Title: **Effects of Protuberances and Tubercles on Wind Turbine Generator Blades**
EWEA 2016 Science and Research: Innovations in the design of rotors, towers, support structures, foundation

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## 1. Introduction

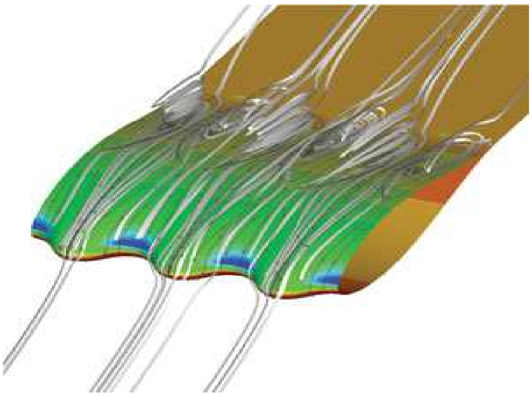
Noise reduction and fatigue load reduction for rotor blades and the entire wind energy turbine is an issue of all wind energy turbine designs. Leading modifications (protuberances) on rotor blades which reduce blade noise and fatigue loads are presented. The physical background of protuberances is outlined. Some investigations regarding noise had been done earlier. This paper presents new results of benefits of protuberances for the fatigue loads of the rotor blade and the entire wind energy turbine.

## 2. Approach

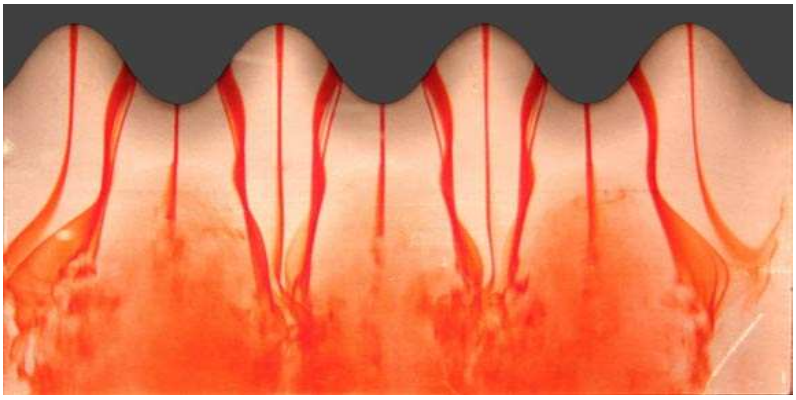
Computational Fluid Dynamics (CFD) as well as wind tunnel test results and aeroelastic load calculations of the entire wind energy turbine (with non-linear aeroelastic code *ADCoS*) are used to illustrate the effects and benefits of lead edge modifications (protuberances). Field tests on a wind energy converter of the 3MW class are ongoing.

## 3. Main body of abstract

Leading edge modifications (sinusoidal shape of the leading edge) lead to secondary vortex. This vortex transport energy into the boundary layer on the airfoil´s top side. This affects the stall characteristics in a positive way.



CFD study



Experimental study

Fig. 1: CFD Simulation and experimental study of wavy leading edge

The effects of these vortex are a prolonged zone of high lift in polar curve, especially at higher angles of attack. Leading edge stall occurs at much higher angles (+10°). There are no abrupt changes in lift /drag. The design of pitch regulated rotor blades can go closer to maximum lift and reduce changes in lift, which means a reduction of fatigue loads.

