curvature surfaces
- Structural integrity
    - How to restrict pull-out of SMA wires, high local stress level, elevated temperature
    - Discontinuities due to SMA wires
        - Interlaminar shear strength
    - Long-term durability

- New manufacturing techniques were developed for fiber reinforced polymer composites with embedded SMA wires

  ⇒ ***Aim: industrial scale manufacturing process***

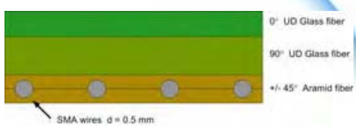


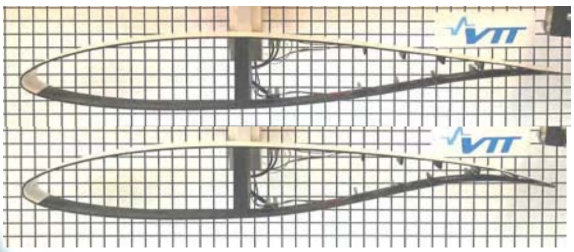
VTT

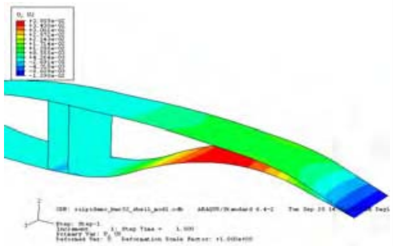
CASE – *Adaptive wing profile*

Active Wind Turbine Blade Cross Section

- SMA wires embedded inside a FRP laminate
- Controlling the trailing edge deflection
- Reducing vibration loads
- Potential in increasing energy production







Adaptive structures co-operation between VTT, HUT and Univ. of Oulu covers the whole chain from modeling and fabrication to testing and control

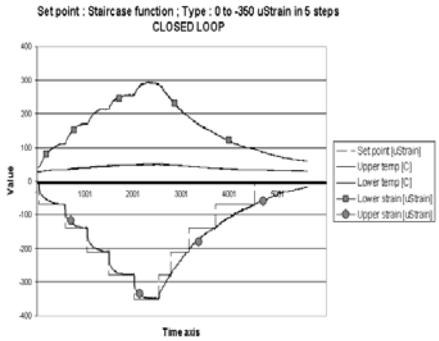
VTT

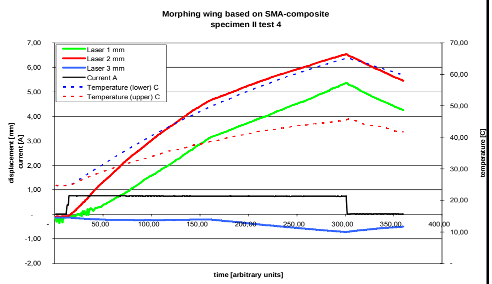
CASE – *Adaptive wing profile*

Control Systems and Measurements

Labview based control and measurement system was developed

- Activation of SMA wires by PWM Joule heating
- Temperature, displacement or strain feedback control





CASE – *Adaptive wing profile*

Future Challenges

Structure optimization

Actuation and cooling frequency

Displacement amplitudes under external loads

Scale up of manufacturing processes

Long-term durability

Cost vs. benefits

Next Steps

Wind tunnel tests of real size adaptive wing profile cross-section spring 2007 (span 700mm, width 1000 mm)

Development work continues at the new projects EU IP / UPWIND and European Science Foundation / MAFESMA

⇒ Co-operation VTT / ASCR

CASE – *Adaptive wing profile*

Some answers to the challenges:

- Utilization of R-phase NiTi wires
  - Narrow hysteresis
  - Higher Clausius-Clapeyron constant gives less shift in phase transformation temperatures due to external stresses
    - ⇒ Higher actuation rate
    - ⇒ Lower temperatures
    - ⇒ Lower power consumption
    - ⇒ Lower thermal stresses to matrix
- Implementation and improvements of the SMA material model

Aerodynamic modelling of flap

Robert Mikkelsen, Niels Troldborg & Jens N. Sørensen
DTU, Denmark
IEA Annex 11 meeting on Smart Structures
Dec.11-12, 2006, TU-Delft

Contents:

Airfoil flap – Why?

- Some sources of fluctuating loads on wind turbines:
  - Wind shear
  - Yaw
  - Tower shadow
  - Turbulence
  - Wake interaction (Parks)
- Fluctuating loads => vibrations
- Pitch control system to slow

Known advantages of airfoil flaps

- High aerodynamic impact
- Smart materials could be used
- High frequency control possible

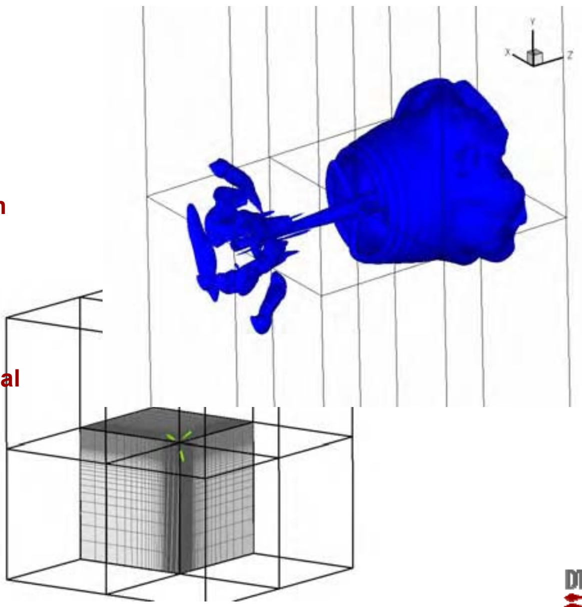
Wind Turbine Wake Aerodynamics

Wake and park interference:

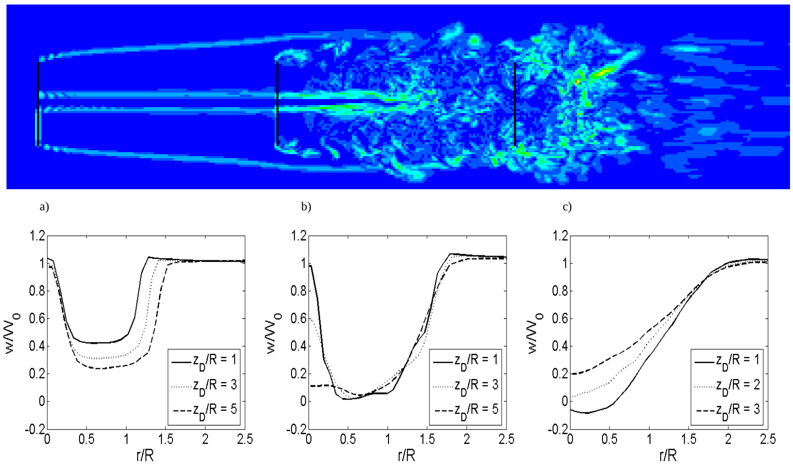
- Scarce information available regarding flow in wind farms
- Turbines affected by upstream wakes experience sever fatigue loads due to increased turbulence and distinct tip-vortex structures
- Can smart structures reduce loads on turbines in parks?

Actuator Line Modelling

- Each turbine blade is represented by an actuator line in a fully 3D flow domain
- The aerodynamics loads is represented by body forces along the lines
- The loads are based on local absolute velocities and aerofoil data

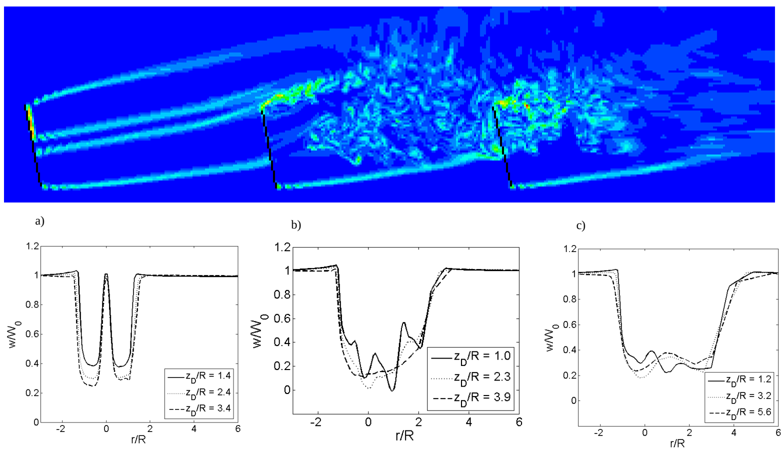


Vortex structures in the wake of a row of rotors



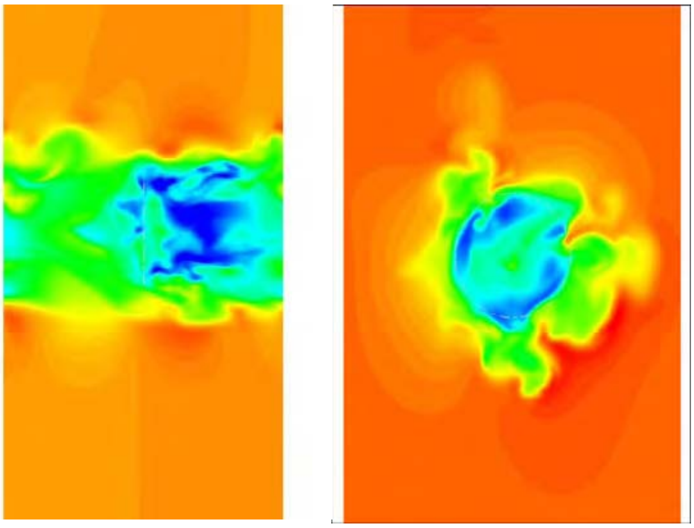
Development of wake behind three rotors in a row at W_0 = 10 m/s; Turbine spacing 6 rotor radii. Computed mean wake deficit profiles downstream a) rotor 1; b) rotor 2; c) rotor 3.

Vortex structures in the wake of a row of rotors



Development of wake behind three rotors in a row at W_0 = 10 m/s and an angle of 9.6˚ Lower figure: Computed mean wake deficit profiles downstream a) rotor 1; b) rotor 2; c) rotor 3.

