

# Investigations for Improvement of Energy Yield of Rotor-blades from the 1.5 MW Class

N Balaesque<sup>3</sup>, S Bicker<sup>4</sup>, C Dollinger<sup>5</sup>, A Fandrich<sup>4</sup>, S Gatz<sup>8</sup>, M Hölling<sup>6</sup>, K Irschik<sup>2</sup>, T Reichstein<sup>7</sup>, A P Schaffarczyk<sup>7,9</sup> and C von Zengen<sup>1</sup>

<sup>1</sup> Deutsche WindGuard GmbH, Varel, Germany

<sup>2</sup> WindGuard Certification GmbH, Varel, Germany

<sup>3</sup> Deutsche WindGuard Engineering GmbH, Bremerhaven, Germany

<sup>4</sup> Deutsche WindGuard Offshore GmbH, Varel, Germany

<sup>5</sup> BIMAQ, University of Bremen, Germany

<sup>6</sup> ForWind, University of Oldenburg, Germany

<sup>7</sup> Kiel University of Applied Sciences, Kiel, Germany

<sup>8</sup> Formerly Kiel University of Applied Sciences, Kiel, Germany

<sup>9</sup> corresponding author

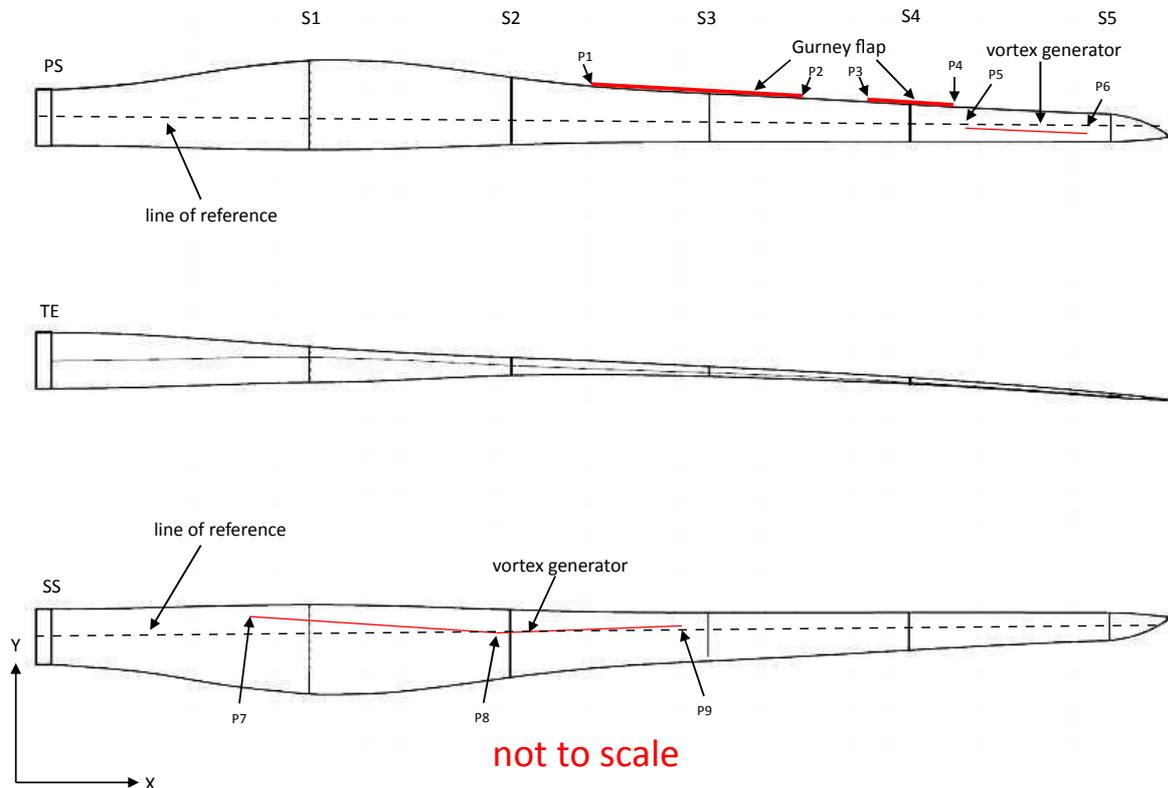
E-mail: Alois.Schaffarczyk@fh-kiel.de

**Abstract.** In a combined approach of extensive measurement and accompanying simulation a wind turbine blade used in the 1.5 MW class was investigated for improvement of aerodynamic properties and especially the energy yield. One blade was dismantled and its geometry was locally measured by a specially designed laser scanning-system. From this geometry data set five 2D wind tunnel models were manufactured and measured in the wind tunnel of Deutsche Wind Guard Engineering GmbH at Bremerhaven, Germany. In addition, extensive CFD investigations were performed to investigate the usefulness of so-called aerodynamic devices like vortex generators, Gurney flaps and others for improving energy yield. As a result it could be shown that the aerodynamic efficiency of the manufactured blades - if measured in terms of lift-to-drag ratio - is at a high level but still can be further improved. 3D CFD investigations were able to show the influence of Gurney flaps and boundary layer fences and their interactions.

## 1. Introduction and Work Objectives

During the first boom of wind energy in Germany around the year 2000 about 20 thousand wind turbines from the first Megawatt class were erected and later on spread around the world. See [1], chapter 1 for a historical overview. A common blade for this class is the LM37 from the danish manufacturer LM and was produced more than 20 