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AN EXPERIMENTAL INVESTIGATION OF WIND TURBINE WAKES USING PARTICLE IMAGE VELOCIMETRY

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ABSTRACT: Determination of the aerodynamic performance of horizontal-axis wind turbines (HAWT) is complicated by problems such as wake deformation effects and free stream turbulence. An accurate prediction of the wake structure is a dominant factor for reliable wind turbine aerodynamic prediction codes. The technique of Particle Image Velocimetry is used to provide detailed full-field data of the wake geometry in the immediate vicinity of the rotor of a reduced-scale wind turbine. The results strongly validate the PIV technique applied to studying wind turbine wakes. The potential for this method is significant and can be used to compare wake data from other experiments as well as wake geometries predicted by theoretical models.

1 Introduction

1.1 Background

Wind turbine performance is critically dependent on the geometry of the rotor wake. The wake structure determines the rotor inflow conditions and hence the forces on the blades. For design purposes it is essential to predict the blade loads accurately, to estimate rotor power output and structural stress. Thus, an accurate prediction of the wake structure is a dominant factor for reliable wind turbine aerodynamic prediction codes.

However, the lack of detailed experimental data in the wake of a turbine, and the difficulty of obtaining it, is widely appreciated. Full-scale visualisation experiments are difficult to perform and are limited by the problems of expense and non-repeatable conditions. Thus, though the investigations of wind turbine wakes are comparatively recent, many have involved simulators and model wind turbine generators. In the late 1970s, wind tunnel simulations began in Holland (at TNO Apeldoorn), Sweden (Aeronautical Research Institute) and in the UK (at CERL Leatherhead). The work was co-ordinated by the International Energy Agency (IEA) and concentrated on hot-wire measurements of flow over tipvane type simulators. A summary of the experimental results for models of size 200-300mm in diameter can be found in Vermuelen[1]. Green[2] later refined and developed the modelling techniques using laser doppler anemometry (LDA) on a modified model aircraft propeller of diameter 150mm.

The problems of poor signal to noise ratio and condensation of seeding in the wind tunnels experienced by LDA workers ([3], [4]) together with the desire to obtain simultaneous multipoint measurements with minimum disturbance to the flow caused by instrumentation, suggest the method of Particle Image Velocimetry (PIV) to studying flows of this type.

PIV is a non-intrusive velocity measurement technique which allows complete two-dimensional flow fields to be captured at a single instant. The basis of PIV is to stroboscopically illuminate a two-dimensional plane of flow containing small neutrally buoyant seeding particles by means of a sheet of pulsed light. A double (or multiple) exposure photograph of this plane is taken. The spacing between the images of each particle on the film gives the local velocity. This photograph is then analysed over a grid of points to determine the local flow velocities across the whole field.

The technique of PIV was introduced to the field of wind turbine aerodynamics by Smith et al.[5] who conducted tests on a Rutland wind turbine using pulsed lasers. The tests established the applicability and usefulness of the PIV technique as a velocimetry tool for wind turbines. However, the high slipstream velocities involved in wind tunnel testing meant that particles separating at the trailing edge of the blades were dispersed out of the light sheet causing problems of illuminating the wake structure. This limited the study to flow close to the blade and again illustrated the problems of seeding in wind tunnels.

In an attempt to overcome the problems of illumination and seeding density experienced by previous investigators in wind tunnel studies, some preliminary tests of a model turbine rig in water were conducted in the Fluid Dynamics Unit of the University of Edinburgh starting in December 1991. The PIV experiments were performed using a high powered continuous wave (CW) laser with the turbine placed in a water tank capable of generating currents. The blade passing frequency of the rotor and the upstream current were carefully arranged so that, Reynolds number apart, aerodynamic similarity existed between the model and a full-scale wind turbine.

1.2 Theory

The most common basis for HAWT performance prediction codes is a combined blade-element momentum theory. In high winds, however, where the rotor is partially or wholly stalled, this method often underpredicts rotor power. This discrepancy has been the subject of experimental and theoretical examination for some time. The theory is also deficient at very low windspeeds, when high blockage exists; empirical methods are usually employed in this region.

