University of Glasgow

DEPARTMENT OF

AEROSPACE ENGINEERING

AN EXPERIMENTAL AND NUMERICAL STUDY TO VALIDATE AN AERODYNAMIC MODEL OF YAWED FLOW OVER A WIND TURBINE

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EPSRC contract number GR/K/14995

R.A.McD Galbraith, F Coton
Department of Aerospace Engineering
University of Glasgow
GLASGOW
G12 8QQ

I.Grant
Dept. of Civil and Offshore Eng.
Heriot-Watt University
EDINBURGH
EH14 4AS

Summary

This project took the form of a joint three year research programme between the Department of Aerospace Engineering, University of Glasgow and the Department of Civil and Offshore Engineering at Heriot-Watt University. The principle objectives of the work were twofold. Firstly, to obtain, by wind tunnel experiments, details of the flow around a wind turbine using both Particle Image Velocimetry (PIV) and unsteady pressure measurement. The second objective was to complete the development of an efficient and robust unsteady aerodynamic model for horizontal axis wind turbines. Both of these objectives were achieved during the course of the project

Numerical modelling focused on the continued development of a prescribed wake vortex model for HAWT performance prediction. This model represents the turbine blades as lifting lines from which emanate filaments of trailed vorticity. In yawed flow, additional filaments of shed vorticity are produced and the unsteady loading on the blades is represented by a semi-empirical unsteady aerofoil model. During the project, the model was extensively validated against field data. In addition, its capabilities were extended to include prediction of the unsteady response due to tower shadow on downwind wind turbines and the prediction of three-dimensional stalling on inboard sections of the turbine blades.

The wind tunnel test programme drew together the expertise of the Glasgow group in the measurement of unsteady pressures and that of the Heriot-Watt group in the application of PIV. Two major testing programmes were conducted during the study. In the first, at Heriot-Watt University, extensive PIV and Digital PIV tests were conducted on an uninstrumented wind turbine model to measure the influence of operating conditions and turbine solidity on the wake structure. Similar test were then conducted in the Glasgow University wind tunnel on a specially designed two-bladed wind turbine model, which incorporated pressure transducers in one blade. The database of experimental results produced by both sets of tests, represents possibly the most detailed information on wind turbine wake structures currently available.

For further information contact:

Dr. Frank N. Coton
Department of Aerospace Engineering
University of Glasgow
Glasgow
G12 8QQ

Tel. 0141 330 4305
Fax. 0141 330 5560
e.mail. frank@aero.gla.ac.uk

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Department of Aerospace Engineering
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I.Grant
Dept. of Civil and Offshore Eng.
Heriot-Watt University
EDINBURGH
EH14 4AS

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ABSTRACT

The following report summarises a joint three year research programme between the Department of Aerospace Engineering, University of Glasgow and the Department of Civil and Offshore Engineering at Heriot-Watt University. The principle objectives of the work were twofold. Firstly, to obtain, by wind tunnel experiments, details of the flow around a wind turbine using both Particle Image Velocimetry (PIV) and unsteady pressure measurement. The second objective was to complete the development of an efficient and robust unsteady aerodynamic model for horizontal axis wind turbines. Both of these objectives have been achieved during the course of the project

OBJECTIVES

- To obtain, by wind tunnel experiments, details of the wake structure and blade loading of a horizontal axis wind turbine (HAWT) in head-on and yawed flow
- To complete the development of an efficient and robust unsteady aerodynamic model for HAWT's.