thousand times [2]. From this background a special project conducted by Deutsche WindGuard Engineering GmbH, Germany, was undertaken to investigate the potential of possible enhancement of energy yield by improving the aerodynamic performance. This is important because these types of turbines still have a considerable remaining life time. Several so-called aerodynamic devices like vortex generators, Gurney flaps and many others [3] are known to be easily mounted or exchanged and have been proven to increase the performance significantly. Therefore, a number of methods combining measurement and simulation were undertaken to investigate these devices for their potential in more detail. In this paper, we only report from findings of wind tunnel measurements and





**Figure 1.** Blade layout and position of used aerodynamic devices. The presented layout is not to scale.

CFD. Results from measurement of acoustic properties (noise radiation) and laminar-turbulent transition [4] (by thermography) will be published later.

## 2. Approach and Methods

The used methods are described more detailed in this chapter.

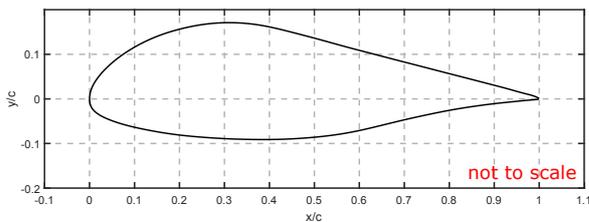
### 2.1. Geometrical measurement

As mentioned in the introduction a typical blade of this class is studied, the LM37P blade, which is used in a large number of turbines manufactured for example by GE (1,5sl), Nordex (S77), REpower - now Senvion - (MD77), Fuhrländer, Leitwind, Goldwind and others. One blade from the LM37P series (see Fig. 1) was dismantled from a turbine and was put into a workshop for a geometrical characterization by a specially developed laser-scanner [2]. The accuracy of this scanning-device was intended to be less than 1 mm. Special post-processing was necessary on the one hand to obtain accurate 2D profile data for manufacturing the wind tunnel models and on the other hand as a proper input for CFD modeling. A comparable measurement set-up was conducted during the DAN-AERO MW experiment [5, 6]. In order to make the methodology as generic as possible and applicable to other wind turbines, it was decided to perform the analysis without any input from the blade manufacturer. It was also decided not to publish any information that is not readily visible from the ground. The airfoil geometries displayed are purposely not to scale.