Simulation of wind farm – axial velocity



MEK Fluid Mechanics

Technical University of Denmark

EllipSys 2D-3D

General purpose flow solver

By: Jess Michelsen, DTU – Niels Sørensen, Risø

Features:

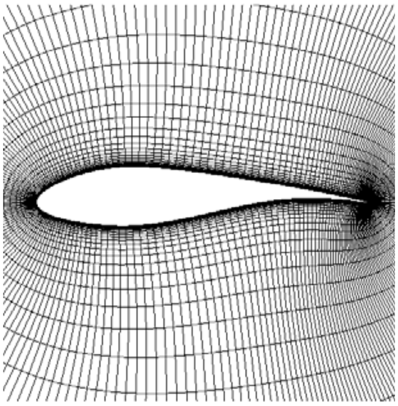
- Incompressible Navier-Stokes, 2D and 3D
- Block structured – Multi block – Multi grid
- Parallelized using MPI – 20mill. points is no problem
- Turbulence models: K-ε, K-ω, DES, (3D Transition)
- Yggdrasil (DTU): 210 CPU's , Mary (Risø): 240 CPU's

MEK Fluid Mechanics

Technical University of Denmark

2D CFD study of a variable flap geometry

Risø-B1-18 airfoil



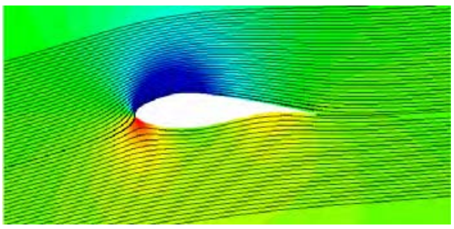
EllipSys2D – RANS solver

$$\frac{\partial u_j}{\partial t} + u_k \frac{\partial u_j}{\partial x_k} = -\frac{1}{\rho}\frac{\partial p}{\partial x_j} + \nu \frac{\partial^2 u_j}{\partial x_i \partial x_i} + f_j$$

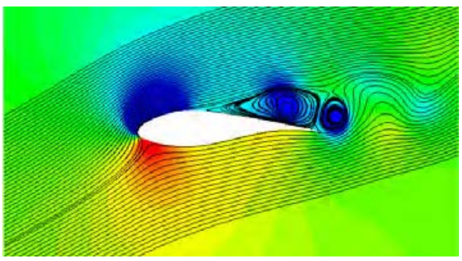
$$\frac{\partial u_j}{\partial x_j} = 0$$

Flow patten - Streamlines and pressure

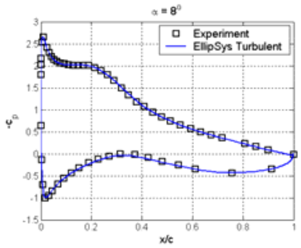
α = 8º

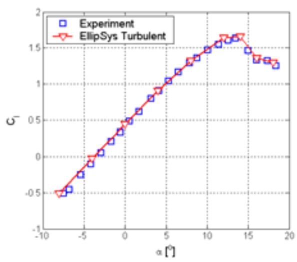


α = 18º



Pressure distribution, Risø-B1-18, AOA=8

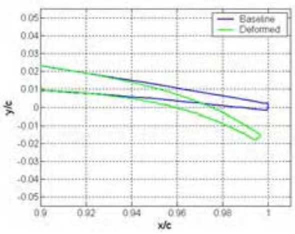




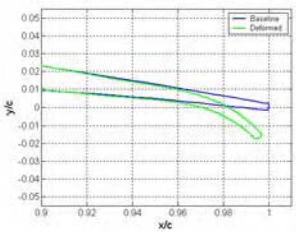
$C_L(\alpha)$

Flap geometries – Parameter study

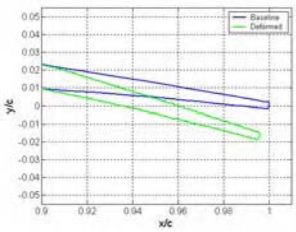
Moderate curvature



High curvature



Stiff flap

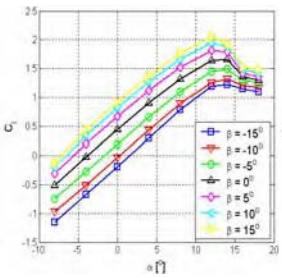


MEK Fluid Mechanics

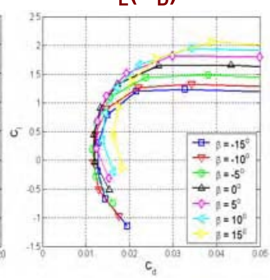
Technical University of Denmark

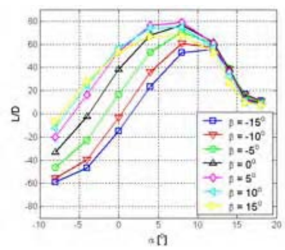
Parameter study – fixed flap

$C_L(\alpha)$



$C_L(C_D)$





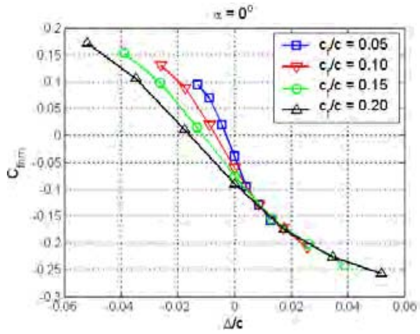
C_L/C_D

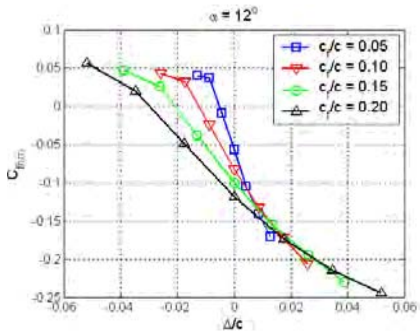
MEK Fluid Mechanics

Technical University of Denmark

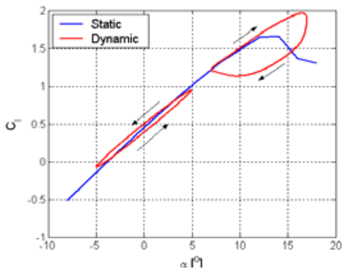
Hinge moments

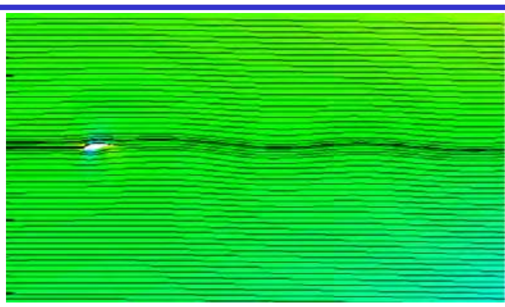
$$C_{fhm} = \frac{M_{fh}}{\frac{1}{2}\rho U^2 c_f^2}$$



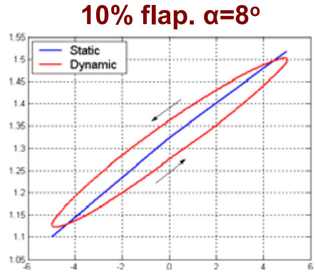


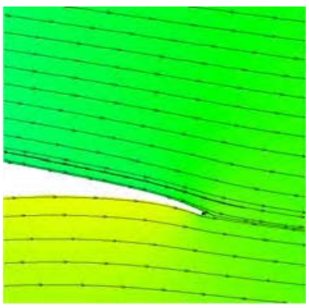
Harmonically pitching flap

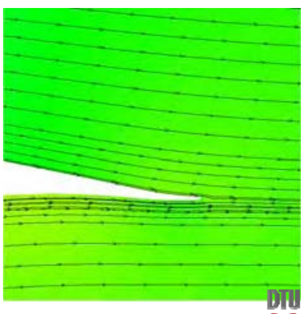




10% flap. α=8º

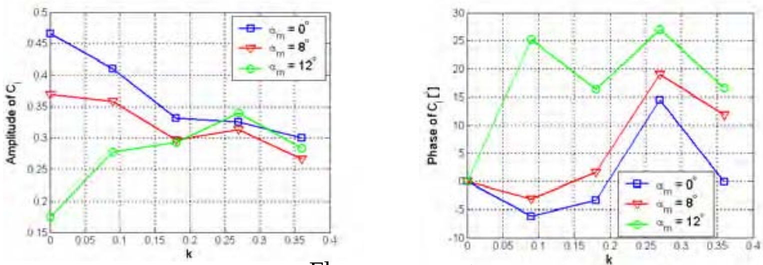




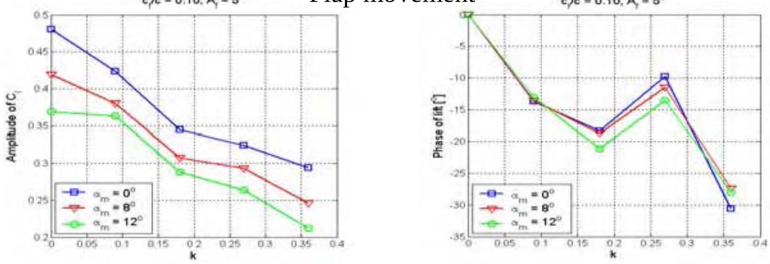


Harmonically pitching flap

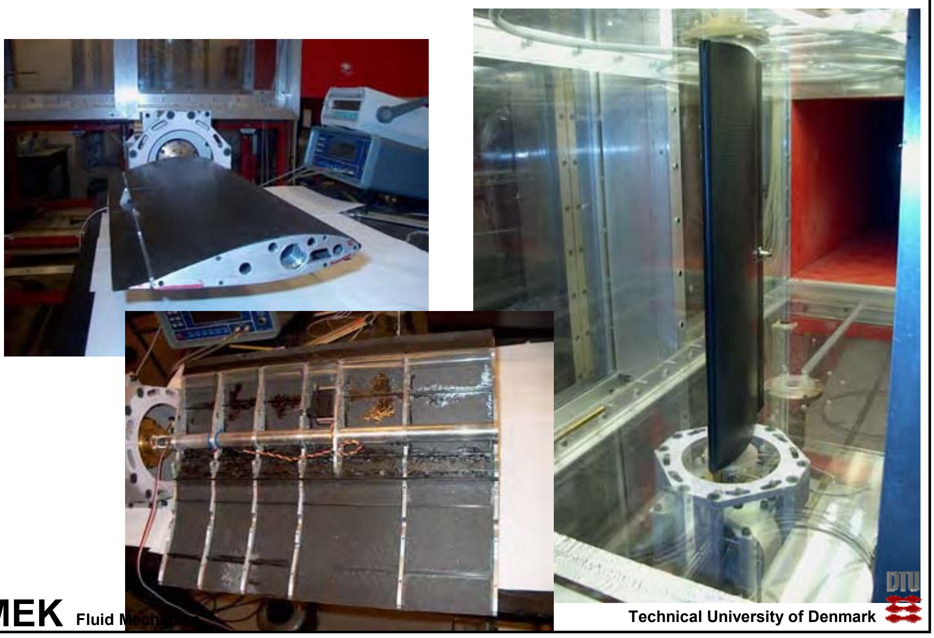
Pitch movement (2º amplitude)



