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THE WAKE STRUCTURE OF A WIND TURBINE - COMPARISON BETWEEN PIV MEASUREMENTS AND FREE-WAKE CALCULATIONS

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ABSTRACT Rotor aerodynamic prediction codes remain inaccurate, as many of the features of the wake flow are not yet fully understood, or are simply unknown. In the present work, this problem has been addressed by comparing the results of a sophisticated free-wake numerical code with wake measurements made using the technique of Particle Image Velocimetry (PIV). Unique images have been obtained at the University of Edinburgh, using PIV to capture wake images at model scale. Detailed maps of velocity and vorticity have thus been obtained in the wake of a number of small-scale models. Simultaneously, the sophisticated free-wake numerical code ROVLM has been developed at the University of Stuttgart. The code has been successfully applied in previous aerodynamic and aeroacoustic EU research projects. The aim of this comparison has been to highlight those areas of current theory where wake modelling is weakest.

Keywords: wakes, particle image velocimetry, free-wake analysis, vorticity

1. INTRODUCTION

Despite the advanced commercial development of wind turbines, some of the fundamental assumptions of the rotor aerodynamic prediction codes currently used by the wind turbine industry are in question. Blade element-momentum theory (BEMT) is deficient at both low and high tip speed ratios. At low λ, where the rotor is wholly or partially stalled, the theory often underpredicts rotor power. At high λ (low windspeeds), where high blockage exists, the basic assumptions of BEMT break down. Predicted values of thrust fail to agree with measured results, and empirical corrections are usually employed in this region. These discrepancies have been the subject of experimental and theoretical examination for some time.

This paper presents a comparison between the results gained by the experimental technique of PIV and the numerical simulations of the ROVLM code. The comparison is based on the study of flow past flat-plate blades, since it represents a fundamental case and also offers simplicity in modelling the rotor. In particular, the study explores extreme operating states of the blades. These correspond to regions of flow where theoretical techniques give least satisfactory results. Stalled flows at low-λ are significant commercially to the wind turbine industry as current design methods for stall-regulated wind turbines are essentially empirical.

2. EXPERIMENTS

There is a need for detailed measurements of the wake, in order to develop and validate numerical codes. At the University of Edinburgh, the technique of PIV has been applied with some success to a series of small-scale model wind turbines[1]. The experiments were the first in which full-field velocity and vorticity maps have been captured in the wake of a wind turbine at any scale.

The PIV experiments were carried out in a glass-based, two-dimensional water channel equipped with a recirculating pump which allows a steady flow velocity to be established. An arrangement of honeycomb section, perforated plate and fine mesh screen were used as flow manipulators upstream of the rotor. A configuration was used which produced a uniform incoming flow of 0.25 m/s and an upstream turbulence intensity of 4 %. A two-blade model with flat-plate blades and rotor diameter of 175 mm was used in the experiments. The model was operated at tip speed ratios in the range $\lambda = 2 - 8$. This corresponded to a range of *chord* Reynolds numbers of Re = 6,400 – 16,000.

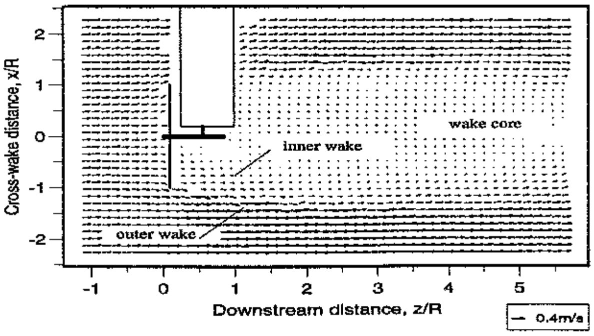


Figure 1: PIV velocity vector map at $\lambda = 8$

A 15 W Argon-ion laser was used to illuminate a region of flow, in the near wake of the model, containing small seeding particles. The images of the seeding particles on film indicate the local velocities in the flow region. This is the basis of PIV, which allows complete two-dimensional flow fields to be captured at a single instant. Averaging the instantaneous PIV records extracts the coherent structure of the trailing vorti[illegible]n the wake from the superposed turbulence. Figure 1 shows an averaged PIV velocity vector map with the flat-plate blades at $\lambda = 8$.