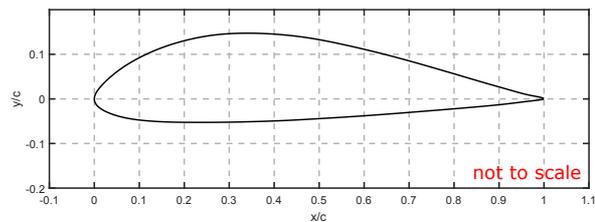
**Table 1.** Position of measured 2D cuts, VG = vortex generator, GF = Gurney flaps

name	position (R/m)	chord (mm)	thickness (%)	add-on 1	add-on 2
S1	9.0	3028	38	VG	( - )
S2	15.6	2245	26	VG	( - )
S3	22.1	1659	20	( - )	GF
S4	28.7	1266	17	( - )	GF
S5	35.3	936	14	( - )	( - )

Table 1 gives the locations of the 2D cuts used for wind-tunnel models. It is important to note that the measured rotor blade had been in operation for several years, hence it did show signs of wear and is affected by manufacturing tolerances. Even though a one-blade sample is not necessarily representative for all blades, it was considered more appropriate than using an ideal design-geometry.



**Figure 2.** Geometrical measurement from section S2 ( $R = 15.6$  m, chord = 2241 mm,  $t/c = 26\%$ ), not to scale

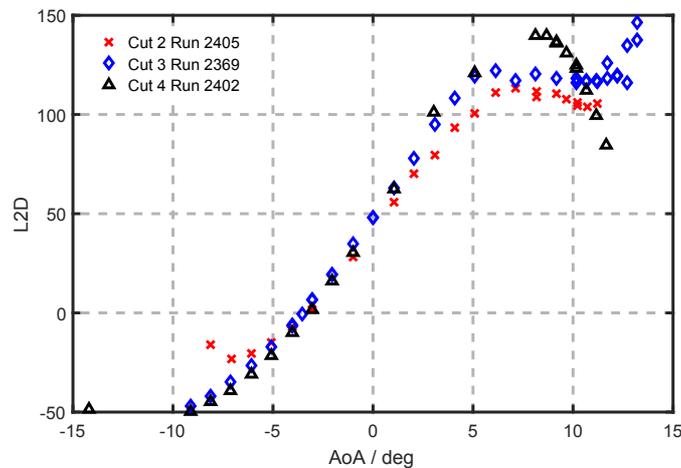


**Figure 3.** Geometrical measurement from section S3 ( $R = 22.1$  m, chord = 1619 mm,  $t/c = 20\%$ ), not to scale

## 2.2. 2D Wind tunnel measurement

From these post-processed data (see Figs. 2 and 3) wind tunnel models scaled down by 3.8 : 1 for the longest chord, 38% thick section, and approximately 1 : 1 for the tip-section, were manufactured by Innoven GmbH, Germany. For each section a number of wind tunnel tests were performed at Deutsche WindGuard Engineering GmbH, Bremerhaven [2, 7, 8]. It is a low-speed, non-pressurized, closed-circuit, aeroacoustic wind tunnel, capable of Reynolds numbers up to  $6 \cdot 10^6$  for airfoils chords of 0.9 m at low turbulence level below 0.4% in the test section [8]. The measurement of airfoil characteristics is possible using force balances (above and below each turntable), airfoil surface pressure and wall pressure integration. All of these methods can be used simultaneously. A wake rake which can be traversed is used for determining the drag in the attached flow regime. When separation occurs, either surface pressure or the force balance are used for measuring drag. During this campaign, the closed 2.75 m x 1.25 m x 5 m (WxHxL) test section was used with 800 mm chord models mounted vertically between two turntables. Due to the fact that the focus of these measurements was to compare original and modified airfoils, force balance and wall-pressure measurements were preferred to surface-pressure integration, which only accounts for the forces acting upon the airfoil itself. Further information about the experimental equipment, calibration and blockage correction may be found in [8].

