Wake Skew Angle Variation with Rotor Thrust for Wind Turbines in Yaw Based on the MEXICO Experiment

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ABSTRACT

The primary objective of the MEXICO (Model Experiments in Controlled Conditions) project was to generate experimental data from which the uncertainties of the computational tools employed to predict wind turbine performance and loads. Pressure sensors were used for pressure measurements while PIV was used with the major aim of tracking the tip vortex trajectory. The aerodynamic forces on the blades were derived found from the pressure measurements and were used in an inverse free wake lifting line model to compute the positions of the tip vortices. From these the wake skew angle was derived. A relationship between the skew angle and the thrust coefficient was thus drawn.

KEYWORDS

Yaw, Skew Angle, MEXICO experiment.

1 INTRODUCTION

The pressure measurements were carried out for both axial and yawed flow conditions with yaw angles of 15, 30 and 45 degrees. For the PIV measurements data was gathered for axial flow but only for the 30 degree yaw case for a single tip speed ratio. A three bladed rotor was used with a diameter of 4.5m and 0.42m hub diameter. For the blade geometry and other details the reader is referred to [1]. Pressure measurements were first validated and used to find the loads acting on the rotor. In this study, an inverse free wake model [2] was used for all of the yaw angles to obtain the skew angles. The forces were prescribed to the program and the induced velocities calculated in an iterative manner until the angle of attack converged. The wake geometry for a number rotor revolutions (depending on the tip speed ratio) was obtained from the inverse free wake model for the mentioned yaw angles for four different tip speed ratios (4.18, 5.55, 6.68 and 10) with a rotor speed of 424.5RPM and with wind speeds of 10, 15, 18 and 24 m/s. From the wake geometry a relationship can be obtained between the skew angle and the thrust coefficient obtained from experiment.

This relationship was also investigated by W. Haans et al. [3] by means of an experiment of a yawed rotor at TUDelft.

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2 RELATIONSHIP BETWEEN SKEW ANGLE AND THRUST COEFFICIENT

2.1 *Methodology*

In order to obtain an estimate of the skew angle, a graphical procedure was employed. A line, oriented at an angle equal to the rotor yaw angle was constructed to be used as reference. Another line at the rotor yaw angle was constructed but this time joining the vortex cores of the wake sheet boundary. If the line cannot pass through the cores exactly, the position of the line and its length are adjusted to another position which intersects an interpolation line passing through the vortex cores. The process is repeated for all the blades for a number of revolutions determined by the numerical stability of the inverse free wake model. The midpoint of each and every line is hence determined and a line of best fit is passed through these midpoints. The angle of this line may then be found and was denoted by θ. The skew angle is then given by

$$\chi = \gamma + \theta \qquad (1)$$

An example is shown in figure 1 for the 30 degree yaw and wind speed of 10m/s.

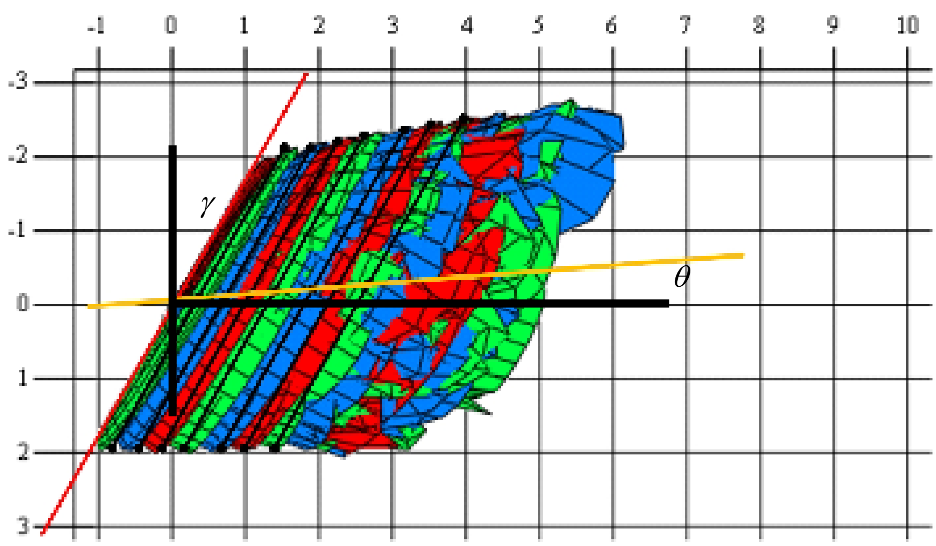

Figure 1: Wake geometry as obtained from the inverse free wake model and geometrical construction of *θ*.

2.2 *Derivation of a linear relationship between skew angle and thrust coefficient*

The skew angle was found for each yawed flow case by means of the inverse free wake code. The thrust coefficients were obtained from the MEXICO data for each test case. The thrust coefficient will vary with azimuth but an average was taken over all rotor revolutions.

The relationships between skew angle and thrust coefficients are shown in figure 2. This is consistent with the results found from Haans et al [3].These linear fits can be represented by means of the linear expression:

$$\chi_\gamma = k_1 \cdot C_T + k_2 \qquad (2)$$

for $\gamma \in [15°, 30°, 45°]$. Table 1 shows the intercept and gradients for the linear fit described by eqn. (2).

