Upwind Work Package 1B3, deliverable 12:

"Final Report, showing the potential of smart rotor blades and rotor control"

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1. Introduction

This is the final report of the work package 1B3 “Smart Rotor Blade and Rotor Control” in the UpWind project. The work package addresses the possible next step in rotor development: rotor blades with aerodynamic control devices distributed along the span. This has not yet been applied on any commercial turbine. Worldwide, several research groups work on this next step in rotor technology, that requires a cooperation of aerodynamicists, material and control experts and designers. The work package team includes all of these expertises. Furthermore, there has been a close cooperation with the aerodynamic work package WP2, some cooperation with the control workpackage WP5 and Materials & Structure workpackage WP3.

The report summarizes the main results, and ends with a paper that is submitted to the journal Wind Energy, where the knowledge is applied to show the benefits of load reduction for the UpWind Reference turbine.

This deviates slightly from what was announced in the project description, where the preliminary title for this report was: “The potential of smart rotor blades and rotor control shown by a preliminary blade design.” A full blade design is not yet possible since several design options are still open. The work package focused on aerofoils with flaps or morphing trailing edges. However, the best actuation, lay-out, structural consequences, type of control are still open since there is not yet a clear winning concept. But the project came up with wind rotor specific detailed investigations and assessments of sophisticated active flow and active load control concepts and will represent a valuable basis for the selection of appropriate actuator concepts for future smart rotors. The smart rotor technology development is still in its infancy, so further development and testing will learn what the best choices are.

2. Partners in the project

DUWind	Thanasis Barlas, Teun Hulskamp, Gijs van Kuik, Harald Bersee
IAG:Uni Stuttgart	Thorsten Lutz, Alexander Wolf, Werner Würz
IPPT	Arkadiusz Mróz, Janusz Grzędziński, Jan Holnicki-Szulc
SWE Uni Stuttgart	Mark Capellaro
IT and IOP ASCR	M Landa, P Sedlak, M Frost and J Zidek, L Heller, P. Sittner, J. Pilch and M. Crhan
Tecnalia[1]	Susana Apiñaniz
ECN/Uni Twente	Hein de Vries, Tom Obdam, Koen Boorsma
LM Wind Power	Jean-Guillaume Jeremiasz, Peter Fuglsang,
VTT	Tomi Lindroos, Merja Sippola, Marjaana Karhu, Vilho Jussila, Samu Aalto
Risø/DTU	Thomas Buhl, Christian Bak

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[1] The former name of the company Tecnalia Innovation & Research was Robotiker. This name is used in earlier project- and progress reports

3. Objectives & goals of the project

This program aims to prepare the knowledge and technology for the 2020 generation of rotor blades with a much more detailed control of the primary energy conversion process than state-of-the-art blades offer. Modern rotor blades can be controlled in one way: full-span pitch adjustment. With the increasing size, a much more detailed control is necessary, to add aerodynamic damping when necessary, and to alleviate blade loads. The specific objectives are to obtain lower loads and to improve stability. Stepping stones are:

- To establish the potential of embedded control by aerodynamic/aeroelastic analysis
- To specify the requirements of the sensors, actuators and control equipment, select the most promising options and verify them by means of component-prototypes
- To develop and verify design codes (models) for the aerodynamic & control aspects and of composite structures including smart materials
- To verify the load alleviation and increased stability by wind tunnel experiments
- To verify the robustness of the construction, by design, construction of a representative part of a blade.
- To verify the aerodynamic performance of this blade section by non-rotating tests in a wind tunnel.

4. General Achievements

The majority of the work was dedicated to the reduction of fatigue loads by active control of aerodynamic devices along the span, accompanied by two complementary research lines: one on the alleviation of extreme loads by very fast blade pitch control, and one on passive load control by bend-twist coupling.