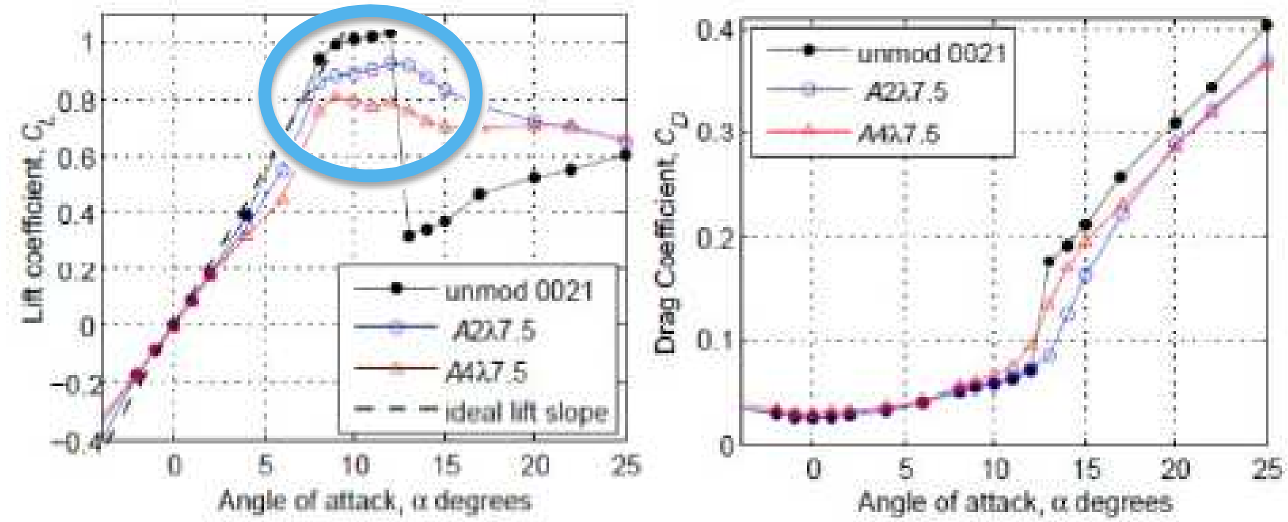



Fig. 2: Effects on lead edge tubercles on airfoil performance
Source: K. L. Hanson PhD thesis page 149

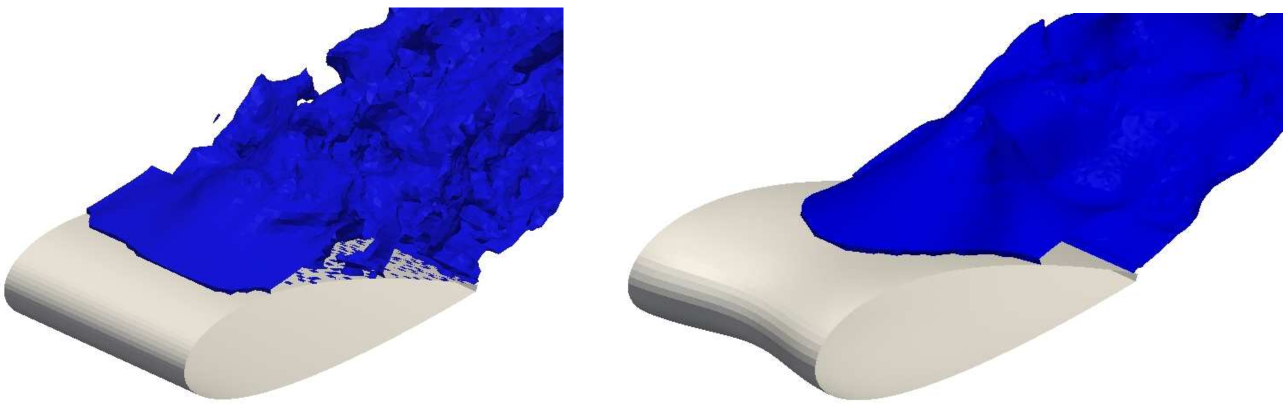


Fig. 3: CFD-simulation of NACA0021 airfoil at high angle of attack

The blue volume in fig. 3 visualizes the flow separation zone. Flow separations occur further downstream. More lift is produced at the same angle of attack with tubercle airfoil. Flow and therefore lift behaves similar if angle of attack is increased further. This leads to the smoother lift curve given in fig. 2

In addition this leads to positive effects on blade noise.