Flap movement



Experimental efforts at DTU, MSc. project



Experimental plans at DTU, MSc. project

Wing:
- NACA 63-418 airfoil
- 20cm chord, 15% stiff flap
- Smart structure – conventional material
- Aluminium rib structure, Carbon fiber shells and flap
- Model servo, 60°/90ms

Tunnel:
- 0.5m x 0.5m, V_{max}= 65m/s
- Force balance measurements
- Pitch system for the hole blade

MEK Fluid Mechanics Technical University of Denmark

Summary

Wake interaction
- Distinct flow structures (tip vortices) in the wake have high impact on loads
- Results indicate that turbine no. 2 in line experiences the highest fatigue loads
- A TE-flap control model combined with actuator line could give new insight

2D CFD study (Niels Troldborg)
- Huge potential in using TE flaps
- Flap with moderate curvature and 5-10% chord length appears to be optimal from numerical 2D study

Experimental
- 2D wing is ready for testing

MEK Fluid Mechanics Technical University of Denmark

…by the way…

Remember EWEC conference at DTU, August 2007

The second conference on

“The Science of Making Torque from Wind”

Abstract deadline: 12 Jan. 2007

ACL – Aerodynamic forces

Local velocity

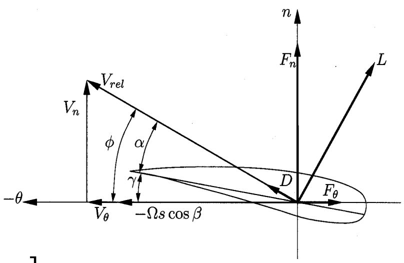
$$\mathbf{V}_{stn} = \mathbf{A}\mathbf{V}_{xyz}^{Field} - \mathbf{e}_s \Omega s \cos\beta + \dot{\mathbf{v}}_{stn}^{Flex}$$

Flow angle and relative velocity

$$\phi = \tan^{-1}\left(\frac{V_n}{-V_t}\right) \quad , \quad V_{rel} = \sqrt{V_n^2 + V_t^2}$$

Lift and drag using aerofoil data

$$[\mathbf{L},\mathbf{D}] = \tfrac{1}{2}\rho V_{rel}^2 c \left[C_L(\alpha,\mathrm{Re})\mathbf{e}_L, C_D(\alpha,\mathrm{Re})\mathbf{e}_D \right]$$



Regularization

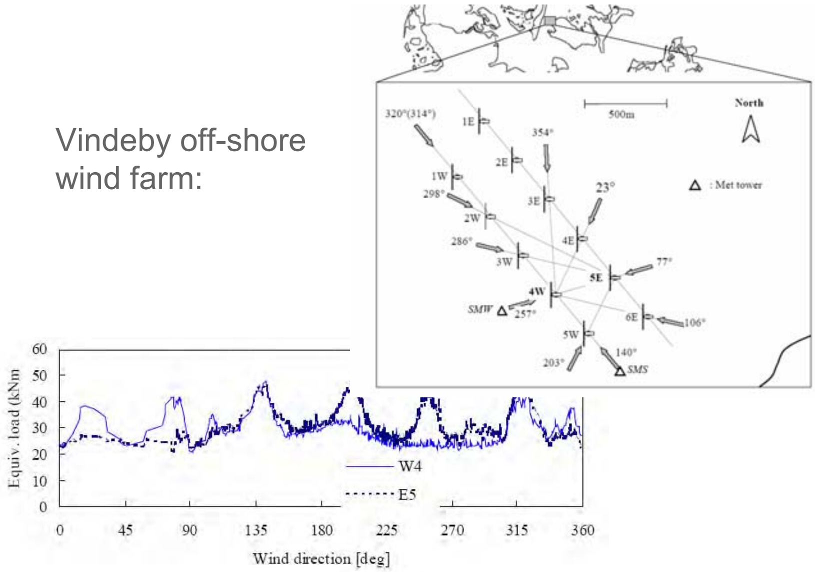
$$\mathbf{f}_\varepsilon^N = \mathbf{f}^N \otimes \eta_\varepsilon, \quad \eta_\varepsilon(p) = \frac{1}{\varepsilon^3 \pi^{3/2}} \exp\left[-\left(\frac{p}{\varepsilon}\right)^2\right]$$

Convolution

$$\mathbf{f}_\varepsilon(\mathbf{x}) = \sum_{N=1}^{B} \int_0^R \mathbf{F}^N(s)\, \eta_\varepsilon\left(\left|\mathbf{x} - s\mathbf{e}_N\right|\right) ds$$

Wind Turbine Wake Aerodynamics

Vindeby off-shore wind farm:



Blank page

Functional behaviors of SMA's and their potential use in actuator design

M Landa
Institute of Thermomechanics ASCR

IT ASCR

SMA group in Prague

http://www.fzu.cz/departments/metals/sma/index.php

Institute of Physics ASCR *P. Sittner, V. Novak*
- Theory, crystallography and thermodynamics of MTs
- Characterisation of material properties of SMA (TEM, RTG X-ray diffraction, DSC, metallography…)
- Functional properties of NiTi wires and hybrid textiles

Institute of Nuclear Physics ASCR *P.Lukas*
- In situ neutron diffraction

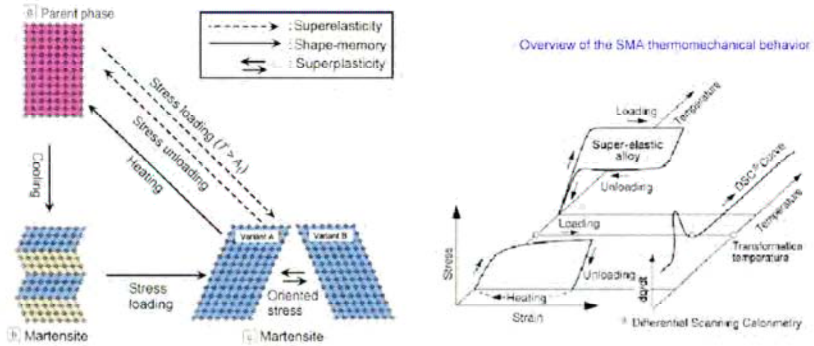
Institute of Thermomechanics ASCR *M.Landa*
- Acoustic and ultrasonic methods, material diagnostics
- Evaluation of material properties
- Characterization of kinetics of phase transitions
- Thermodynamical modelling

Charles University *T. Roubicek, M. Kruzik*
- Modelling of microstructures and mechanical properties of SMAs

IT ASCR

Shape-Memory Alloys

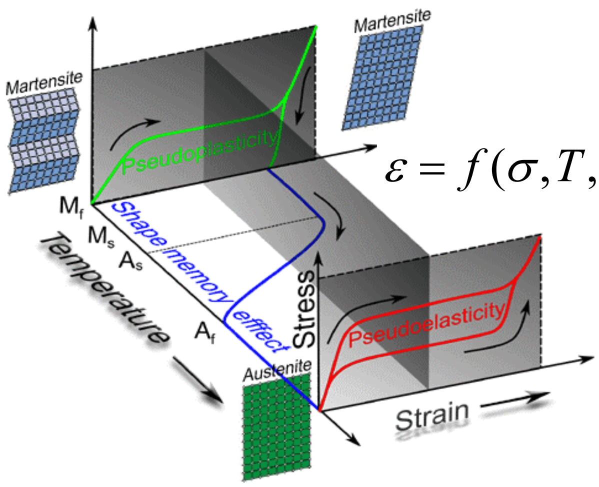
Shape memory alloys (SMA) are intermetallic ordered alloys changing macroscopic shape in dependence on the temperature, undergo recoverable deformations of the order of 7% or develop very high force when heated in constrained shape. These unique properties derive from thermoelastic martensitic transformation /MT/ driven by temperature and/or external stresses.



[modified after K.Otsuka, T. Kakeshita, MRS Bulletin Feb. 2002, 91-100]

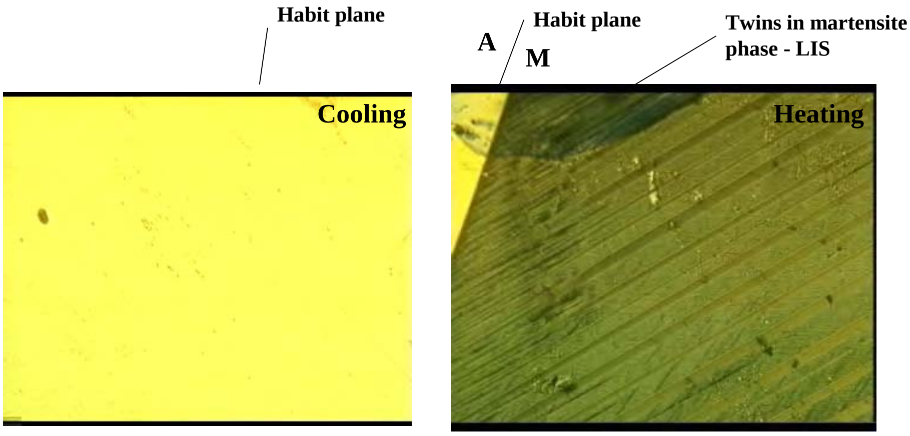
The high-temperature parent β-phase (cubic structure - austenite) of the SMA alloy undergoes reversible diffusionless first order transformation into a low-symmetry martensite phase (orthorhombic or monoclinic) upon cooling or mechanical loading.