Active Distributed Control

Several aerodynamic devices can be implemented in this regard, such as trailing edge flaps, (continuous) camber control, synthetic jets and micro tabs. Except the latter, all options are investigated: Risø, TU-Delft, University Stuttgart and LM Wind Power looked at flaps, VTT at camber control, ECN at synthetic jets. All have done simulations and wind tunnel experiments on two-dimensional or quasi-two-dimensional models to find the unsteady aerodynamic properties and the effectiveness of the device for control purposes. Based on these measurements and on the functional specifications developed in the project, University of Stuttgart" has designed a new airfoil with 10% trailing edge flap specifically for the purpose of load control. Besides maximum performance and flap efficiency, low trailing-edge noise emission was considered in the design and confirmed in wind tunnel tests. The flap efficiency, which describes the impact of a certain flap deflection on the load, could be improved by 7% up to more than 30% for high flap angles. TU-Delft has tested rotor blades with flaps, coupled to a dedicated controller, on a model rotor. The experiments confirmed the potential of the concept. The overall conclusions with respect to the aerodynamics and control are:

- Flaps and variable camber are effective devices for load control
- Synthetic jets are less powerful in controlling lift at low frequencies. At high frequencies this improves, but this needs more study and experiments
- Using flaps, a reduction of the fatigue damage equivalent load to 30% is possible, as shown by the TU-Delft experiment, and, depending on the number and spanwise length of the flaps, up to 50% according to simulations.

The aerodynamic/control performance is not the sole criterion to select a promising concept. The actuator and the structural lay-out are equally important. Two *types of actuators* are looked upon: piezo-electric materials and shape-memory-alloys (SMA).

- Risø and TU-Delft used the same piezo-electric benders to drive the flaps in the experiments. Due to the high activation voltage, piezo-electric actuators are not considered as a viable solution for full-scale application.
- VTT, ACSR and TU-Delft developed SMA actuators. To do so, fundamental material research on SMA was required (ACSR) and on SMA-embedded-in-composites (VTT). VTT developed a concept with a modular trailing-edge-part, with embedded SMA's and sensors (microphones). The wind tunnel tests give promising results, but the control frequency is limited. This is caused by the restricted cooling of the SMA wires due to the heat conductivity of the polymer. TU-Delft developed an SMA actuator for full-scale application with active cooling by force air flow through the channels in which the SMA wires are located. Laboratory tests have shown that the heating (by current) and cooling are now equally fast up to 1 Hz.

The *structural lay-out* of the blade was studied by VTT and TU-Delft. VTT developed the modular trailing edge for easy replacement in case of maintenance or failure. TU-Delft developed the SMA-driven flap with forced cooling to be mounted in a blade made of thermoplastic composite material. The advantage of this material is that local heating allows welding or removal of the trailing edge part.

With respect to *sensors and control* Tecnalia Innovation & Research and TU-Delft investigated centralized and decentralized control concept, and sensors to provide input for the system. Decentralized control, with local sensors and actuators, are preferable. Several flow sensors are considered like pitot tubes or pressure tappings (Risø), microphones (VTT), bending moment sensors (TU-Delft).

Furthermore, a new *aeroservoelastic* model DU_SWAMP was developed and is used to evaluate global control concepts for smart rotors. This code is used to analyze the TU-Delft wind tunnel experiments, but also to analyze the concept on the 5MW reference turbine. The work includes the design of multivariable controllers for distributed flaps, investigation of the influence of actuator dynamics, and the impact of physical constraints (like actuation speed etc). For a 5MW turbine with a blade length of 63m, this technique can reduce the fatigue damage equivalent load by 15 to 30%, see chapter 6.

Passive Load Reduction by bend-twist coupling

When the blade twists during bending, the angle of attack will change due to the induced twisting of the blade. The advantage of this system is that it is fully passive and does not need sensors, actuators or specialized controls. Bend-twist coupling is studied by University Stuttgart using aeroelastic tailoring of the blade structure. Tuning of the fiber direction in the blade spar caps allows the optimization of the coupling in a trade-off with other design constraints, such as tip deflection and annual energy production. The bend twist coupled blades showed a potential 8-10% reduction of fatigue damage equivalent loads.