METHODOLOGY

As indicated in the project objectives, there were two main activities associated with this project. Numerical modelling focused on the continued development of a prescribed wake vortex model for HAWT performance prediction. This model represents the turbine blades as lifting lines from which emanate filaments of trailed vorticity. In yawed flow, additional filaments of shed vorticity are produced and the unsteady loading on the blades is represented by a semi-empirical unsteady aerofoil model. For comparison with the wind tunnel tests, this model was coupled to a source panel method which provided a representation of the tunnel walls. The wind tunnel test programme drew together the expertise of the Glasgow group in the measurement of unsteady pressures and that of the Heriot-Watt group in the application of PIV. Two major testing programmes were conducted during the study. In the first, at Heriot-Watt University, extensive PIV and Digital PIV tests were conducted on an uninstrumented wind turbine model to measure the influence of operating conditions and turbine solidity on the wake structure. Similar test were then conducted in the Glasgow University wind tunnel on a specially designed two-bladed wind turbine model, which incorporated pressure transducers in one blade.

VARIATION FROM THE ORIGINAL PROPOSAL

There are two main differences between the original proposal and the work actually carried out. Firstly, a series of logistic and staffing problems influenced the phasing of the work. These were reported to the EPSRC through the contract monitoring process as the work progressed. The main effect of the problems was to delay the test programme in the Glasgow University wind tunnel until the last few months of the project. Despite these delays, however, the main elements of the work have been completed within the contract term. Secondly, several aspects of the work have been developed far beyond the original scope of the project. In particular, it has been possible to extensively validate the prescribed wake prediction scheme against field data supplied through a collaboration with the National Renewable Energy laboratories (NREL) in the U.S. and to extend its capabilities to include the prediction of tower shadow response and to account for strongly three-dimensional flows on the inboard sections of wind turbine blades. Similarly, the PIV studies conducted at Heriot-Watt University have, in addition to proving the PIV system, provided extensive information on both the formation and subsequent convection of turbine wake structures and how these are influenced by operating conditions.

DETAILED DESCRIPTION OF WORK CARRIED OUT

The work programme had a series of key elements, each of which are discussed in detail below. These were:

- Further development of features of the numerical model including provision of a wind tunnel wall representation
- PIV proving trials on a wind turbine model in the Heriot-Watt wind tunnel.
- Two-dimensional testing of the wind turbine test blade section at low Reynolds numbers
- Measurement of unsteady blade pressures and wind turbine wake geometry in the Glasgow University wind tunnel.

Numerical Modelling

The Prescribed wake model used as the basis for the present work was developed during a previous EPSRC funded study [1]. In the model, the spanwise blade loading distribution is represented by a series of straight-line vortex filaments which lie along the quarter chord line of each blade element. By representing the turbine blades in this manner, a discontinuity in spanwise bound circulation is created at each element boundary. This is redressed by the introduction of trailed vortex filaments whose strengths correspond to the differences in bound circulation between adjacent blade elements. The direct consequence of a yawed onset flow is that the blades also experience an azimuthal incidence variation. Thus, in the present model, the bound circulation on a given blade element changes as the blade rotates and this necessitates the introduction of shed vorticity elements in the wake structure. The geometry of the wake is defined by previously described prescription functions [2].

If the reduced frequency of rotation of a wind turbine operating in yawed flow is high enough, the blades experience unsteady aerodynamic effects. In some cases these are severe enough to result in full dynamic stall. To represent these effects, the prescribed wake model is coupled to the unsteady aerodynamic model of Leishman and Beddoes [3]. This model requires information such as the reduced pitching rates, the local relative velocity and the instantaneous angle of attack which the turbine blade experiences. In the unsteady prescribed wake method [4,5,6] this information is determined by initial application of the prescribed wake scheme using static aerodynamic characteristics. This stage of the calculation procedure also produces the wake geometry for the subsequent dynamic calculation. On completion of this stage, the unsteady aerodynamic model is used iteratively with the wake model to obtain a more accurate estimate of the turbine performance.

Comparison of this type of numerical model with wind tunnel tests can be problematic because of the wall constraint effect [7]. It is, therefore, necessary to provide a representation of this constraint effect within the calculation scheme. To do this, the basic model was used together with a three-dimensional source panel method which, in isolation, could be used to calculate the incompressible, inviscid, potential flow through the wind tunnel. To predict the wake structures generated during the wind tunnel tests, it was necessary to find an effective mechanism to couple this scheme to the prescribed wake model.