Focus on mechanical aspects



$$\varepsilon = f(\sigma, T, history)$$

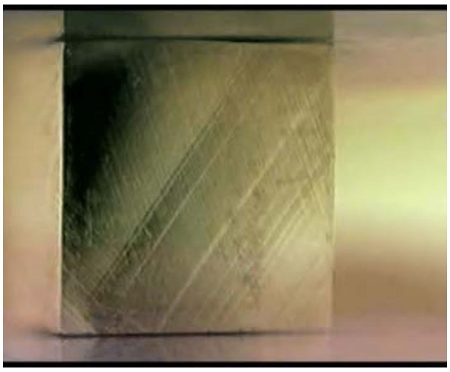
Stress free thermal cycle in temperature gradient



CuAlNi single crystal – single habit plane mode transformation can be achieved using cooling /heating in a controlled temperature gradient

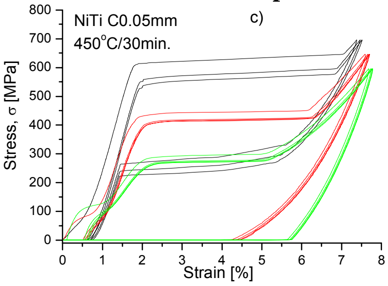
IT ASCR

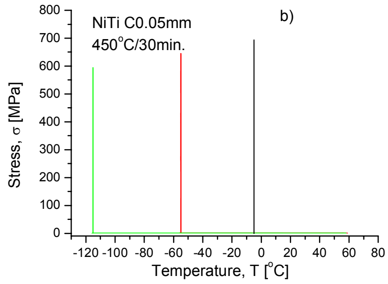
Stress induced transformation under constant temperature

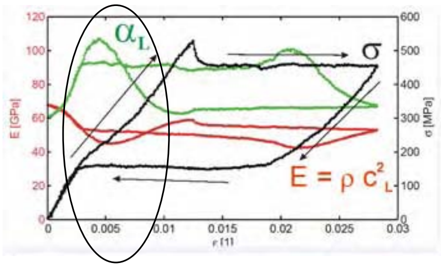


IT ASCR

R-phase in NiTi







Complex testing (USERIST)

1. Stress σ
2. Strain ε
3. Speed of L and T acoustic waves

   $E = \rho\ c^2_L$, $G = \rho\ c^2_T$

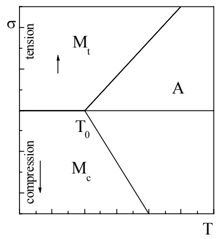
5. Attenuation of acoustic wave α_L, α_T
6. Electrical resistivity ρ^{el}

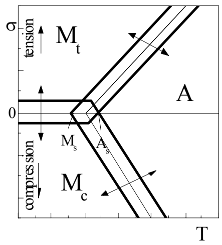
IT ASCR

Basic Characteristics of Pseudoelastic SMA's

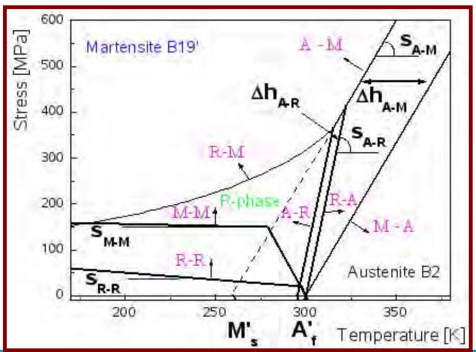
Phase diagram stress-temperature

Equilibrium Nonequilibrium





NiTi Alloy



IT ASCR

Functional quasistatic behaviors of SMA : deformation mechanisms, experiment and modelling
(present activity)

IT ASCR

Functional quasistatic behavior of NiTi polycrystals wires: experiments

SMA tester WALTERBAI for tensile tests on thin NiTi wires

A dedicated deformation machine for efficient thermomechanical testing of NiTi wires in tension (*modified for thin wire tests*)

$\sigma-\varepsilon-T-\rho$

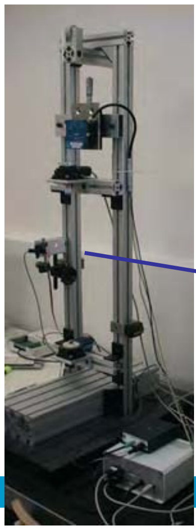
1. **Electromechanical deformation machine LFM-L**
   - Forces up to 5kN,
   - Strain rate up to 2000 mm/min,
   - Electrically isolated grips
   - Digital *closed-loop* control system
2. **Peltier furnace**
   - Temperatures -50°C-+200°C
   - Active cooling and heating
   - Temperature control integrated into software
3. **Integrated electric resistance measurement**
4. **Videoextensometer LM46**
   - Contactless strain measurement on thin wires
   - On-line 2D strain measurement on 2D objects (resolution 0.0005 mm (strain $5x10^{-6}$), on-line CCD kamera 795x596 pix.,)

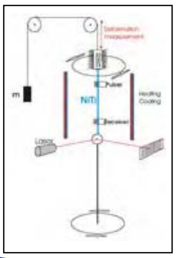
http://www.walterbai.com/

IT ASCR

Functional quasistatic behavior of NiTi polycrystals wires: experiments

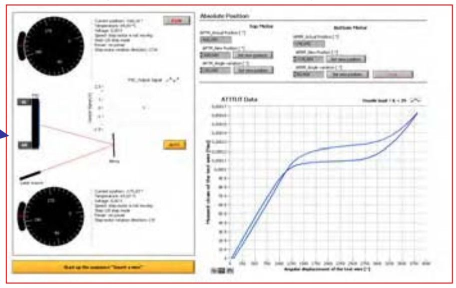
A selfdesigned dedicated deformation machine for Tension-Torsion thermomechanical tests on ultrathin NiTi wires (d= 0.01-0.1 mm)





A torsion moment comparator device allows:

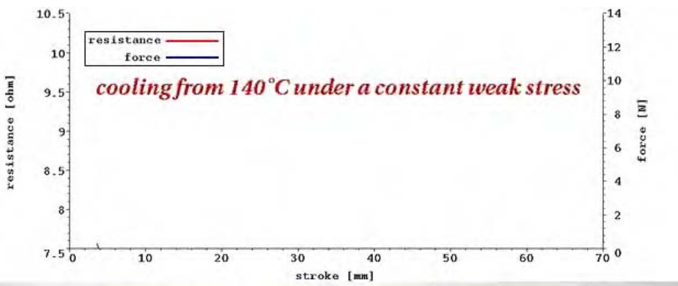
1. Evaluation of temperature dependence of elastic moduli E,G, in -100C - +200C range
2. Evaluation of strain responses upon thermal loading under biaxial stress state (tension-torsion)
3. Stress-strain-temperature curves in tension-torsion
4. in-situ electrical resistance and ultrasonic measurements during thermomechanical loadings



IT ASCR

Functional quasistatic behavior of NiTi polycrystals wires: experiments

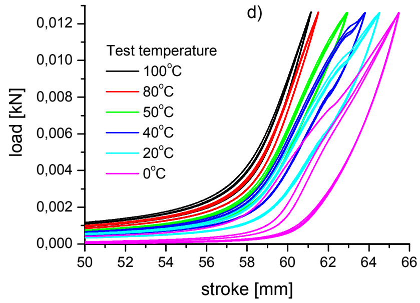
Snake spring behavior upon tensile loading
(tension-bending combined loading)



IT ASCR

Functional quasistatic behavior of NiTi polycrystals wires: experiments

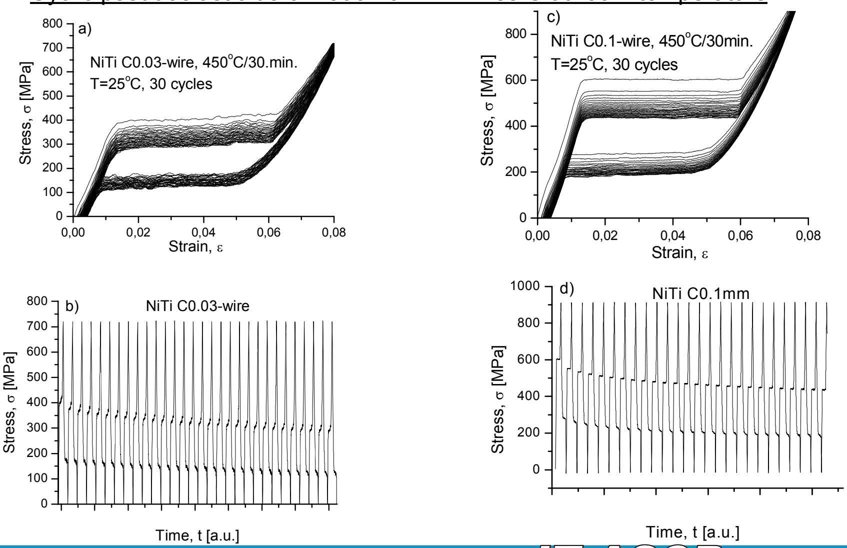
Snake spring behavior upon tensile loading
(tension-bending combined loading)



IT ASCR

Functional quasistatic behavior of NiTi polycrystals wires: experiments

Cyclic pseudoelastic deformation of NiTi wires C at room temperature



IT ASCR

Functional quasistatic behavior of NiTi polycrystals wires: experiments

Material parameter tables

E_A..Young modulus of austenite,
E_M..Young modulus of martensite evaluated from pseudoelastic σ–ε curves,
Ms, Rs, A_f… transformation temperatures defined as temperatures, where transformation lines meet the T-axis,
ε_M^{tr} ε_R^{tr}..transformation strain of the martensite and R-phase transformations (plateau strain),
s_M s_R slopes of temperature dependencies of transformation stresses for martensite and R-phase transformations,
σ_M^{re} , σ_R^{re}.. minimal reorientation stresses for martensite and R-phase
s_M^{re} s_R^{re} ... slopes of temperature dependencies of reorientation stresses
σ^Y …..Yield stress for plastic deformation at RT

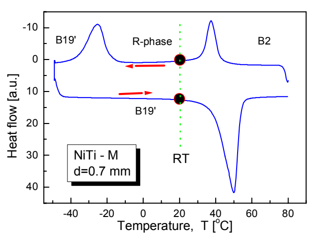
Set of 14 material parameters for modelling the functional behaviors of NiTi wires C and H

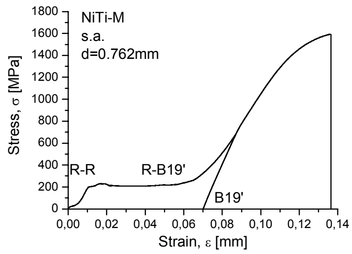
Wire	E_A	E_M	M's	R's	A'$_f$	ε_M^{tr}	ε_R^{tr}
	GPa	GPa	ºC	ºC	ºC	%	%
C	**72**	**33**	**-110**	**12**	**-30**	**6.3**	**1**
H	**60**	**45**	**46**	**71**	**80**	**5.2**	**0.6**