Extreme load control by Pitch Interface

IPPT developed an interface, based on Magneto Rheological Fluid, between the hub and the pitch bearing which can temporarily remove the torsional stiffness of the pitch system, by which very fast pitching is possible in case of extreme loads. During a gust the aerodynamic moment will pitch the blade, when the system is uncoupled, to feather after which the control system restores the stiffness in a controlled way. Simulations of 5MW Reference Turbine show 15-20% reduction in tower response and blade root reaction moments due to wind gusts as compared with the standard pitching mechanism. Tests in the TU-Delft wind tunnel on a 2m rotor indicate high efficiency of an MRF-based device in fast alleviating of blade root loading.

The overall conclusion is that many options are still open, and a most promising concept cannot yet be determined. The proof of concept in the laboratory has been demonstrated, and the feasibility for the 5MW Reference turbine has been shown.

5. Specific results from the work package of general interest

Technology

1. *Thermoplastic blades*
   TU-Delft: The development of thermoplastic blade structures and manufacturing processes, which started in this work package, has a future on its own since the potential benefits are general: recyclable blades, welding of blade components, shorter mould times.
2. *Smart Pitch interface*
   The Smart Pitch Interface can be an add-on placed on top of the pitch control mechanism of existing turbines. Another option is to integrate it in the blade root, which would require, for existing blades, prior blade disassembling. It is hard to say whether the first option is feasible without the insight into the blade root construction. This could be the subject of further investigations with industrial partners. In all cases, it should be activated only in extreme situations, as opposed to the regular pitch control mechanism acting continuously.

3. *Aerofoil*

IAG – Uni Stuttgart has developed a new airfoil with Trailing Edge Flaps for load control. Coordinates are available on request.

Design and analysis tools

1. *DU_SWAMP*
   TU-Delft has developed a novel design tool in Matlab- Simulink. It represents a full aeroservoelastic wind turbine analysis tool, extended with distributed active control capability features. The model layout offers the opportunity to use system identification and various controller design tools utilizing any available signal in the model. The tool comprises of a BEM-based rotor aerodynamics sub-module, including all necessary additions (dynamic inflow, tip corrections, turbulent wake state), coupled to a multi-body structural dynamics sub-module. Wind input and controllers sub-modules are also included. The tool is well-validated, and is available on request. It is open source, well-described, but without help desk and support.
2. *SMA – Matlab Toolbox*
   ACSR has developed a Matlab Toolbox including a thermomechanical model of NiTi SMA for actuators.
3. *ABIT: Aero Elastic Blade Improvement Tool*
   At SWE- Uni Stuttgart the code ABIT is developed, based on a new method to optimize the blade shape under loaded conditions. The torsional deflection of the blade under load required a dynamic modeling of the blade to determine the optimal un-deformed blade shape. The method iterates to determine first the actual deformed blade shape and load, both dependent upon the angle of attack, and then iterates towards an improved blade shape (twist angle). The result is an improved twist angle for the un-deformed blade. The blade twists to the optimal twist angle (design angle of attack) when loaded. In this way the structural coupling between bending and torsion of large blades and blades with aft sweep or forward bending can be included in the design.

6. Application of the results at the 5MW UpWind Reference turbine

Active Distributed Control

The reduction of the fatigue damage equivalent load for the Upwind reference turbine equipped with flaps has been determined, using the TU-Delft code DU_Swamp. Three independent flaps per blade, each covering 10% of the chord at the section where they are located, have been modeled, covering a total blade span of 11.6 m (18% of rotor radius). For the purpose of collocated control, local sensor signals, providing displacement and sectional resultant velocity, are utilized, simulating local acceleration sensors and five-hole Pitot tubes respectively. Realistic physical and hardware constraints for the actuators have been applied. The maximum flap rate is 100°/s, the maximum flap angle is 8°. The Model Predictive Control (MPC) is based on a System Identification model obtained by DU_Swamp. Feed Back MPC control using the acceleration sensor only, and with added inflow sensors (pitot tubes) has been applied, and compared with Individual Pitch Control, at wind speeds below, at and above the rated wind speed, all at 2 turbulence levels. The reduction of the fatigue damage equivalent load at these load cases ranged from 14-27%. Individual Pitch Control gave a reduction of 2-5%. The standard deviation of the tip deflection using flap control was 15-35% lower. For the pitch control this was 2-6%. A drawback of these advanced controls is that the average power per loadcase is lower compared to the unmodified reference turbine. For the flap control the average power below rated wind speed was 1-5% lower. The pitch control showed identical numbers. However, it should be emphasized that all results hold for blades that were not designed to operate with flaps. Newly designed blades-with-flaps may cancel this lowering of output power.