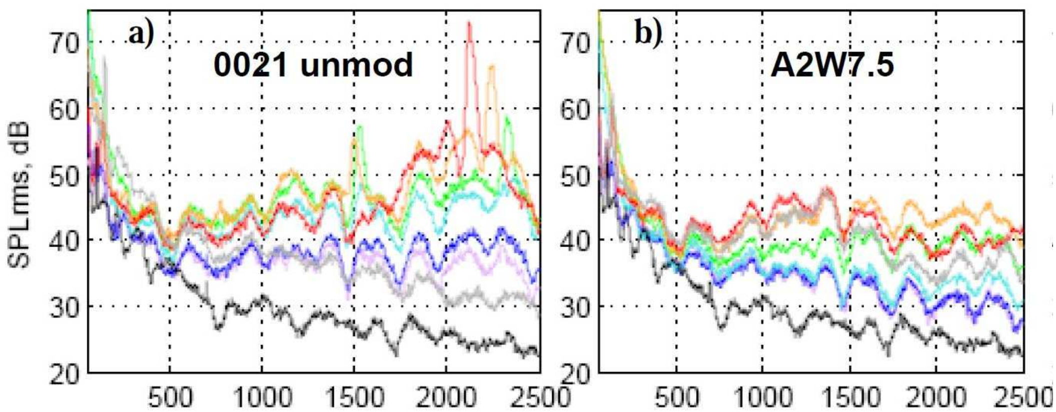
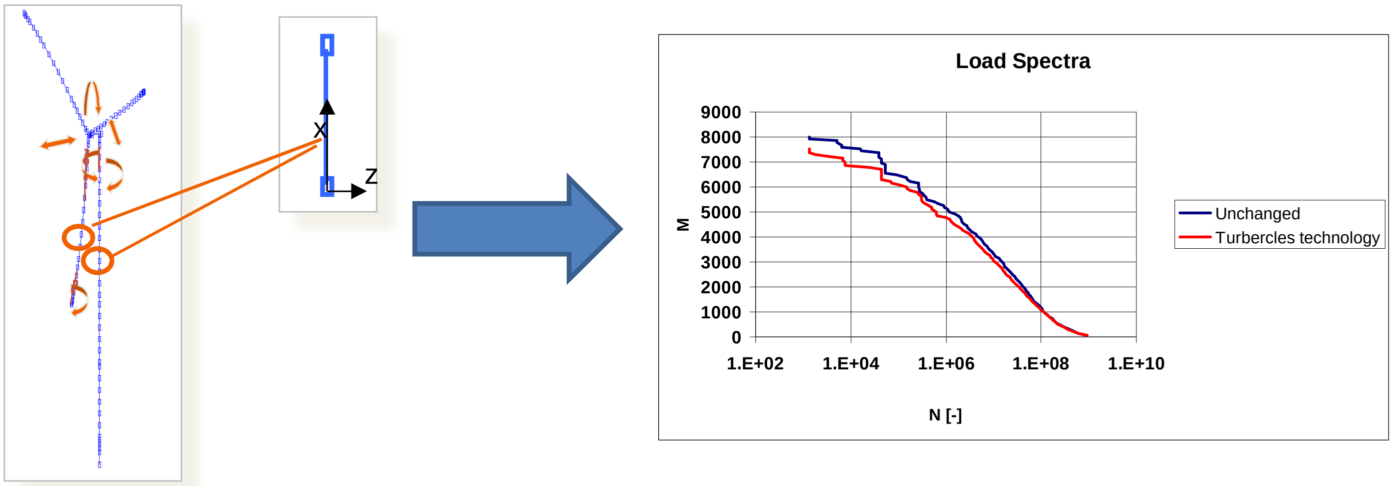



Fig. 4: Source: “Reduction of Flow Induced Tonal Noise through leading edge tubercle modifications“, K. L. Hansen, R. M. Kelso and C. J. Doolan

The improved stall behaviour of WTG leads to much lower variability of loads due to the absence of „real stall“. Therefore there will be less structural vibrations for wind turbines in gusty conditions and lower wake sensitivity of turbines in wind park situations will be observed.
These effects are validated by aeroelastic load calculations using a complete dynamic “state of the art” WTG-model of a 3,5 MW turbine.




Aeroelastic load calculation with non-linear software *ADCoS*

Fig. 5: Finite Element aeroelastic model of WTG and Load spectra

The reduction of damage equivalent loads (DEL) as a result of these aeroelastic calculations for an IEC turbulence class A site of a 3,5 MW WTG is around 8-10%.
For steel parts of the wind energy turbine with a Woehler slope of m=3 (material value describing fatigue behaviour) this leads to an **increase of life time of 26%-33%**. For cast parts (i.e. hub) and the rotor blade (glass/carbon fiber reinforced plastic) with higher numbers of the Woehler slope the increase of life time is much higher.

## 4. Conclusions

Leading modifications (protuberances) on rotor blades have multiple benefits for wind energy turbines, such as noise reduction and smoother lift curves at high angles of attack of the rotor blade.

Detailed aeroelastic load calculations and the determination of the fatigue loads for a “state of the art” 3,5MW WTG illustrate the huge potential of leading edge protuberances for a reduction of fatigue loads for the entire turbine. Wind tunnel tests of airfoils and load measurement at a specific site are ongoing.

## 5. Learning objectives

Learning objectives are to understand the physical background of leading edge modifications (protuberances) inducing vortex at the leading edge of the rotor blade. Beside noise reduction and better stall behaviour of the rotor blade lower fatigue loads can be realised with leading edge protuberances. Since fatigue loads are more and more important for larger turbines and turbines in wind park wake conditions leading edge protuberances and its influence on fatigue loads shall be investigated later on.

Abbreviations:

CFD: Computational Fluid Dynamics
IEC: International Electrotechnical Commission
DEL: Damage Equivalent load
WTG: Wind Turbine Generator