Wire	s_M	s_R	σ_M^{re}	σ_R^{re}	s_M^{re}	s_R^{re}	σ^Y
	MPa/ºC	MPa/ºC	MPa	MPa	MPa/ºC	MPa/ºC	MPa
C	**4.8**	**17**	**-**	**0-180**	**-**	**-1**	**1546**
H	**7**	**14**	**170**	**20**	**-0.36**	**0**	**830**

IT ASCR

In-situ thermal infrared imaging on deforming thin NiTi wires





NiTi -M wire in tension

Detection of localized deformation of NiTi -M wire in complex bending

IT ASCR

Functional quasistatic behavior of NiTi polycrystals wires: experiments

Material parameters needed for simulation of electric resistance of NiTi wire

	Austenite	R-phase	Martensite
Phase el. res.	$\rho_{0A} = 75\mu\Omega\ cm$ $T_{0A} = 373K$	$\rho_{0R} = 85.0\mu\Omega\ cm$ $T_{0R} = 333K$	$\rho_{0A} = 86.5\mu\Omega\ cm$ $T_{0M} = 283K$
Temperature dependence	$\frac{\partial\rho_A}{\partial T} = 0.05\mu\Omega\ cm\ K^{-1}$	$\frac{\partial\rho_R}{\partial T} = 0.05\mu\Omega\ cm\ K^{-1}$	$\frac{\partial\rho_M}{\partial T} = 0.15\mu\Omega\ cm\ K^{-1}$
Stress dependence	$\frac{\partial\rho_A}{\partial\sigma} = 0.0005\mu\Omega\ cm\ MPa^{-1}$	$\frac{\partial\rho_R}{\partial\sigma} = 0.0005\mu\Omega\ cm\ MPa^{-1}$	$\frac{\partial\rho_M}{\partial\sigma} = 0.0015\mu\Omega\ cm\ MPa^{-1}$
Strain dependence	----	----	$\frac{\partial\rho_M}{\partial\varepsilon} = 180\mu\Omega\ cm$
Other (R-phase distortion)	----	$\frac{\partial\rho_R}{\partial\alpha} = 20\mu\Omega\ cm\ \deg^{-1}$	----

IT ASCR

Functional quasistatic behavior of NiTi polycrystals wires: modelling

Algorithm Rloop: Reliable quantitative description of uniaxial stress – strain – temperature responses of SMA elements in general thermomechanical loads

The core of the hysteretic algorithm is the proposed governing differential kinetics equation
=> In fact 2 slightly different equations for the forward and reverse MT yielding

evolution functions for martensite phase fraction
ξ=ξ(φ) as history dependent solutions for various thermomechanical cycles

Driving force variable $\varphi = T - \frac{\sigma}{s}$

***Reverse MT**, dφ/dt>0:*

$$\frac{d\xi}{\mathrm{dt}} = -c\frac{G}{s}\xi^{l}(1-\xi)^{(m+n)}e^{-G(\varphi-T_0)}\frac{d\varphi}{dt}$$

***Forward MT**, dφ/dt<0:*

$$\frac{d\xi}{\mathrm{dt}} = -c\frac{G}{s}\xi^{(n+l)}(1-\xi)^{m}e^{G(\varphi-T_0)}\frac{d\varphi}{dt}$$

Constitutive equation

$$d\varepsilon = \frac{d\sigma}{E^{w}} + \alpha dT + \gamma_m \tanh\left(k_1\frac{\sigma}{\sigma^{re}-k_2}\right)d\xi$$

- **Reliable description of four basic thermomechanical functional behaviors of SMAs in stress-strain-temperature space: pseudoelasticity, pseudoplasticity, shape memory effect, recovery stress cycle**

- **3D models and its implementation to FEM system under development**

Download Rloop at: http://www.fzu.cz/departments/matals/sma/18.html

IT ASCR

Functional quasistatic behavior of NiTi polycrystals wires: modelling

Modelling of variation of electric resistance of NiTi wires during thermomechanical cycles

Wire resistance: $\rho_{tot} = \rho_A(1- \xi_R - \xi_M) + \rho_R . \xi_R + \rho_M . \xi_M$

where ρ_{tot} is total resistance of specimen, ρ_A , ρ_R and ρ_M are specific resistivity of austenite, R-phase and martensite, respectively, ξ_R and ξ_M are volume fractions of R-phase and martensite.

austenite resistance:

$$\rho_A = \rho_{0A} + (T_{0A} - T).\frac{\partial \rho_A}{\partial T} + \sigma \frac{\partial \rho_A}{\partial \sigma}$$

R-phase resistance:

$$\rho_R = \rho_{0R} + (T_{0R} - T).\frac{\partial \rho_R}{\partial T} + \sigma \frac{\partial \rho_R}{\partial \sigma} + (90 - \alpha_R).\frac{\partial \rho_R}{\partial \alpha_R}$$

Martensite resistance:

$$\rho_M = \rho_{0M} + (T_{0M} - T).\frac{\partial \rho_M}{\partial T} + \sigma \frac{\partial \rho_M}{\partial \sigma} + \varepsilon_M^{tr}.\frac{\partial \rho_M}{\partial \varepsilon_M^{tr}}$$

where T is temperature, σ is stress, α_R is rhomboedricity of R-phase, ε_M^{tr} is transformation strain induced by martensite, all other symbols are parameters determined from experiment.

IT ASCR

Main activities in WP 1B3 UpWIND Project: Smart rotor blades and rotor control

Task 1: Knowledge database

- **Investigation of functional quasistatic and dynamic properties of SMA's in a form of wires, bars, strips etc.**
- **Classification of functional phenomena**
  - shape memory effect,
  - superelasticity with a large(small – R-phase in NiTi) strain range,
  - thermally driven actuation
  - energy dissipation – vibration damping
- **based on structural and lattice orientation changes**
  - martensite transformation
  - martensite reorientation
  - R-phase transformation

  for smart structure applications in smart rotors
  (actuators, passive damping)

- **Modelling approaches**
  - **Hysteretic algorithm Rloop:** Reliable quantitative description of uniaxial stress – strain – temperature responses of SMA elements in general thermomechanical loads. - http://www.fzu.cz/departments/matals/sma/18.html
  - 3D models and its implementation to FEM systems

IT ASCR

Main activities in WP 1B3 UpWIND Project: Smart rotor blades and rotor control

Task 3: Development of aerofoil, control devices, sensors, actuators, communication

SMA actuators are expected to be used in smart structures for
- i) position control of moving parts
- ii) vibration control

Design of SMA actuators :
1. Choice of suitable material,
2. Choice of suitable heat treatment conditions
3. Proposition of various shape of actuators
   (single wires, strips, wire bundles, wire textiles)
   with respect to loading
   (tension, compression, torsion, bending)
   adopting of material characteristics obtained from Task 1

Models for optimal adjustment of actuator behavior

IT ASCR

Main activities in WP 1B3 UpWIND Project: Smart rotor blades and rotor control

Task 4: Structural models of smart materials in composite structures

Main functionalities of embedded SMA parts in composite shell structures:
- passive vibration dumping - consuming of vibration energy,
- improvement of impact protection of composite structures .
- Improvement of strength and decrease of weigth of rotor blade

Collaboration IT ASCR with VTT on production and testing hybrid composite specimens

IT ASCR

Functional dynamic behaviors of SMA : deformation mechanisms, experiment and modelling

(planned activity)

IT ASCR

Functional dynamic behaviors of SMA

The use of shape memory alloys (SMA) in the form of wires has been identified as a one of means to solve the problems treated within the Up-Wind projects. It is intended to benefit from the unique shape memory alloys properties by using them as an actuator and/or damping element embedded in composites for the active and/or passive vibration control. In order to apply the SMA wires for these purposes in a correct and most efficient way, it is necessary to understand their dynamical behaviour (i.e. the response on an applied dynamic excitation, energy dissipation during vibrations).The unique properties of SMA arise from the first-order martensitic structural transformations taking place during thermo-mechanical loading and providing a complex dynamical behaviour being strongly nonlinear. Due to this, the dynamic response depends on many parameters such as amplitude of vibrations, temperature and prestress.

The **experimental observation** and identification of the dynamic behaviour of SMA wires will be crucial point of the project for two main reasons. First, it will allow to find out the achievable efficiency of their use in vibration control.

Second, related to the development of **mathematical model** of dynamic behaviour of SMA wire which is to be developed within this project, the experimental data will provide a necessary confrontation experiment-simulation and possibly calculate internal parameters of the model.

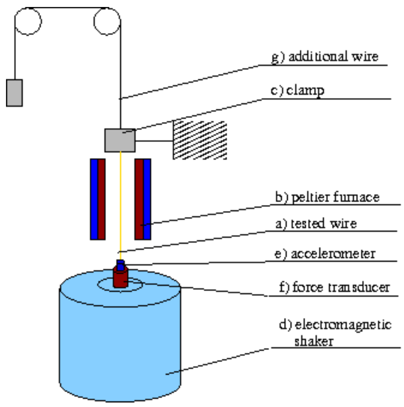
IT ASCR

Functional dynamic behaviors of SMA: experiments the measurement system is under construction

The tested wire (a) surrounded by the peltier furnace (b) to control the temperature conditions, is fixed between a clamp (c) and electromagnetic shaker (d) ensuring the excitation function.

A piezoelectric accelerometer (e) with a force transducer (f) are mounted on the shaker to provide identification of the frequency response function at the end of the wire. To ensure a known value of prestress, the tested wire is first preloaded, when clamp being removed, via a mass attached to the end of an additional wire (g).

After the this operation the clamp is applied to simulate the clamp-free boundary conditions for longitudinal vibrations.



IT ASCR

Functional dynamic behaviors of SMA: experiments

- The measuring methods to be applied are as follows:
- **Sub-resonant mode** – forced oscillation with an imposed frequency in a large frequency range (100Hz – 15KHz)
  - measuring as a function of frequency at a constant temperature – identification of the loss tangent *tan(φ)* (a measure of damping) and storage module *E'*.
- **Resonant mode** – the tester work at the resonant frequency of the wire which can be adjust by using an additional mass attached to the end of the wire. Loss tangent *tan(φ)* corresponding to the resonant frequency is identified with higher precision then with sub-resonant mode.
  - measuring of the frequency response function peak with changing temperature allows us to measure the evolution of the damping ≈ *tan(φ)* (thickness of the peak) and stiffness ≈ *E'* (position of the peak) with respect to the temperature.
- Further, the identification of harmonics and their level can provide a measure of the level of nonlinearities which are also related to the transformation processes in SMA wire. Hence the dynamical response can be seen as probe to obtain information about the micro structure of the material, without disturbing it.