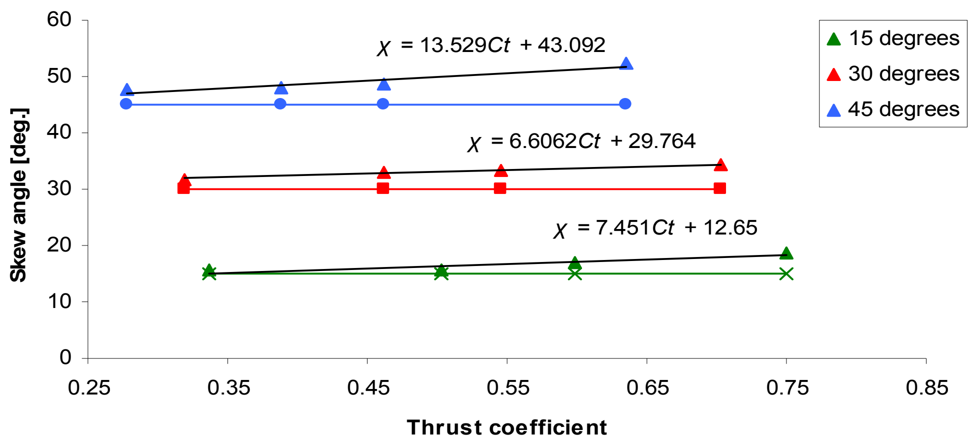

Figure 2: Skew angle against thrust coefficient for different rotor yaw angles. Coloured lines show the yaw angle while bold black lines show a linear fit for the skew angle.

Table 1: Intercept and gradients for linear fit for different yaw angles

γ [deg.]	k_1	k_2
15	13.529	43.092
30	6.6062	29.764
45	7.451	12.65

A general relationship can be found in terms of the yaw angle by considering these gradients and the intercepts. For the axial flow condition the skew angle must necessarily pass through 0. Figure 3 shows linear fits of the gradient and intercept with yaw angle. For a higher order approximation more points would be required but the MEXICO data is limited to just three yaw angles. The linear fits shown in figure 3 seem to make sense as the data points do not show too much scatter. Further investigation can however be done in future experiments with a larger number of data points. The linear equations for the gradient and intercept are also shown on figure 3. Using these equations in (2) and rounding up:

$$\chi \approx \gamma\left(0.3C_T + 1\right) \tag{3}$$

3 CONCLUSIONS

In this paper, the MEXICO experimental data was used as an input to an inverse free wake vortex model. From the wake geometry a relationship was obtained between the thrust and the skew angle. It was found that the rate of increase of the skew angle with thrust coefficient increases with rotor yaw error. This was expected since the induced velocities at high yaw angles will deflect the wake in a more pronounced manner. In future work, a PIV experiment will be performed for yawed conditions at TUDelft and more yaw angles will be considered to be able to reconstruct a higher order relationship between thrust coefficient and skew angle.

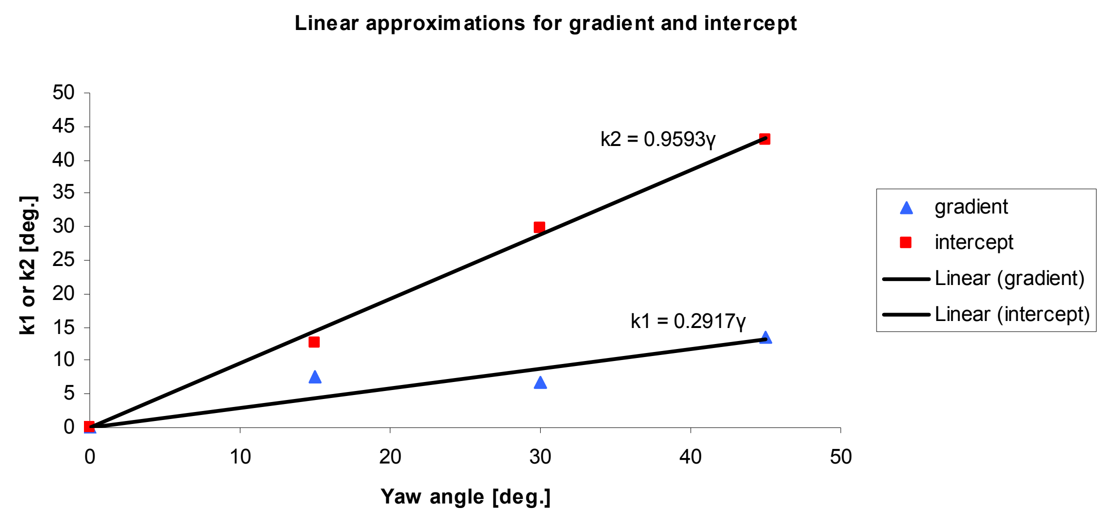

Figure 3: Linear fits for gradient and intercept quantities in terms of the yaw angle.

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