In Fig. 4, the lift to drag ratio (L2D) for the three intermediate sections are presented. It can be seen that for all three sections (S2 at  $R = 15.6$  m, S3 at  $R = 22.1$  m and S4 at  $R = 28.7$  m) L2D is well above 100 reaching 130 for section S4 at an angle of attack of about  $8^\circ$ .



**Figure 4.** Measured lift to drag ratio (L2D) for S2 at  $R = 15.6$  m, S3 at  $R = 22.1$  m, S4 at  $R = 28.7$  m. Reynolds number equals 3 million.

### 2.3. Computational Fluid Dynamics

For accurate prediction of lift and drag data DLR's CFD code TAU [9] was used for quasi-2D (aerodynamic polar curves for 2D section) as well as 3D simulations (aerodynamic devices). The code was primarily developed for aerospace application and uses the compressible Navier-Stokes equations. Unstructured meshes may be used and a range of different implicit and explicit solvers may be used. The standard solver module uses an edge-based dual-cell approach, i.e., a vertex-centered schema, where inviscid terms are computed employing either a second-order central schema or a variety of upwind schemes using linear reconstruction for second-order accuracy.

It is also capable for using overlapping meshes, called *Chimera technique* by DLR. Parallel computing mode is possible via MPI and was tested at HLRN, a high-performance computing facility operated by Germany's most northern states.

The turbulence models implemented within the TAU code include linear as well as non-linear eddy viscosity models spanning both one- and two-equation model families. The standard turbulence model in TAU is the Spalart-Allmaras model with Edwards modification, yielding highly satisfactory results for a wide range of applications while being numerically robust. The  $k-\omega$  model provides the basis for the two equation models, where the one mostly used is probably the Menter SST model. Besides this, a number of different  $k-\omega$  models like Wilcox and Kok-TNT are available. Also nonlinear explicit algebraic Reynolds stress models (EARSM) and the linearized LEA model have been integrated. The implementation of RSM models is ongoing work. A number of rotation corrections for vortex dominated flows are available for the different models. Specific universal wall-function have been introduced to achieve a higher efficiency of the solver, especially for use in design or optimization.

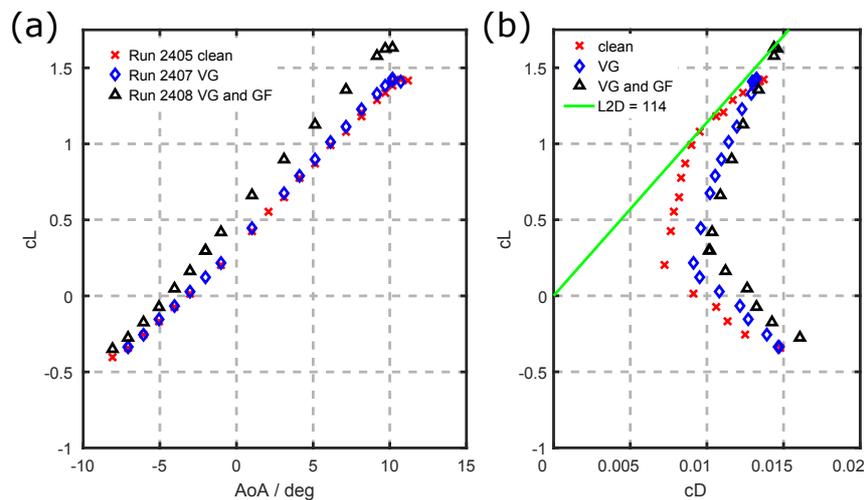
Finally, there are options to perform Detached Eddy Simulations (DES) based on the Spalart-Allmaras or the Menter SST model or the so-called Extra-Large Eddy Simulation (XLES). Since the DES method is a development strategy that in principal can be applied to any eddy viscosity turbulence model, the original implementation within the TAU code required only the calculation of additional terms and a suitable switch to activate the DES model within the calculation of the source term of the turbulence model. In computational terms, the overhead for the solution of a time step using DES is negligible compared to URANS in three-dimensional cases.