3. SIMULATIONS

Despite twenty years of research, the theory for wind turbine wakes remains incomplete. The main reason is that prediction codes often neglect the important influence of unsteady, 3D or viscous effects. In addition, most models do not take into account the concentration of the trailing vorticity, leading to inaccuracies in modelling the induced velocities at the tips of the blades.

The Rotor Vortex Lattice Method (ROVLM) code has been developed at the Institut für Aerodynamik und Gasdynamik (IAG), University of Stuttgart and is able to predict the wake geometry and strength of the vorticity on the rotor blades and in the wake[2]. The code has been successfully applied to the calculation of rotor loads and induced velocities in previous EU R&D projects[3], [4].

The code incorporates a time-dependent simulation of the rotor movement. The blades start their rotation in the first time interval and in every subsequent time step a new portion of the wake is shed from the trailing edge of the blades. A steady state solution develops after a few rotor revolutions, depending on the loading of the rotor and the oncoming flow.

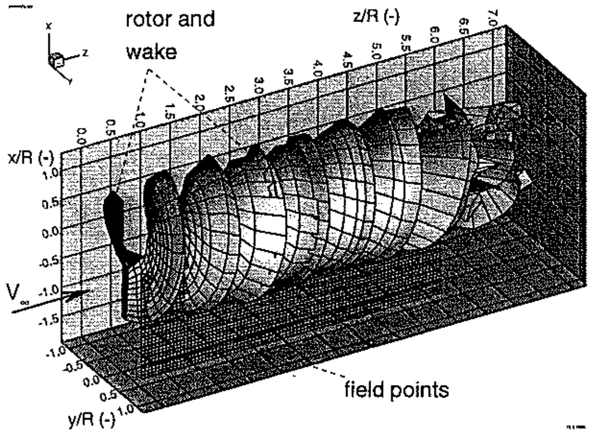


Figure 2: Simulated wake with plane of comparison

Blade geometry, rotor operating states and size and location of the measurement area in the channel were used as input to the ROVLM code in order to simulate the PIV measurements. Figure 2 shows a typical result of the ROVLM calculations. A two-dimensional region is depicted, corresponding to the laser sheet in the PIV set-up, from which wake velocities are extracted for the purpose of comparison with the PIV data.

4. RESULTS

The velocity information from the PIV experiments and the ROVLM simulations was processed to produce vorticity contour maps. These are displayed in Figure 3 for tip speed ratios of $\lambda = 4$, 6 and 8. The contours of the maps join points of equal vorticity with vortex strengths represented by varying degrees of lightness. Data is absent from a region of the PIV contour plots corresponding to the position of the tower of the experimental rig. The vorticity data was used to gain information about the structure, transport, dissipation and instability of the vortex system in the wake.

Vortex structure in the wake

At low tip speed ratios, mild wake expansion is observed from the contour plots. This pattern concurs with simple wake theory. At $\lambda = 6$ and $\lambda = 8$, there are signs of contraction at around 2.0D downstream of the rotor. This is observed to precede the breakdown of the structured wake into a highly turbulent state. The large slipstream expansion around the rotor and marked contraction in the wake are characteristic of a wind turbine operating in a turbulent wake state[5]. The PIV tests and ROVLM simulations compare reasonably well in terms of overall wake geometry. The numerical results appear to model wake contraction with some success, although the wake contraction of the PIV results is more sensitive to tip speed ratio.

The vorticity contour plots for the PIV tests reveal structures that are consistent with the expected pattern of a cross-section of a helical vortex spiral. The PIV contour plots also reveal a second region of concentrated vorticity in the wake of the model, inboard of the tip. Close study of Figure 1 shows that this 'inboard' vorticity is likely to be due to a region of sheared flow between the outer flow containing the tip vortex system and the retarded flow in the wake core. The stretching of smoke traces in tests by Pedersen & Antoniou[6] give credit to the existence of this shear layer at full-scale. No evidence of shear layer vorticity is found from the ROVLM simulations.