IT ASCR

Functional dynamic behaviors of SMA: modelling

•adding the heat transfer equation to RLoop algorithm:

$$\rho C \frac{\partial T}{\partial t} - \nabla \cdot (k \nabla T) = Q$$

•determination of material parameters (heat capacity, thermal conductivity, heat source) using temperature field measurement by infrared camera

•solving the equation with different boundary condition:

$$\mathbf{n} \cdot (k \nabla T) = q_0 + h(T_{inf} - T) + C_{const}(T_{amb}^4 - T^4)$$

assuming frequency dependence Joule heating, air cooling, water cooling, wire embedded in composite...

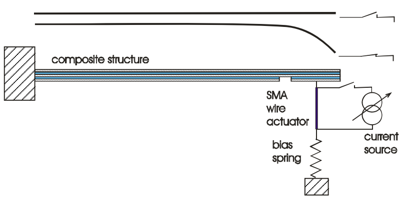
•adding kinetic terms in RLoop equation – will be added (if necessary) after performing the vibration tests

IT ASCR

Structural models of smart materials in composite structures

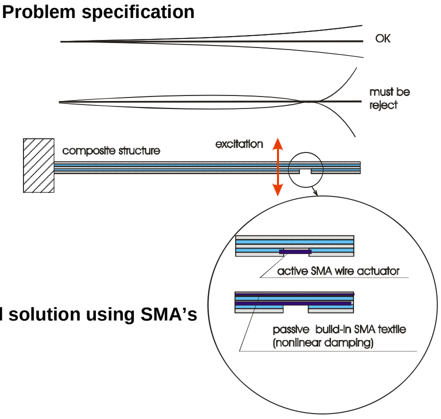
... some suggested possibilities, which will be specified after december bilateral meeting with VTT

Shape setting of composite structure



Vibration control

Problem specification



Suggested solution using SMA's

IT ASCR

Airfoil design for wind turbines at IAG

IEA Topical Expert Meeting, Delft, 11./12. December 2006

Dipl.-Ing. Andreas Herrig

Institute of Aero- und Gas Dynamics (IAG)

University of Stuttgart

Overview

- Previous related projects
- Airfoil design and analysis
  - constrained direct numerical optimizations
  - trailing edge noise prediction code
- LWT aerodynamic tests
- LWT aeroacoustic tests
  - CPV method

Previous related projects

- STENO (tip noise)
- DRAW (trailing edge noise prediction code)
- DATA (design of airfoils with reduced trailing edge noise emission and validation on model rotor)
- SIROCCO (design of airfoils with reduced trailing edge noise emission and full-scale validation)

IAG Universität Stuttgart

Noise prediction code

XFOIL mod.

Velocity distribution $U_e(s)$ and initial values for δ_1, δ_2

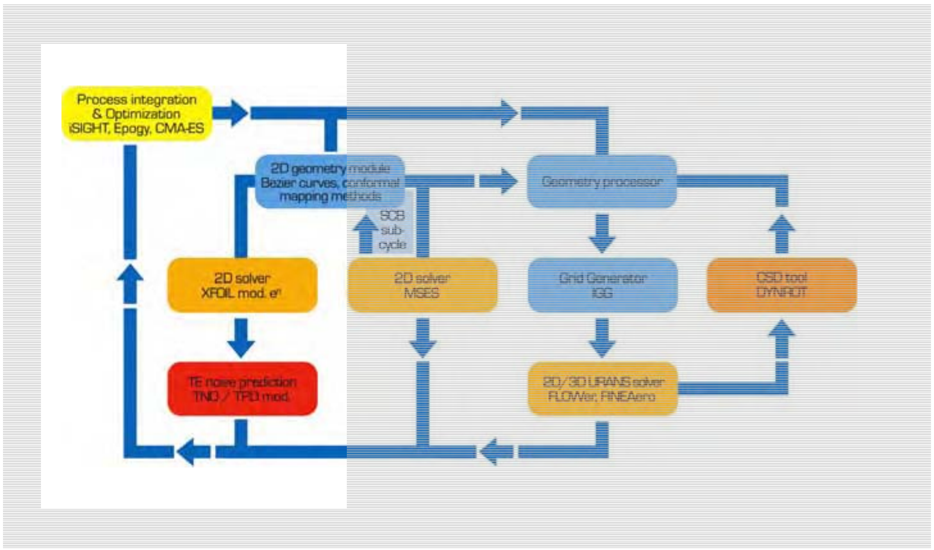
- Calculation of the mean velocity pofiles + distribution of turbulence properties across the boundary layer ($\overline{v'^2}, \omega, k_T, L$) by means of EDDYBL FD code
- Semi-empirical determination of Λ_2 from calculated turbulence length scale L

- Approximation of the $\overline{v'^2}$ spectrum
- Determination of the surface pressure fluctuations
- Evaluation of the diffraction integral

Spectrum of the trailing-edge far-field noise

IAG Universität Stuttgart

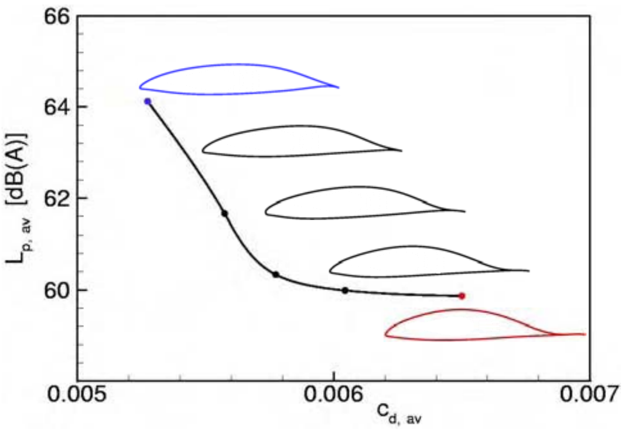
Optimization Environment POEM



IAG Universität Stuttgart

Optimization process

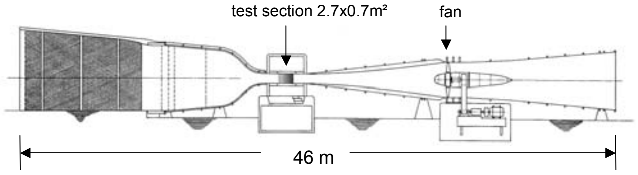
- Pareto-front for multi-criteria optimization (noise vs. drag)



no constraints except t/c

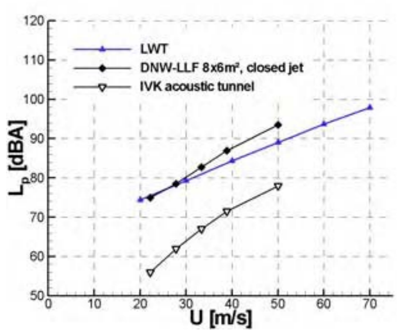
IAG Universität Stuttgart

Laminar Wind Tunnel (LWT) Stuttgart



U < 90m/s
Re < $5x10^6$
Ma < 0.26

very low turbulence (0.02%) <==> high background noise level

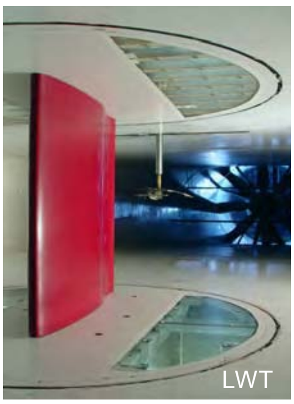


Comparison of LWT to other european wind tunnels.
(data from SAE 950625)

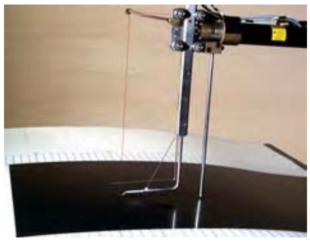
IAG Universität Stuttgart

Laminar Wind Tunnel (LWT)

➢ measurement capabilities (outline)



- standard polar measurements α - c_l, c_d
- pressure distribution c_p
- transition and separation position



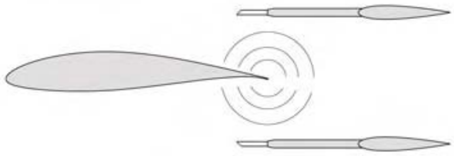
boundary-layer measurements

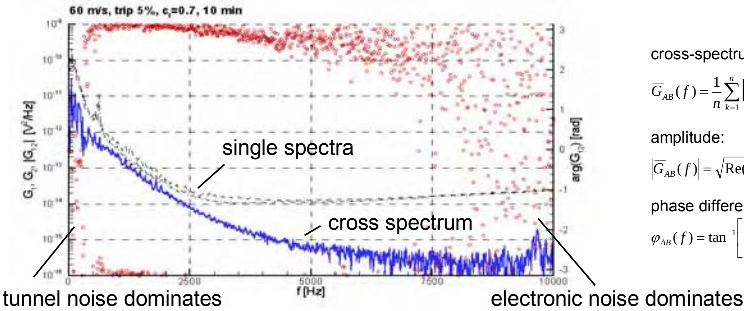
New: aeroacoustic measurements

IAG Universität Stuttgart

Aeroacoustic verification – CPV-method

- basic principle





cross-spectrum:

$$\bar{G}_{AB}(f) = \frac{1}{n}\sum_{k=1}^{n}\left[X^{*}_{Ak}(f)X_{Bk}(f)\right]$$

amplitude:

$$\left|\bar{G}_{AB}(f)\right| = \sqrt{\mathrm{Re}(\bar{G}_{AB}(f))^2 + \mathrm{Im}(\bar{G}_{AB}(f))^2}$$