In order to allow for modeling of transitional flow the turbulent production terms are suppressed in regions which are flagged in the grid as being of laminar flow type. Flagging of laminar regions can be done in the pre-processing by the definition of polygon-lines which

encircle the laminar region on the surface grid and the definition of a maximum height over the surface. The polygon lines for laminar regions can be defined by the user for simulations with fixed transition to turbulent flow or can be computed by a transition prediction module, which is ongoing development. It is coupled to boundary-layer and stability routines and handles laminar-turbulent transition by a simplified  $e^N$ -database method.

Its quality to reproduce Reynolds number as well as turbulence intensity effects was recently proven in connection to the European AVATAR Blind Test Campaign [10]. As an example, Fig. 6 clearly shows that an accurate modeling of the aerodynamic performance needs a sophisticated transitional modeling as well which is not at all a standard in most CFD codes. Prediction of  $c_{L,max}$  however, remains very much depending on the turbulence model used. In our case, we used a modified Spalart-Allmaras model or Menter's SST- $k-\omega$  model.

Meshes were generated with ICEM/CFD (now ANSYS) and consist of 5.8 millions tetrahedra. Inside the boundary layer of the wing we used 1.7 million prisms. A typical run on a 16 core computer takes about 10 hours computing time for 4000 iterations thereby decreasing the residuals by four orders of magnitude.

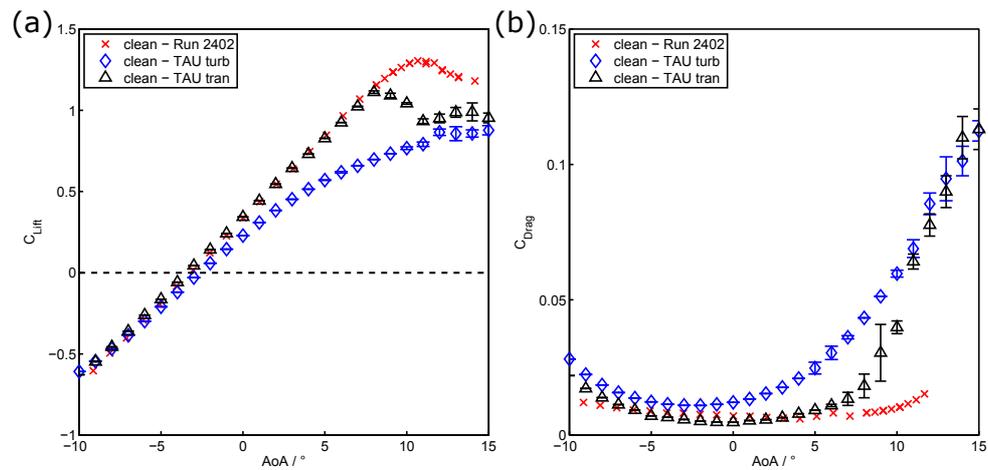


**Figure 5.** (a)  $c_L$  vs AOA and (b)  $c_L$  vs  $c_D$  for S2 clean (Run 2405), with VG (Run 2407) and VG combined with GF (Run 2408)