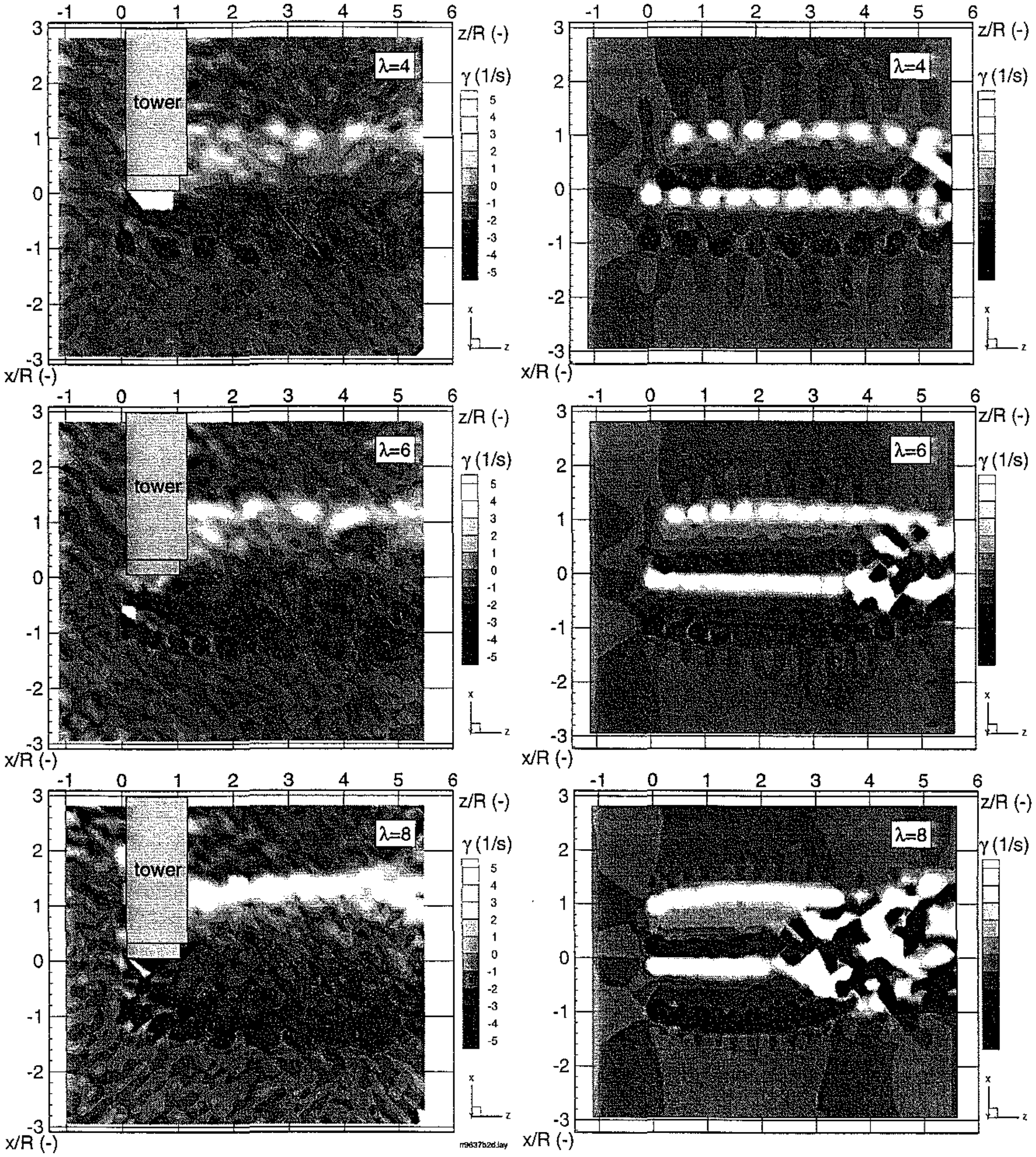
Transport of vorticity in the wake

Figure 4 compares the tip vortex pitch in the wake as a function of $1/\lambda$ for the PIV experiments and ROVLM results. The tip vortex pitch is defined as the non-dimensional travelling speed of the tip vortex,

$$p = 2\pi \frac{V_z}{\Omega R}$$

where V_z is the axial transportation velocity of the tip vortex and Ω is the rotation speed of blades of radius R.