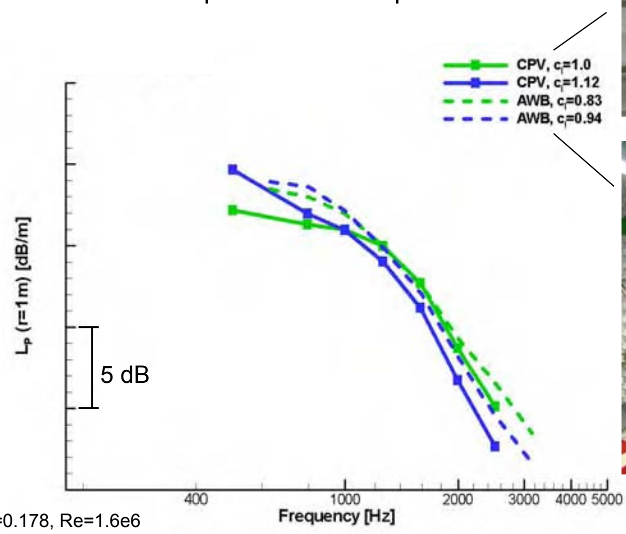
phase difference:

$$\varphi_{AB}(f) = \tan^{-1}\left[\frac{\mathrm{Im}(\bar{G}_{AB}(f))}{\mathrm{Re}(\bar{G}_{AB}(f))}\right]$$

IAG Universität Stuttgart

Validation of CPV-method

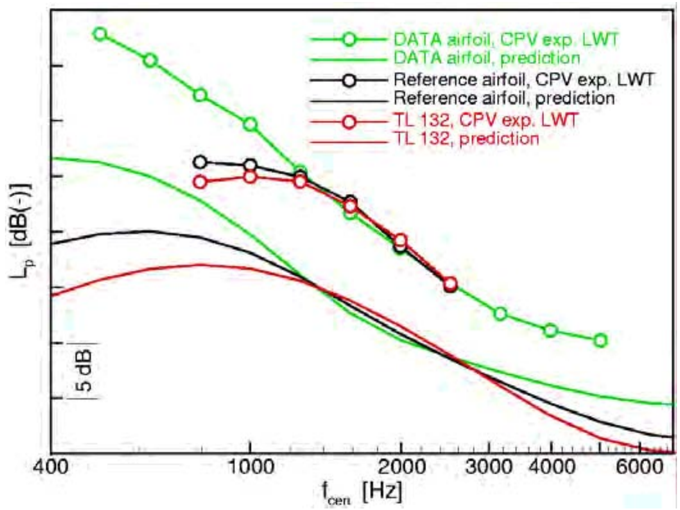
- 1/3-octave spectra of sound pressure level



Ma=0.178, Re=1.6e6

IAG Universität Stuttgart

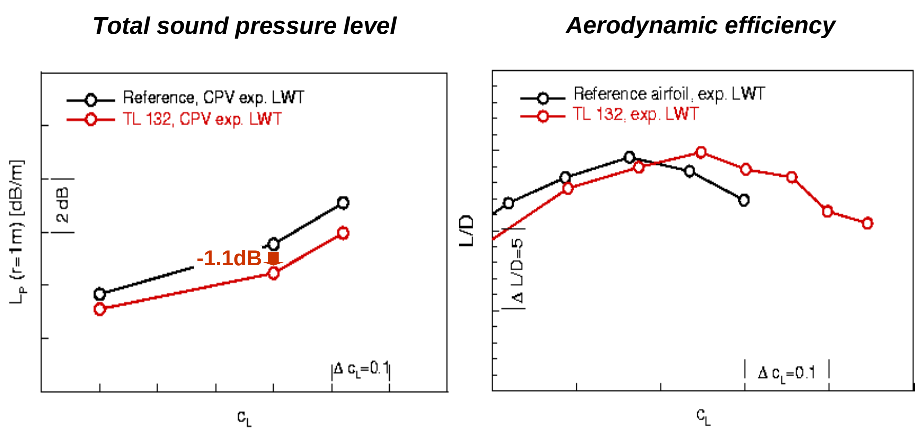
Noise prediction validation



Predicted & measured noise spectra (Re=1.6·10^6, forced transition x_{trans}/c=0.05)

IAG Universität Stuttgart

Wind-Tunnel Verification of the New Designs *Airfoil TL 132*

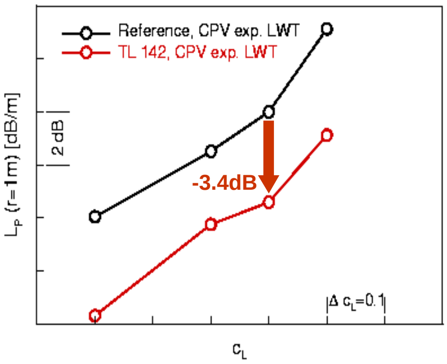


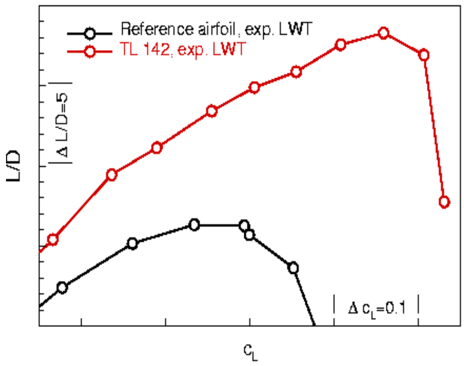
Measured properties around main design lift coefficient,
Re=1.6·10^6, forced transition x_{trans}/c=0.05

IAG Universität Stuttgart

Wind-Tunnel Verification of the New Designs — *Airfoil TL 142*

Total sound pressure level — ***Aerodynamic efficiency***



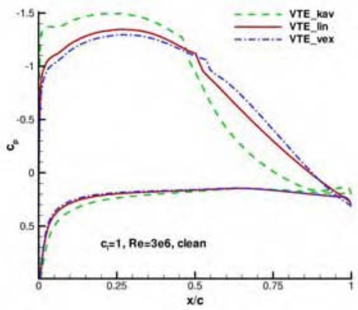


Measured properties around main design lift coefficient,
$Re=1.6 \cdot 10^6$, forced transition $x_{trans}/c=0.05$

IAG Universität Stuttgart

Variable-Trailing-Edge (VTE) Airfoil

- deformable suction side
- change of main pressure recovery region
- purpose: investigation of boundary layer development

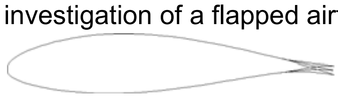


IAG Universität Stuttgart

Conclusions and Outlook

- further development of noise prediction code for airfoils with flaps
- RANS coupling

- aerodynamic and aeroacoustic investigation of a flapped airfoil in LWT (NACA 64-418?)



- need to fix parameters (*Re*, c_L-range, chord length, flap chord length, deflection range, etc...) for the tests
- flap construction details in cooperation with project partners

IAG
Universität Stuttgart

Summary of IEA RD&D Wind – 50th Topical Expert Meeting on

THE APPLICATION OF SMART STRUCTURES FOR LARGE WIND TURBINE ROTOR Blades

December 2006, Delft, theNetherlands

Harald E.N. Bersee and Sven-Erik Thor

Background

Wind turbines become larger and larger. Modern wind turbines designed for offshore application have become the largest rotating machines on earth, with the length of one blade almost equal to the entire span of a Boeing 747. This upscaling has, until now, not led to significant changes in the blade structure: all blades are constructed as one single component, with the blade skin as load carrying element. On the contrary, the control of the blade loads has changed in the past. Until the nineties in the previous century, the 'Danish concept' was very successful. The turbines making use of this concept combine constant rotor speed with stall of the flow around the rotor blades: increasing wind speeds automatically induce increasing drag forces that limit the absorbed power. All other control options were considered too complex. Most modern large wind turbines run at variable rotational speed, combined with the adjustment of the collective pitch angle of the blades to optimize energy yield and to control the loads. This is a big step forward: the control of the blade pitch angle has not only led to power regulation, but also to a significantly lighter blade construction due to the lower load spectrum and a lighter gear box due to shaved torque peaks.

The next step in blade load control is almost ready for commercial application: pitch angle adjustment per blade instead of collective. This will further alleviate the rotor loads, specially the periodic loading due to yaw and wind shear. Not only blades will benefit from this, but also the drive train and nacelle structure.

A further step, probably for the 2020 wind turbine generation with even larger rotor size, probably requires a much more detailed and faster control of the loads. Control should be possible for each blade at any azimuthal position and any spanwise station, by aerodynamic control devices with embedded intelligence distributed along the span. The correspondence with the control devices at airplane wings (flaps at leading and trailing edge, ailerons) is apparent, but the requirements for blade control devices are probably much more severe. Modern blades are very reliable and require only limited maintenance at the blade pitch bearing. Future blades with distributed control devices should be as reliable, without adding maintenance requirements.

The development of this kind of technology, often named in popular terms 'smart structures' or 'smart technology', is an interdisciplinary development par excellence.

Objective

The objective of the meeting was to report and discuss progress of R&D on all of the above mentioned topics. Since this area of research is relatively new (for wind turbines), many challenges and solutions are still to be discussed and tested. It was expected that the expert meeting will result in new and challenging directions in R&D as a result of the discussions between experts of different origin.

Participants / Presentations

A total of 29 participants attended this meeting with representatives from Denmark, Finland, Germany, Norway, Spain, Sweden, the Netherlands, UK and USA. Observers the Czech Republic and Poland were present at the meeting. This was in line with the strategy to involve more countries into the IEA work. This opportunity gave these participants a possibility to evaluate some of the benefit being a member. The participants mainly represented National Research Organizations.

The large number of participants in the meeting reflected the new borne interest in this research topic and application of basic research from other disciplines.

The meeting was a co-arrangement between IEA and the EU UPWind-project. The first 1 ½ days were dedicated to the IEA meeting and the remaining of day two covered topics relevant to UPWind participants only.

A total of 19 presentations were given on the following topics:

1. Introductory Note to Meeting
2. Smart Rotor Blade Control for Wind Turbines
3. Active Control Devices for Wind Turbine Blades
4. Load Alleviation on Wind Turbine Blades using Variable Airfoil Geometry
5. Aeroelastic Modeling forSmart Rotors: Issues
6. Turbine Blade Flow Fields and Active Aerodynamic Control
7. Collocated Damping of Rotating Wind Turbine Blade
8. Smart Rotor Blade Control for Wind Turbines
9. MAFESMA Material Algorithms Finite Elements Shape Memory Actuators
10. Smart Rotor for Wind Turbine Blades - Materials and Structure
11. An example for adaptive technology
12. Modeling of a ‘Smart’ rotor from the control point of view
13. Adaptronics for Wind Energy Plants
14. Smart interfaces between blades and hub
15. The Application of Smart Structures for Large Wind Turbine Blades
16. Embedded structural intelligence - Development of adaptive wing profile
17. Aerodynamic modelling of flap
18. Functional behaviors of SMA’s and their potential use in actuator design
19. Airfoil design for wind turbines at IAG

Discussion

At the finalizing discussion a number of different topics were handled. A general attitude was that this is a new an challenging area in the wind turbine research which in the future may result in more effective ways of controlling power production. This may in the end result in lower cost per produced kWh.