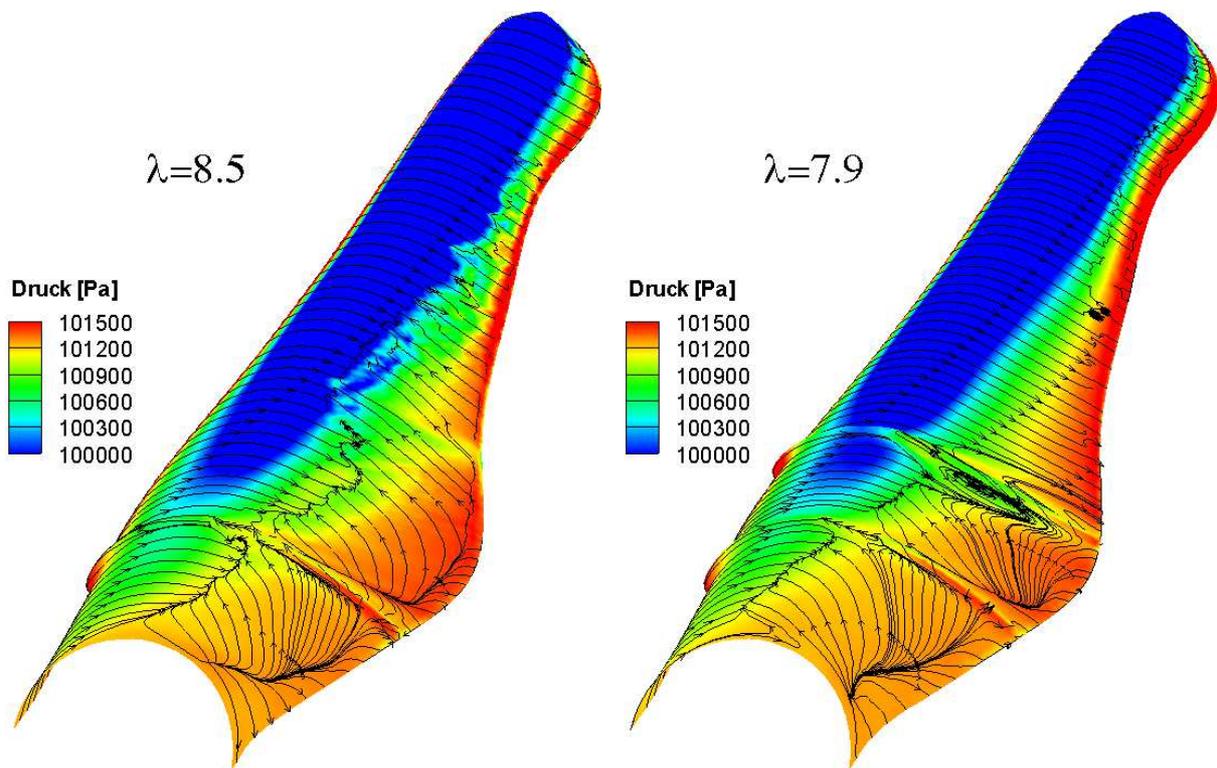
### 3. Results

From these extensive investigations a number of results could be obtained:

- From geometrical measurements it could be seen that several *non smooth* sections obviously not corresponding to the original defined shape exist. However, scaled down wind tunnel models show remarkably high aerodynamic performance around 120 if measured in terms of lift-to-drag ratio (Fig. 4).
- Part of the investigated blade already was equipped with vortex generators, Gurney flaps and zigzag tape. Fig. 5 shows that by using aerodynamic devices it is possible to increase design lift from 1.0 (clean profile) to about 1.13 (profile with VGs and GFs) while keeping angle-of-attack **and** L2D constant.
- 2D CFD investigations only reproduce measured performance ( $L2D := c_L/c_D$ ) if a sophisticated transitional model ( $e^N$ ) is used (Fig. 6) when no leading edge roughness is present as it is the case in our measurements.