Vortex wake models attempt a more realistic representation of the wake, consistent with the notion of a helical vortex sheet shed from the trailing edge of each blade and convected downstream at the wake velocity. These trailing vortex filaments undergo self-induced distortions as well as being influenced by other filaments. The wake deforms into a vortex system comprising of an intense tip-vortex outer region and a weak diffused vortex sheet inner region (See Figure 1). In the flow recording process, the PIV illumination extracts behaviour in the wake corresponding to a cross-section of the helical vortex system.

Many references can be cited for the development and application of vortex wake models (e.g. [6], [7]). There is a lack of consensus, however, in the way the vortex wake geometry should be represented, and the models are sensitive to the choice of assumed wake geometry. Inaccuracies must be expected as many of the features of the flow are not yet fully understood, or are simply unknown, due to the lack of quantitative experimental data on the wake. By providing full-field wake geometry data, PIV experiments provide the opportunity to validate some of the assumptions made in performance prediction codes.

2 Experiments

The experiments were carried out in a glass-based, two-dimensional wave flume equipped with a recirculating pump which allows a steady flow velocity to be established. The model turbine rig was placed across the tank subjecting the rotor to a uniform current. The turbine was driven by a electric motor/generator suspended on a frame above the water level. The rotor is located at the end of an inverted tube, or tower, which was perpendicular to the oncoming flow to ensure symmetric inflow conditions.

It is important that the mechanism of wake generation is accurately produced. As well as geometric similarity between the model and a full-scale machine, an appropriate range of tip speed ratios λ are used (ratio of blade rotation to freestream velocity) so that, notwithstanding the Reynolds number, kinematic similarity is assured. Motor speed was altered to achieve the desired tip speed ratios

$$\lambda = \frac{\omega R}{V_0},$$

where R is the radius of the rotor, ω is the blade passing frequency and V_0 is the freestream velocity.

The PIV set-up at Edinburgh is based on the scanning beam system of flow illumination[8]. The beam from the 15W CW Argon ion laser scans over a parabolic mirror which directs the beam vertically upwards through the base of the flume, illuminating a vertical cross-section of the flow. The water was seeded with conifer pollen of average diameter 70μm with concentrations maintained at a level to ensure a high density of particles on the resulting film record.

Two types of rotors were used in the experiments. In the preliminary investigations the turbine was a 2-blade model aeroplane propeller of 175mm diameter and 16mm in chord length at a blade span of 70%. The propeller was run in reverse so that its twist and chord distributions approximated those of a wind turbine rotor. Tip speed ratios of approximately 3-12 were used with Reynolds number based on tip chord in the range 6,000 - 35,000. Photographs of the flow were taken with a standard 35mm Nikon camera with a f2.8 50mm flat focus lens (e.g. Figure 2).

The second set of experiments involved some improvements in generating a more realistic wind turbine simulator and enhancing the quality of the measurement data. The propeller was not an ideal turbine model as its aerofoil section operated trailing edge first so it was replaced by flat-plate blades of the same diameter with varying thickness, camber and taper. The tower of the rig was streamlined with a foam plastic shroud in order to limit its wake interfering with the top half of the turbine wake structure, as was noticeable in early tests. Also, the nacelle of the model was moved out of the laser sheet so that just the tips of the blades passed through the sheet. A wide range of velocities were recorded in the previous experiments, from the undisturbed upstream flow to the region of almost stagnant fluid behind the rotor. Thus, for these experiments, an image shifting system was used to impose a translational velocity on the recorded image to increase dynamic range and eliminate directional ambiguity. The shift system was comprised of a Hasselblad 500 EL/M camera and 80mm lens mounted on a turntable and controlled by a microcomputer which rotated the turntable to a given shift speed and triggered the camera when it reached the correct position.