Results are also included from wind-tunnel experiments on a 1.2 m diameter model turbine conducted at TU Delft[7]. The ROVLM simulations are contrasted with predictions using an empirical formula given by Miller et al.[8]. From Figure 4, the empirical formula seems to underpredict the measured data whereas the ROVLM calculations appear to successfully reproduce the trends indicated by the measurements.



(a) measurement

(b) calculation

Figure 3: Comparison of measured and simulated vorticity in the flow field.

The exception is at λ = 8 where the measured values show significant scatter.

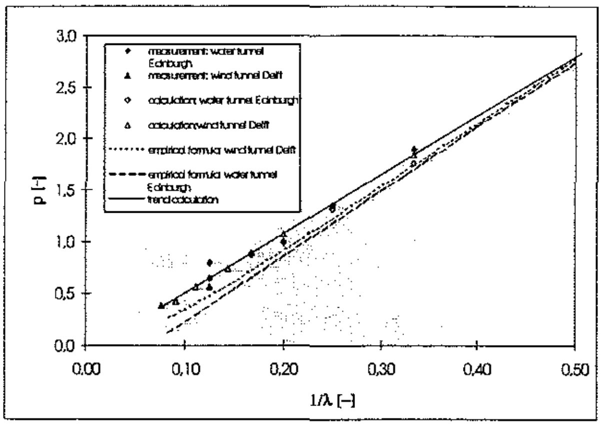


Figure 4: Comparison of tip vortex pitch.

The PIV results suggest an increase in tip vortex pitch at λ = 8, contrary to BEMT which assumes an asymptotic slow down of the wake with tip speed ratio. At such high λ, vortex pairing in the tip vortex system leads to uncertainties in determining the spacing of the vortices. It is plausible, however, that re-entrainment of the freestream may cause a wake acceleration which uncoils the densely packed spiral. This phenomenon has been reported by Montgomerie[9], referring to wind tunnel tests where smoke studies on model wind turbine rotors revealed strong acceleration of the wake spirals, following an initial deceleration.

Dissipation of the vortex system

The PIV contour plots of Figure 3 indicate that the tip vortices persist up to 2D downstream. This is in accordance with observations made at full-scale by Savino & Nyland[10].

Due to inviscid assumptions, the vortex system of the ROVLM simulations is not subject to dissipation. In particular the root vortices are very strong and persist far downstream. Also, with no viscous effects, a large angle of attack near the hub produces a large circulation instead of separated flow. In contrast, the PIV contour plots reveal that, due to stall near the hub, the root vortices are much smaller than those of the ROVLM simulations and dissipate within a blade revolution. This is consistent with observations from full-scale by Pedersen & Antoniou.

Instability of the vortex system

The instability of the vortex system in the simulations appear to be due to the interaction of strong root vortices from the two separate blades rather than mixing of the freestream or dissipation. Wake breakdown is absent from most rotor codes, of either BEMT or vortex-wake type.

5. CONCLUSIONS

The ROVLM code and the PIV data have been used in a direct comparison of the wake of a small model 2-blade rotor operating in the range λ = 2 – 8. It is believed that this is the first time such comparisons have been made on the full wake, up to 2.5D downstream.

The ROVLM code needs to be modified to incorporate Reynolds number effects and stalled flow at the inboard sections. It makes sense to use the PIV data rather than try to map the vorticity behind a full-scale wind turbine. Athough the Reynolds numbers of the PIV tests is lower than a typical full-scale machine by a factor of 1000, there is a strong possibility that the wake structures at different scales will share fundamental similarities.

The potential for this work is significant. To date, comparisons between simulation and measurement on wind turbine performance give little information on the reason for discrepancies, as the only comparisons are of integrated quantities (power, thrust, etc.). In this study, however, the whole flow field has been compared at a detailed level, revealing properties of the wake structure that suggest the current design codes used by the wind turbine industry are inadequate. This work may be viewed as a first step in developing an advanced rotor performance method that will incorporate the detailed physical processes governing wake behaviour and ultimately lead to the design of more reliable and efficient wind turbines.

6. ACKNOWLEDGEMENTS

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