An iterative scheme was, therefore, developed in which the mutual influence of the wake and walls on each other was evaluated and used to determine the wake trajectory. In this scheme, the starting point was the wake shape generated by the prescribed wake method in an unconstrained flow. The velocities induced on this wake by the wall source panels were then calculated and used to distort the wake structure. The induced effects at the tunnel walls were then calculated and the source distribution on the wall panels adjusted accordingly. This process was then iterated until a converged solution was obtained. This technique is currently being applied to generate comparisons of blade loads and vortex trajectories with the recently completed tests in the Glasgow University wind tunnel.

In addition to the above, much emphasis was placed on the validation and enhancement of the basic prescribed wake model itself. Field data from the National Renewable Energy Laboratories in the U.S., supplied, as part of an on-going collaboration, provided a focus for these validation exercises. It also provided the scope to extend the capabilities of the model to predict tower shadow response and the stall delay due to three dimensional effects on inboard blade sections. These developments are described below.

An initial estimate of the effect of tower shadow was obtained by simply applying a prescribed velocity deficit in the tower shadow region[8]. This velocity deficit not only influences the onset flow conditions at the blade but also substantially modifies the local wake structure, as shown in Fig. 1. It should be noted here that the resultant wake structure was not produced by a single pass application of the velocity deficit but was obtained through an iterative process where the induced effect of the distorted wake influenced the velocities at the blades and vice versa. There were, however, practical difficulties with this approach. In particular, the azimuthal resolution of the wake calculation, in the tower shadow region, was insufficient to provide a basis for convergent iterative application of the Leishman and Beddoes unsteady aerofoil model unless the computational time was increased to unacceptable levels. The reason for this problem lies in the sensitivity of the dynamic model to the time derivatives of velocity, blade incidence and pitch rate.

The requirement for high temporal resolution is analogous to the case of a helicopter rotor blade undergoing dynamic stall or blade vortex interaction. To reduce the computational effort required to solve this type of problem, Beddoes [9] developed a novel near wake solution methodology which allowed high resolution air loads to be calculated efficiently. In this method, only the downwash from the most recent wake element trailed in a given time step is calculated directly. The contribution from the remainder of the near wake is taken to be the downwash from the previous timestep reduced by an exponential decay function. The resulting calculation scheme is extremely efficient and is of sufficient accuracy to provide a suitable basis for the calculation of unsteady aerofoil behaviour in tower shadow.

In the present study, the Beddoes near-wake model was coupled with the prescribed wake scheme to produce a method which was capable of producing high temporal resolution in the tower shadow domain whilst minimising the computational overhead for the gross calculation of the turbine performance. Before this could be achieved, however, two enhancements were made to the original Beddoes model. Firstly, the original model ignored the out-of-plane motion of the wake due to the relatively low through-plane velocities associated with a helicopter rotor. In the case of a wind turbine, this effect cannot be neglected and so the model was modified accordingly. In addition, the original model provided a poor representation of the induced effect of an inboard vortex filament on outboard sections of the blade. Again, in the case of a wind turbine the loading distribution can be such that this effect is not entirely negligible and so it was necessary to improve this feature of the model. These developments are outlined in detail in Ref. [10].

The coupled tower shadow model, which is described in detail in Ref. [11], has been used to conduct a parametric study of the unsteady response due to tower shadow. As an example, Fig. 2 shows the influence which the width of the tower shadow velocity deficit region has on the normal force response. In addition to the expected change in azimuth range affected, this parameter also has a significant influence on the impulsive load produced. Further results of this parametric study are available in Ref. [11].