The PIV negatives were analysed on a 32 bit microcomputer to yield 2D velocity vector maps. The film was interpreted point by point over a dense grid using methods of optical and digital analysis. This involves scanning a small part of the negative at a time with a probe laser to produce an interference pattern from the multiple particle images in that area. The interference fringes are measured and recorded in digital form and the data Fourier transformed to yield the particle velocities at that point. The whole negative is scanned in this way to build up a flow velocity map, which forms the basis of all subsequent analysis. Firstly the shift velocity was removed to reveal the actual flow pattern and then the mean horizontal component of the velocity was subtracted at all points in order to highlight the induced flow velocities. The velocity information can also be processed to produce vorticity maps. The contours of the plots join points of equal vorticity with vortex strengths represented by varying degrees of lightness.

3 Experimental Results

At low tip speed ratios, the rotor is in the windmill state. The wake of the turbine contains an area of expanding flow with reduced velocity. This is verified by the PIV velocity map of the propeller at $\lambda = 2.7$ (See Figure 3) in that the velocity vectors in the wake point upstream after subtracting the mean horizontal velocity. In the lower half of the wake, angled strips of vorticity can be clearly seen; the expected pattern for the cross-section of a helical vortex sheet. Also seen from the velocity map is a sinusoidal pattern imposed on the boundary of the wake. This is consistent with the prescence of trailing tip vortices originating from the rotating blades and passing downstream.

Figure 4 displays the corresponding vorticity map of Figure 3. Note how the wake is roughly divided into regions of positive(light) and negative(dark) vorticity, lying on either side of the centreline. This is again as expected from the cross-section of a helical vortex. The appearance of two sets of trailing vortices in each half of the wake can be explained from the design of the model propeller which has a rapid change in chord and twist near the hub as well as a change in chord near the tip. The subsequent rate of change of circulation around these parts of the blade induces velocities which roll up the vortex sheet both at the tip and at the hub.

Figure 5 is a PIV velocity vector map for a flat-plate blade in the windmill state ($\lambda = 3.4$). The flat-plate had a thickness of 1.26mm, a camber of 6% and a linear taper with a chord length of 83% of the hub chord at the 70% span position. It can be seen from Figure 5 that the image shifting system was successful in resolving small velocities in the almost stagnant region of flow and produced a more complete vector map. Figure 6 is the vorticity contour plot corresponding to Figure 5. It shows the presence of the tip vortices highlighted by moving the nacelle out of the light sheet. Streamlining the tower also proved effective in reducing the inteference with the top half of the wake and produced a more symmetrical flow pattern.

Figures 7 and 8 are for the same flat-plate blade at a higher tip speed ratio ($\lambda = 9.0$). The rotor is in the turbulent wake state and the boundary of the wake is characterized by initial expansion followed by marked contraction. Figure 8 displays a large increase in the strength of areas of concentrated vorticity compared to Figures 4 and 6. This is because, as the tip ratio is increased, the wake becomes turbulent preserving the energy within the trailing vortices and producing a very strong vortex pattern.

4 Conclusions

The models clearly exhibited operating states characteristic of a wind turbine, namely the windmill state and the turbulent wake state. The windmill state is the intended state for wind turbine operation. However, turbulent wake states do occur during operation and much modelling needs to be done to have a complete understanding of the forces and moments on a rotor in this state.

Care must be taken when comparing the performance of a model wind turbine to that of a full scale machine. As pointed out by Galbraith et al.[9], interpretation of turbine performance requires reliable data on the characteristics of the aerofoil at the appropriate Reynolds number; the overall properties of the downstream wake, however, are less sensitive to Reynolds number and inferences can be made from bulk-flow phenomena.

The results strongly justify using the PIV technique to study flows of this type. PIV provides the means whereby detailed full-field data can be obtained and an experimental data base for wake velocities and structure established. The amount of high quality detailed data of the entire flow field obtained by the uncomplicated, quick and flexible approach of

PIV compared favourably with the previous methods explored by investigators. The potential for this method is significant and can be used to compare wake data from other experiments as well as wake geometries predicted by numerical codes. In particular, it could provide information about those regions of flow where theoretical techniques give least satisfactory results, for example in stalled flows. This is a question of some importance to the wind turbine industry as current design methods for stall-regulated wind turbines are essentially empirical.

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