

# Airfoil characteristics of rotating wind turbine blades

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## Summary

This paper contains a description of the experiments that are currently being conducted at the Delft University of Technology in order to get more quantitative data of the effects of rotation on the lift and drag distribution of a rotor blade. In January 1991 the two-dimensional characteristics of the rotor blade were measured in the wind tunnel. The same blade is used for the rotating measurements on the rotor test facility. This gives the possibility for a good comparison of the effects of rotation on the lift and drag distribution without the influence of geometrical imperfections of two different test models. Some results of the wind tunnel measurements are included.

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## 1. Introduction

For aerodynamic calculations of wind turbines usually two-dimensional airfoil data are used. Especially in the stall region there is a significant difference with measurements carried out on rotors, which indicate radial flow and stall at higher angles of attack [1], [2]. This means that the flow around a rotor blade is in reality three dimensional. This can be attributed to:

- the limited length and the change of the twist and taper in spanwise direction and
- the rotation of the blade.

The effect of this first item is important at the tip and root of the blade. For a fixed wing of an aircraft a simple correction on the lift and drag is possible with Prandtl's lifting line theory. For a wind turbine blade the situation is more complicated due to rotation. However such a method of correction for the finite length of a rotating wind turbine blade is available, e.g. the semi-empirical correction method of Viterna and Corrigan [3]. Also in use for aerodynamic rotor calculations is the tip correction factor of Prandtl, specially "designed" for the rotating situation. The flow around the blade tip has the most important effects. The flow around the blade root has only small influence on the total rotor performance and loads of the blade.

The geometrical effects are taken into account in today's standard rotor performance calculation methods to a certain extent.

Effects due to blade rotation are not yet implemented because of lack of sufficient experimental data.

## 2. Test setup of the 2D–3D measurements

In [4] a fair, however not complete, overview is given of the research on rotating blades until 1985. More recent results are described in [2,5]. In most cases the experiments were carried out in a wind tunnel with relatively small models and low Reynolds numbers or at high rotational speed.

The Institute for Wind Energy is carrying out measurements on a wind turbine blade. The rotor blade is equipped with pressure holes at four radial positions to collect more reliable quantitative data concerning the influence of the rotation on the lift and drag distribution on a reasonable wind turbine scale.

### 2.1. Test setup

The rotor blade has no twist or taper, a chord of 0.5 m and a tip radius of 5 m. The blade length is 4.4 m. The airfoil section is a NLF(1)-0416 airfoil. In January 1991 pressure measurements were carried out on the wind turbine rotor blade in the Low Speed Wind Tunnel Laboratory of the Department of Aerospace Engineering of the Delft University of Technology. After that the same rotor blade is mounted on the Rotor Test Facility of the Institute for Wind Energy to measure the characteristics in the rotating situation. The fact that the same rotor blade is measured in the 2D situation and rotating situation has big advantages:

- there are no uncertainties of the 2D characteristics of the rotor blade;
- in the rotating situation the correct angle of attack is difficult to determine accurately. Assuming that the effects of rotation on the pressure distribution at the first 10% to 20% of the chord are small, the angle of attack will be determined with pattern matching of the pressure distribution of the first 20% of the chord;
- In the first phase of the rotating tests no wake rake is available for measuring directly the total drag of the airfoil section. But the total drag of the rotating airfoil section can be calculated from the pressure distribution if the viscous part of the drag is known. The total drag of the airfoil section was measured with a wake rake in the wind tunnel. This gives the possibility to determine a relation between the total drag and pressure drag calculated from the pressure distribution (the difference is the viscous drag). It gives the opportunity to estimate the local drag in the rotating situation if there is no separation and assuming the viscous part of the drag is the same. When the flow is

separated the drag can be obtained by integration of the pressure distribution, because the viscous drag is then relatively small.

For the latter two points it is important to know the pressure distribution at the leading edge accurately. If the method of pattern matching of the pressure distribution will not give satisfactory results for determining the angles of attack of the rotating blade section, it will be necessary to use a five-hole pitot tube or a small vane. Provisions for such extensions have been made.

In the future it might be useful to measure the drag with a wake rake mounted on a support sting at the trailing edge of the rotating blade.

The total pressure for obtaining the local flow speed is measured with a Kiel total probe, which produces a correct total pressure between  $\pm 45^\circ$  of the flow direction.

Due to centrifugal force and radial pressure gradient boundary layer material is swept away. This effect may be compared with the effect of boundary layer suction. This phenomenon can be influenced with vortex generators or boundary layer fences. This will also be investigated.

## *2.2. Instrumentation*

The blade is equipped with two PSI advanced electronic pressure scanners. Each scanner has 32 ports and has a measuring speed of up to 20 kHz. Such a speed is necessary to scan all ports within  $5^\circ$  and  $10^\circ$  rotation of the rotor. The rotor blade is equipped with 59 pressure holes at four spanwise locations: 90%, 70%, 50% and 30%. The diameter of each hole is 0.4 mm. Slip rings are used for signal transmission of the scanners. The voltage output from the scanner is transformed to a current amplified signal to eliminate the influence of variation of the resistance of the slip rings and wires. Strain gages are mounted on the hub to measure the flapping moments in the future.