Extreme load control
The UpWind Reference Turbine has been equipped with the Smart Pitch Interface, and subjected to the Extreme Operating Gust (EOG), defined in the IEC standard. The amplitudes of the excursions of tower top displacement, axial load, rotational speed, and blade root reaction moments are reduced by 15-20%, compared to ordinary pitch control without device, and ca. 60%-65% compared to a case, where no pitching in response to EOG is active.

Passive Load Reduction by bend-twist coupling
Altering the fiber angle in the composite material produces the coupling but also reduces the bending stiffness of the blade. Small angles in the fiber material (≤ 10 degrees) used in the spar cap of standard blades showed the ability to reduce the fatigue loads without the need for significant extra material to reinforce the bending stiffness. Bend twist coupled blades can reduce damage equivalent loads up to 10% while maintaining an equivalent annual energy production and blade tip deflection when compared to the uncoupled Upwind Reference Turbine blades.

7. Proposed future work in the scientific/technical field of the work package.

In general one may conclude that the concept of distributed control is proven at simulation and at windtunnel level. The same holds for the pitch device alleviating extreme loads. The next step is to upscale the concept and technology, and to combine this with outdoor experiments. In order to do so, the major hurdles to be taken are:

- develop full fluid-structure-control interaction codes, that accurately simulates the unsteady aerodynamic and inertia loads, and the interaction with the controller
- expand the controller to - multiple flaps per blade – full span pitch control – extreme loads control – power and torque control and make it consistent with the control for the safety system.
- develop sensors for inflow measurements
- integrate the flaps in the blade structure, including the activation, energy supply, sensors, communication of local control to supervisory control.

- upscale the concept, manufacturing process
- most important: start reliability studies, system reliability as well as structural reliability.
- Testing, testing, testing, from a medium scale turbine to MW size.

8. Conclusions

The control of loads is one of the most important aspects in the upscaling of wind turbines. Extension of the current control possibility (rotational speed and full-span pitch angle) with along-the-span distributed control facilities has been the topic of this work package. On top of that, reductions of the extreme load was investigated, by applying a smart interface at the pitch bearing A major step has been set: both concepts are proven in the laboratory (wind tunnel) and in simulations: reductions of fatigue damage equivalent load up to 30% is possible in realistic conditions, and reduction of extreme loads up to 20% is possible. Both concepts (smart pitch and smart flaps) require more components to be built in the rotor: sensors, actuators, moving surfaces, communication, power supply. These results can be compared with a passive method to limit the loads: blades with built-in coupling of bending and torsion. Up to 10% reduction of the fatigue load is attainable in such a way, without the need to include sensors, actuators, specific controllers.

The proof of the pudding is to test the technology outdoors, and upscale it. The results of the work package show that lower loads can be achieved when accurate and robust controllers are used. The major aspects that determine the success of the smart rotor development are the structural lay-out of the blade-plus-devices, and above all, the reliability of the concepts. The smart rotors should be as reliable as current rotors are. This is not yet studied.

Another big step to take is to include the smart rotor in a complete turbine design, with an analysis of all load cases, safety system, power production etcetera. A mix of the possibilities studied in the work package could be a result: a rotor with the smart pitch system for extreme load control, and a mix of bend-twist coupling and flap control.