A summary of topics raised during the discussion was:

Challenges related to “smart structures” are:

- It is difficult to find the costs in real life for these new technologies. It is too early to ask this question. You should aim for 30% (substantial) load reduction to compensate for the risks. Reliability is nr one.
- SMA[1] materials have an on/off characteristic, but the need in wind turbines is to have a variable amplitude.
- Control issues related to SMA is cooling, temperature range and loads
- Damages from lightning strikes in SMA materials and conductors must be handled. On Helicopter blades it is certified and thus they have solved the problem of lightning strike.
- It is important to try to damp edge wise oscillations in blades. Can this be handled by these techniques? Damping figures of 0,5 to 1,5% was mentioned as needed.
- Bending/torsion coupling in the blades may be introduced to control power. It has been utilized in small scale. Not used commercially since the tools are not sufficient to claim efficiency increase, structure will cost more so trade off can not be made accurately.
- Missing in the discussion is the need for sensors and energy supply of the actuators. For information, there is a national Danish program on sensoring.
- Efficiency of actuator depends on airfoil. Is there a need to develop an airfoil specifically for these actuators? Both Riso and University of Stuttgart are developing such an airfoils.
- Aerodynamicists are beginning to understand effects caused by non stationary phenomenon, which were thought of being stationary. Non stationary, high frequency phenomenon should be investigated.

Continuation

At the end of the discussion there was an exposition of the possibilities to continue the exchange of information relevant to the topic. The possibilities were considered to be either to prepare for a new Task or to arrange another Topical Expert Meeting in the near future. The participants were very enthusiastic to support a continuation in the form of a new Topical Expert Meeting. The suggestion is to have annual meetings on smart structures with some added topics like new structural and 3 D aerodynamical concepts. The Operating Agent was advised to present this to the Executive Committee.

[1] SMA = Shape Memory Alloy

Blank page

List of participants

IEA RD&D Wind Task 11, Topical Expert Meeting #50
The application of smart structures for large wind turbine rotor blades

No	NAME	COMPANY	ADDRESS 1	ADRESS 2	ADRESS 3	COUNTRY	CC	PHONE	E-mail
1	Thomas Buhl	Risö Wind Energy Department	Building VEA-118	P.O. Box 49	DK-4000 Roskilde	Denmark	45	46775467	thomas.buhl@risoe.dk
2	Robert Mikkelsen	Technical University of Denmark	Dept. of Mechanical Engineering	Nils Koppels Alle, Bldg. 403	DK-2800 Lyngby	Denmark	45	45254320	rm@mek.dtu.dk
3	Jan Riess Høgsberg	Technical University of Denmark	Dept. of Mechanical Engineering	Nils Koppels Alle, Bldg. 403	DK-2800 Kgs. Lyngby	Denmark	45	45251971	jhg@mek.dtu.dk
4	Merja Sippola	VTT	Otakaari 7 B, Espoo	PO Box 1000	02044 VTT	Finland	358	503287001	merja.sippola@vtt.fi
5	Tomi Lindroos	VTT	SINITAIVAL 6	PO Box 1300	33101 TAMPERE	Finland	358	503020227	tomi.lindroos@vtt.fi
6	Christoph Kensche	Fraunhofer-Center für Windenergie und Me	Experimentelle Simulation und Prü	Am Lunedeich 158	27572 Bremerhaven	Germany	49	471 902629-20	christoph.kensche@ifam.fraunhofer.de
7	Thilo Bein	Fraunhofer-Institut für Betriebsfestigkeit und Systemzuverlässigkeit		Bartningstraße 47	64289 Darmstadt	Germany	49	6151 705-463	thilo.bein@lbf.fraunhofer.de
8	Mark Capellaro	Institut für Flugzeugbau	Universität Stuttgart	Allmandring 5B	70550 Stuttgart	Germany			capellaro@ifb.uni-stuttgart.de
9	Martin Kuhn	Institut für Flugzeugbau	Universität Stuttgart	Allmandring 5B	70550 Stuttgart	Germany	49	7116853406	kuehn@ifb.uni-stuttgart.de
10	Thorsten Lutz	Institut für Aerodynamik und Gasdynamik	Universität Stuttgart	Pfaffenwaldring 21	70550 Stuttgart	Germany	49	7116853406	lutz@iag.uni-stuttgart.de
11	Werner Wuerz	Institut für Aerodynamik und Gasdynamik	Universität Stuttgart	Pfaffenwaldring 21	70550 Stuttgart	Germany	49	71168563470	wuerz@iag.uni-stuttgart.de
12	Andreas Herrig	Institut für Aerodynamik und Gasdynamik	Universität Stuttgart	Pfaffenwaldring 21	D-7055 Stuttgart	Germany	49	71168569976	herrig@iag.uni-stuttgart.de
13	Andreas Knauer	Institutt for energiteknikk	Postboks 40	2027 Kjeller		Norge	47	63806386	Andreas.Knauer@ife.no
14	Susana Apinanez	Robotiker	Parque Tecnológico, .	Edificio 202	E-48170 Zamudio (Bizkaia	Spain	34	94 600 22 66	apinaniz@robotiker.es
15	Sven-Erik Thor	Vattenfall	Windenergy	162 87 Stockholm		Sweden	46	8 73 969 73	sven-erik.thor@vattenfall.com
16	Jan-Willem van Wingerden	Delft Center for Systems and Control	Faculty of Design, Engineering an	Mekelweg 2	2628 CD Delft	the Netherlands			J.W.vanWingerden@tudelft.nl
17	Jaap 't Hooft	SENTER Novem	P.O. Box 8242	3503 Utrecht		the Netherlands		302 393 468	j.t.hooft@senternovem.nl
18	Thanasis Barlas	Delft Univ of Techn, DUT	Faculty of Aerospace Engineering	Kluyverweg 1	2629 HS Delft	theNetherlands	31	152782877	A.Barlas@tudelft.nl
19	Teun Hulskamp	Delft Univ of Techn, DUT	Faculty of Aerospace Engineering	Kluyverweg 1	2629 HS Delft	theNetherlands	31	152789746	a.w.hulskamp@tudelft.nl
20	Benjamin Marrant	Delft Univ of Techn, DUT	Faculty of Aerospace Engineering	Kluyverweg 1	2629 HS Delft	theNetherlands			B.A.H.Marrant@tudelft.nl
21	Harald Bersee	Delft Univ of Techn, DUT	Faculty of Aerospace Engineering	Kluyverweg 1	2629 HS Delft	theNetherlands	31	152788175	h.e.n.bersee@tudelft.nl
22	Gijs van Kuik	Delft Univ of Techn, DUT	Faculty of Aerospace Engineering	Kluyverweg 1	2629 HS Delft	theNetherlands	31	152785170	g.a.m.vankuik@tudelft.nl
23	Pieter van Langen	ECN	Wind Energie	P.O. Box 1	1755 ZG Petten	theNetherlands	31	224564764	vanlangen@ecn.nl
24	Hein de Vries	University Twente	Eng. Fluid Dynamics	P.O. Box 217	7500 AE Enschede	theNetherlands	31	534891187	h.devries@ctw.utwente.nl
25	Michel Verhaegen	Delft Center for Systems and Control	Mekelweg 2	2628 CD	Delft	theNetherlands	31	152785119	M.Verhaegen@dcsc.TUDelft.NL
26	Tomas Vronsky	Vestas Technology UK	Head of Blade Structure			UK			tvr@vestas.com
27	Gunjit Bir	National Renewable Energy Laboratory	NWTC-3811	1617 Cole Boulevard	Golden, CO 80401-3393	USA	1	303 384-6953	gunjit_bir@nrel.gov
28	Scott Schreck	National Renewable Energy Laboratory	NWTC-3811	1617 Cole Boulevard	Golden, CO 80401-3393	USA	1	303 384-7102	scott_schreck@nrel.gov
29	Paul Veers	Sandia National Lab	Wind Energy Technology	MS-1124	Albuguerque, NM 87185	USA	1	505-844-5522	psveers@sandia.gov

Observers									
1	Michal Landa	Institute of Thermomechanics AV CR	Dolejskova 5	182 00 Praha 8		Czech Republic	420	266053672	ml@it.cas.cz
2	Ludek Heller	Institute of Thermomechanics AV CR	Dolejskova 5	182 00 Praha 8		Czech Republic			heller@it.cas.cz
3	Arkadiusz Mroz	Inst for Fundamental Techn. Research	Smart-Technology Centre	Swietokrzyska 21	00-049 Warsaw	Poland	48	228287493	amroz@ippt.gov.pl

Proceedings will be distributed to									
1	Peter Fuglsang	LM Glasfiber	Rolles Møllevej 1		DK- 6640 Lunderskov	Denmark	45	79840469	PFU@lmglasfiber.com
2	Ben Hendriks	ECN	Wind Energie	P.O. Box 1	1755 ZG Petten	theNetherlands			hendriks@ecn.nl
3	Esa Peltola	VTT Processes	PO BOX 1606	FI-02044 VTT		Finland	358	207225790	esa.peltola@vtt.fi
4	Stefan Ivanell	Högskolan på Gotland	Kramergatan 3	621 57 Visby		Sweden			Stefan.Ivanell@hgo.se
5	Jan Holnicki-Szulc	Inst for Fundamental Techn. Research	Smart-Technology Centre	Swietokrzyska 21	00-049 Warsaw	Poland	48	228287493	holnicki@ippt.gov.pl

Paul Veers

Thilo Bein

Gunjit Bir

Tomas Vronsky
Mark Capellaro
Scott Schreck
Gijs van Kuik

Michel Verhaegen
Benjamin Marrant
Harald Bersee

Jaap t'Hooft
Hein de Vries

Ludek Heller

Andreas Herrig
Thanasis Barlas

Merja Sippola
Christoph Kensche
Jan-Willem van Wingerden

Michal Landa

Teun Hulskamp

Tomi Lindroos

Robert Mikkelsen

Jan Riess Høgsberg
Arkadiusz Mroz
Thomas Buhl

Pieter van Langen
Susana Apinanez
Andreas Knauer