## *2.3. Calibration*

The PSI scanners have a pneumatically operated calibration switch. With this switch all 32 ports can be switched at once to the same calibration pressure. By generating different calibration pressures and measuring it with an accurate manometer, for each port an individual calibration curve is determined before a measuring run is started. The temperature is also determined since the scanners are sensitive to temperature changes. The calibration procedure is not yet automated.

The tiltable tower of the Rotor Test Facility of the Institute of Wind Energy can be lowered and erected in a few minutes. This gives the possibility for easy access to the nacelle and rotor system to make modifications during the tests, for instance blade pitch changes or calibration of the pressure scanners. The stationary influence of rotation on the air column in the connecting tubes from the holes to the scanners can be measured by sealing off the holes with tape

and measuring the pressure at different rotation speeds. The measurements can then be corrected with this data.

Dynamic effects due to the acoustic behavior of the pressure tubes are not expected to raise problems for frequencies below 50 Hz to 100 Hz [6].

#### 2.4. Some wind tunnel results

In December 1990 and January 1991 the pressures at the 70% spanwise location were measured at Reynolds numbers between  $0.5 \times 10^6$  and  $2 \times 10^6$  and angles of attack from  $-9^\circ$  to  $+25^\circ$ . Also the effects of fixed boundary layer transition with zigzag tape were measured. These measurements were carried out with the multi manometer of the Low Speed Wind Tunnel Laboratory [7].

The multi manometer has an accuracy in the order of 1 Pa to 2 Pa. For angles of attack between  $+2^\circ$  and  $+10^\circ$  and at Reynolds number of  $1 \times 10^6$  the same data were collected with the 2 PSI scanners. The accuracy of the scanners is

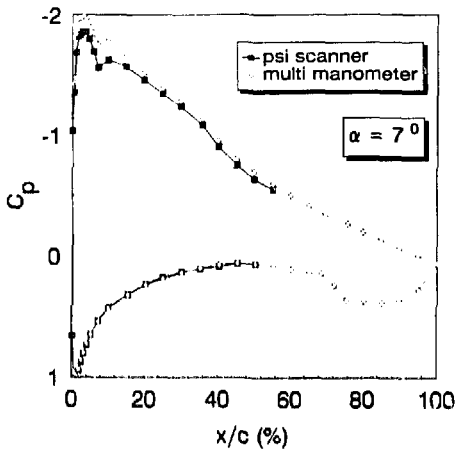


Fig. 1. Comparison of measured  $C_p$  for  $\alpha = 7^\circ$  of PSI scanners and multi manometer at Reynolds number  $1 \times 10^6$ . No tunnel wall corrections. NLF 416 airfoil section.

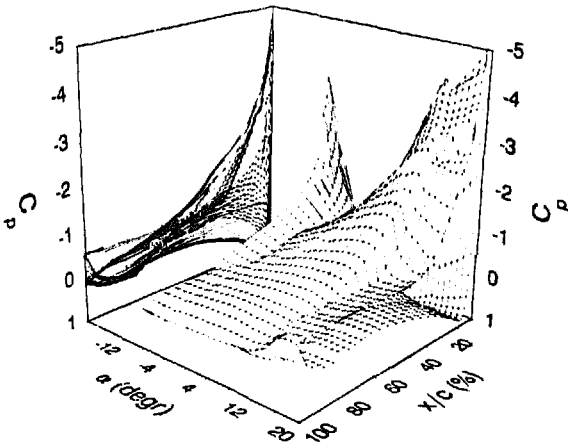


Fig. 2. Measured pressure distribution of the NLF 416 rotor blade airfoil section at Reynolds number  $1 \times 10^6$  and angles of attack between  $-8^\circ$  and  $+19^\circ$ . No roughness. Back plane contains projection of the  $C_p$  curves.

in the order of 10 to 20 Pa. In Fig. 1 an example is given for these comparative measurements for an angle of attack of  $7^\circ$  and fixed boundary layer transition. The  $C_p$  values of the scanner data were a little bit smaller, probably due to a little difference in the registered dynamic pressure and inaccuracy in calibration of the scanners. Due to a small geometrical imperfection of the upper surface of the measured airfoil section at the 8% chord position a small dip in the  $C_p$  curve occurred. These data were not corrected for tunnel wall effects. In Fig. 2 a three-dimensional overview of the pressure distributions is given at Reynolds number of  $1 \times 10^6$  and angles of attack between  $-8^\circ$  and  $+19^\circ$ . These data were corrected for tunnel wall effects [8].

### 3. Conclusions

With the results of the tests now in execution it becomes possible to improve the aerodynamic rotor calculations. Not only the performance calculations, but also the prediction of stall can be calculated more reliably. The wind tunnel tests showed that the scanners can be used for collecting pressure data of an airfoil section in a sufficiently reliable way.

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