Appendix A: List of Deliverables

The following reports have been made (apart from progress reports and Descriptions of Work):

Deliverable number	Title
1B3.1	Database of existing knowledge
1B3.2	2 D numerical comparison of trailing edge flaps
1B3.3	Inventory of actuators and first order evaluation of 2 actuators and structural concepts (included in 1B3.1)
1B3.4	Inventory of control concepts
1B3.5	1st order evaluation of smart blade-hub connection
1B3.6	2nd order simulation aerodynamic concept 1
1B3.7	2nd order simulation aerodynamic concept 2, included in 1B3.6
1B3.8	Design and Verification of an Airfoil with Trailing-Edge Flap and Unsteady Wind-Tunnel Tests
1B3.9	Scale model of a dedicated airfoil
1B3.10	Scale model of wind turbine rotor which is used to verify the potential and functional requirements of the sensors, actuators and control.
1B3.11	Adaptive wind turbine blade based on SMA composites
1B3.12	Final Report, showing the potential of smart rotor blades and rotor control for the UpWind RWT

Appendix B: List of publications and PhD theses

The list gives the status per January 2011

Journal papers and book chapters:

2011

1. T. K. Barlas, G. J. van der Veen, G. A. M. van Kuik, Model Predictive Control for wind turbines with distributed active flaps: Incorporating inflow signals and actuator constraints , Wind Energy, to appear**.**
2. T. K. Barlas, J.-W. van Wingerden, A. Hulskamp, G. A. M. van Kuik, and H. Bersee. Smart dynamic rotor control using active flaps on a small scale wind turbine: Aeroelastic modeling and comparison with wind tunnel measurements. Wind Energy, to appear.

2010

3. Janusz Grzędziński and Arkadiusz Mróz, Gust load reduction concept in wind turbines, Wind Energy, Volume 13, Issue 2-3, March - April 2010, Pages: 267-274
4. T.K. Barlas and G.A.M. van Kuik, Review of state of the art in smart rotor control research for wind turbines, Progress in Aerospace Sciences, Volume 46, Issue 1, January 2010, Pages: 1-27
5. A.W. Hulskamp, J.W. van Wingerden, T. Barlas, H. Champliaud, G.A.M. van Kuik, H.E.N. Bersee, M. Verhaegen Design of a scaled wind turbine with a smart rotor for dynamic load control experiments, Wind Energy, 2010, Published online, DOI: 10.1002/we.424
6. A.W. Hulskamp, H.E.N. Bersee, Implementation of the 'smart' rotor concept, in: Wind Power Generation and Wind Turbine Design, Edited by Tong, WIT Press, 2010
7. M. Frost, P Sedlak, M Sippola and P. Sittner, "Thermomechanical model for NiTi shape memory wires", Smart Mater. Struct. 19 (2010) 094010, doi: 10.1088/0964-1726/19/9/094010
8. van Wingerden, J.-W. and Hulskamp, A. and Barlas, T. and Houtzager, I. and Bersee, H. and van Kuik, G. and Verhaegen, M., Two-degree-of-freedom active vibration control of a prototyped `smart' rotor, Journal of IEEE transactions on controls system technology, published online, 2010.
9. Karhu, Marjaana; Lindroos, Tomi, Long-term behaviour of binary Ti-49.7Ni (at.%) SMA actuators - the fatigue lives and evolution of strains on thermal cycling, doi-link: 10.1088/0964-1726/19/11/115019, Smart Materials and Structures. Vol. 19 (2010) No: 11, 115019, 10 p.