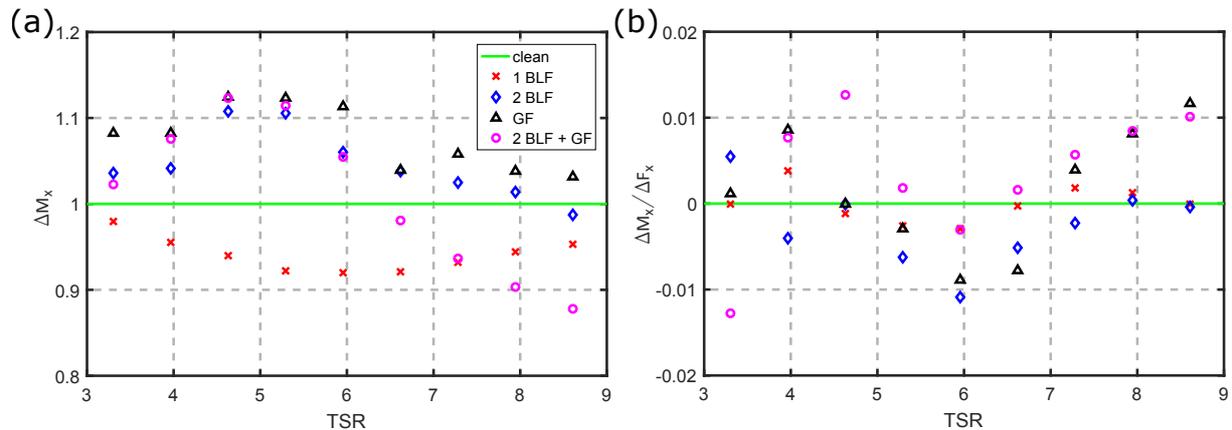
**Figure 6.** 2D lift (a) and drag (b) data for S4 ( $R = 28.7$  m), compared with results from CFD



**Figure 7.** Flow pattern with one boundary layer fence

**Figure 8.** Flow pattern with two boundary layer fences

- Thermography and 3D CFD investigations showed that the used blade is prone to separation not only in the very inner part of the blade. The effect of Gurney flaps (used) and boundary layer fences (not used) showed the strongest positive influence on performance. Using only one fence showed in all investigated cases a significant decrease of both thrust and power. Similar results have been obtained by [11]. Flow pattern for these cases are shown in Figs. 7 and 8.



**Figure 9.** Influence of aerodynamic devices on: (a)  $\Delta M_x$ , i.e., relative power output and (b)  $\Delta M_x/\Delta F_x$ , i.e., relative change in power to thrust ratio. TSR = tip speed ratio, BLF = boundary layer fence

- For a more detailed analysis of the influence of aerodynamic devices on power and thrust, forces and torque obtained from 3D CFD simulations were studied. Since the direction of wind and the rotational axis coincide with the  $x$  axis, the  $x$  components of force ( $F_x$ ) and torque ( $M_x$ ) are proportional to thrust and power, respectively. In Fig. 9(a),  $\Delta M_x = M_{x,dev}/M_{x,clean}$ , i.e., the relative change in power is shown as a function of the tip speed ratio (TSR). While the use of one boundary layer fence (BLF) results in an overall decrease in power in the order of several percent, the use of two BLFs or a GF results in an increase in power. For a combination of both devices, the power change is strongly dependent on the tip speed ratio.

In order to get a net gain in the efficiency of the wind turbine, the power has to increase more than the thrust. In Fig. 9(b),  $\Delta M_x/\Delta F_x$ , i.e., the ratio of power change to thrust change is shown as a function of the TSR. For values  $> 0$  a net gain is reached. In the partial load case up to rated TSR, the combination of 2 BLFs and GF results in an overall power gain together with a net gain.

#### 4. Conclusions

From these findings the following conclusions may be drawn:

- Modern (i.e. transition modeling enhanced) RANS codes are able to predict 2D performance (L2D ratio of profiles) as well as 3D (influence of aerodynamic devices) accurately.
- In particular, from 3D CFD investigation of a blade replicated from five representative laser-scanned sections it could be shown that a potential in improvement of energy yield in the order of a few percent is available if aerodynamic devices are used. Improvement are predominantly found in the partial load range, and therefore is particularly interesting for low-wind locations.
- Aerodynamic devices may interact strongly with each other and may even lead to a decrease in performance.

#### Acknowledgments

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