2009

10. Boeije, de Vries, Cleine, van Emden, Zwart, Stobbe, Hirschberg, Hoeijmakers, “Fluidic Load Control for Wind Turbine Blades,” AIAA paper 2009-684, January 2009.
11. Smid, van Noort, Hirschberg, van Emden, de Vries, Stobbe, Zwart, Hoeijmakers, “Experimental Study of Fluidic Control of a Diffusor: influence of slit geometry,” AIAA paper 2009-742, January 2009.
12. Ahola, Jari; Makkonen, Tomi; Nevala, Kalervo; Lindroos, Tomi; Isto, Pekka, Model-Based Control of SMA Actuators with a Recurrent Neural Network in the Shape Control of an Airfoil , doi-link: 10.4028/www.scientific.net/SSP.147-149.278 http://www.scientific.net/SSP.147-149.278 , Solid State Phenomena. Vol. 147-149 (2009)
13. Ruotsalainen, Pasi; Kroneld, Petter; Nevala, Kalervo; Brander, Timo; Lindroos, Tomi; Sippola, Merja, Shape Control of a FRP Airfoil Structure Using SMA-actuators and Optical Fiber Sensors , Solid State Phemomena. Vol. 144 (2009), 196 - 201

2008

14. L. Heller, et al., "Quasistatic and Dynamic Functional Properties of Thin Superelastic Wires", Eur. Phys. J. Spec. Top., 2008, 128, p 7–15
15. L. Heller, et al., "Thermomechanical Characterization of Shape Memory Alloy Tubular Composite Structures", Advances in Science and Technology, Volume 59 (2008), pp. 150-155
16. van Wingerden, J.-W., Hulskamp, A. W., Barlas, T., Marrant, B. and van Kuik, G. A. M. and Molenaar, D-P. and Verhaegen, M., Proof of concept of a `smart' wind turbine rotor blade for load reduction, Wind Energy, Volume 11, 2008
17. Peltonen, Marjaana; Lindroos, Tomi; Kallio, Marke, Effect of ageing on transformation kinetics and internal friction of Ni-rich Ni–Ti alloys doi-link: 10.1016/j.jallcom.2007.05.102, Journal of Alloys and Compounds. Vol. 460 (2008) No: 1 - 2, 237 - 245

2007

18. Lutz, Th., Herrig, A., Würz, W., Kamruzzaman, M., Krämer, E.: Design and Wind-Tunnel Verification of Low-Noise Airfoils for Wind Turbines, AIAA Journal Vol. 45, No. 4, April 2007.
19. T. K. Barlas and G. A. M. Van Kuik. State of the art and prospectives of smart rotor control for wind turbines. In Journal of Physics: Conference Series (2007) 012080 (12pp), page 012080, 2007.

More papers have been submitted to different journals and are awaiting review or publication.

Conference Proceedings:

2010

1. van Kuik, G.A.M. Opportunities for Adaptive Structures Technologies in Wind Energy, Keynote speech at the 21th International Conference on Adaptive Structures and Technologies, October 4-6, 2010, Pennsylvania State Unversity, USA
2. Sedlák, P., Frost, M., Ben Zineb, T., Šittner, P., Thermomechanical Models for NiTi Shape Memory Alloys and Their Applications, Proceedings of the ASME Conference on Smart Materials, Adaptive Structures and Intelligent Systems 2010, SMASIS2010, 2010
3. Mark Capellaro and Martin Kühn, Boundaries of Bend Twist Coupled Blades, Science of Making Torque from the Wind 2010, Heraklion Greece
4. A.W. Hulskamp, H. Champliaud, J.-W. Wingerden, T. Barlas, H. Bersee, G. van Kuik, and M. Verhaegen. Smart dynamic rotor control: Part1, design of a smart rotor. Proceedings of the Conference on The Science of making torque from wind conference, June 2010, Heraklion, Greece
5. Barlas, T. and van Wingerden, J.-W. and Hulskamp, T. and van Kuik, G. and Verhaegen, M. and Bersee, H., Smart dynamic rotor control: Part 2, aeroelastic analysis. Proceedings of the Conference on The Science of making torque from wind conference, June 2010, Heraklion, Greece
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8. Kamruzzaman, M., Lutz, Th., Herrig, A., Krämer, E.: Semi-empirical Modeling of Turbulent Anisotropy for Airfoil Self Noise Prediction, Submitted to 16th AIAA/CEAS Aeroacoustics Conference, Sweden, 7 - 9 Jun, 2010.
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10. Wilson, D. and Reson, B. and Berg, D. and Barlas, T. and van Kuik, G. A. M., Active aerodynamic blade distributed flap control design procedure for load reduction on the UpWind 5MW wind turbine, Proceedings of the 48th AIAA/ASME Conference, 2010, Orlando, FL, U.S.A.
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12. D. Berg, D. Wilson, J. Reson, B. Berg, T. Barlas, C. Halse, and A. Crowther. The impact of distributed control on fatigue damage reduction due to active aerodynamic

load control. In Proceedings of the Conference on the Science of Making Torque from Wind, Heraklion, Greece, 2010.

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2009

14. Modelling and testing of a load-limiting sandwich structure, M. Sippola and T.Lindroos, ESOMAT 2009
15. Finite element modelling of shape memory alloy actuated FRP Laminate structures using the irloop sma model in abaqus M. Sippola, T. Lindroos, P. Sedlak, M. Frost, THERMEC 2009
16. Barlas, T. K. and van Kuik, G. A. M., Aeroelastic modelling and comparison of advanced active flap control concepts for load reduction on the Upwind 5MW wind turbine, Proceedings of the EWEC 2009, Marseille, France
17. A.W. Hulskamp and H.E.N. Bersee, A Shape Memory Alloy Activated Morphing Surface for Aerodynamic Load Control on Wind Turbine Rotor Blades, 20th International Conference on Adaptive Structures and Technologies, October 20-22, 2009, Hong Kong
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20. Sedlák, P., Frost M., "Two dimensional thermomechanical model for combined loading of NiTi wire structures". Proceedings of the ASME 2009 Conference on
21. Smart Materials, Adaptive Structures and Intelligent Systems SMASIS2009, September 20-24, 2009, Oxnard, California, USA
22. Frost, M., Sedlák, P., Modeling of Two-dimensional Thermomechanical Loading of NiTi Wires, EDP Sciences, ESOMAT 2009, 08002 (2009)

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23. Mark Capellaro and Martin Kühn, Aeroelastic design and simulation of a bend twist coupled wind turbine rotor blade, DEWEK 2008 Bremen, Germany
24. Kamruzzaman, M., Lutz, Th., Herrig, A., Krämer, E.: RANS Based Prediction of Airfoil Trailing Edge Far-Field Noise: Impact of Isotropic and Anisotropic Turbulence, AIAA paper 2008-2867, 14th AIAA/CEAS Aeroacoustics Conference, Vancouver, Canada, 5 - 7 May 2008.
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Application of Smart Structures for Large Wind Turbine Rotor Blades, Sandia, Albuquerque, The Netherlands, 2008.

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27. Kamruzzaman, M., Lutz, Th., Krämer, E.: An Approach to RANS Based Prediction of Airfoil Trailing Edge Far-Field Noise, Second International Meeting on Wind Turbine Noise, Lyon, France, September 20-21, 2007.
28. Mark Capellaro, Modelling of an Analytically Determined Bend Twist Coupled Blade, EAWE 2007 Pamplona, Spain
29. A. K. Barlas. Progress in smart rotor research for wind turbines: Experimental and computational approaches to active aerodynamic control. In Proceedings of the 3rd EAWE PhD Seminar on Wind Energy in Europe, CENER, Pamplona, Spain, 2007.

2006

30. A. K. Barlas. How to test a smart rotor blade. In Proceedings of the 2nd EAWE PhD Seminar on Wind Energy in Europe, Risø, Roskilde, Denmark, 2006.
31. T. Barlas and M. Lackner. Smart rotor blade control for wind turbines.In Proceedings of the 50th IEA topical expert meeting on the Application of Smart Structures for Large Wind Turbine Rotor Blades, TUDelft, Delft, The Netherlands, 2006.

PhD dissertations:

In 2011 5 PhD dissertations are expected:

Thanasis Barlas	Technical University Delft
Teun Hulskamp	Technical University Delft
Arkadiusz Mróz	IPPT
Mark Capellaro	University Stuttgart
Hein de Vries	ECN / University Twente