Contemporary numerical models of HAWT aerodynamics suffer from an inability to accurately represent blade loads on inboard blade sections. A plausible explanation for the poor level of correspondence between the field data and the predictions is the combined influence of three-dimensional and rotational flow effects. There are various indications that, at the most inboard stations, the blade does not stall in the manner predicted by two-dimensional data but, rather, that stall is delayed to higher incidence. This kind of delayed static stall has been attributed to three-dimensional and rotational effects. This phenomenon can also be observed in Fig.3a, where the predictions of the prescribed wake model are compared with field data from the NREL combined experiment, at the 30% -span location and for the first half revolution at the 46.7%-span station. Further outboard, where the angle of attack is low, the calculation results match the measured data very well because the rotational effects in the attached flow regime are minimal .

During the course of this project it has been possible to evaluate empirical and semi-empirical methods for 3-D stall using the prescribed wake model. This has required significant modification of the model input structure and to the way in which the Leishman-Beddoes unsteady aerofoil model is configured. Of the methods considered, the 3-D stall model of Selig has proved to be the most effective. As may be observed in Fig. 3b, the correlation with field data on inboard blade sections is greatly improved by the use of this method.

PIV tests at Heriot-Watt University

In this study the Heriot-Watt closed return, low-turbulence wind tunnel was used in an open jet configuration in order to minimise blockage and wake deflection effects. The test turbine was a full size, Marlec commercial wind turbine having an overall rotor diameter of 0.9 m and hub diameter of 0.24 m. The turbine was mounted in the open jet of the wind-tunnel on a 60 mm diameter cylindrical tower fixed to the floor with the central axis of the rotor hub, in the normal orientation, co-incident with the wind tunnel principal axis. The hub front face was 0.6 m downstream of the contraction exit and on the centre axis of the wind-tunnel. The turbine was fitted with either two or three, tapered blades of a possible six each having an aerofoil cross section and set at a pitch angle of 12 degrees. This ensured that the vortices trailing from the blades were independent of each other and increased the comparability with larger full-scale wind turbines of similar geometry.

The rotation rate of the turbine at a particular incident wind speed was limited by the blade characteristics and the electrical load generated on the turbine armature coils. The electrical load was modified by the introduction of a variable shunt resistor to enable a realistic tip speed ratio, corresponding to non-stalled blade flow, to be maintained. For convenience in measurement the turbine yaw condition was represented by rotating the turbine about the horizontal axis since this greatly simplified the laser illumination geometry.

The flow was seeded with synthetic polycrystalline particles and illuminated by two, synchronised pulsed Nd:YAG lasers providing a maximum output of 180 mJ per 6 ns pulse. The lasers were aligned so that their beams followed the same optical path and were shaped to produce an expanding vertical illumination sheet coplanar with the mean wind flow vector. The lasers were discharged, with a typical time between units of 300 ms, on receipt of a signal from an infra red trigger attached to one of the turbine blades. The trigger signal was electronically retarded, where appropriate, in order to ensure data was collected at a constant azimuth blade angle. During the tests sufficient background seeding was present from residual particles in the tunnel to enable continuous data collection.

In this study both conventional wet film PIV and digital PIV (DPIV) were used to measure the flow characteristics. The DPIV measurements were made using an electronic image capture system comprising a CCD camera, video recorder for bulk storage, and a frame board with a 512 by 512 image size. The camera was placed with its optical axis normal to the light sheet, fitted with a Nikon, flat field, macro lens having a focal

length of 105 mm and positioned such that a resolution of 0.2 mm/pixel in the horizontal (x) and direction and 0.15 mm/pixel in the vertical (y) direction was obtained. The camera image corresponded to an area of 0.1 m by 0.077 m. in the object plane.

The results of the study demonstrated that the number of blades, blade profile and tip speed ratio determine the nature of the interaction between the wake streamtube and turbine. For yawed flow, the extent to which the turbine wake was skewed with respect to the onset flow at a given tip speed ratio was found to depend on the solidity. To illustrate this, Fig. 4. shows the tip vortex trajectory from one side of the turbine for both the two and three bladed configurations over a range of yaw angles at tip speed ratio 6.7. The skew of the wake can be obtained by averaging the tip vortex trajectories for corresponding positive and negative yaw angles. This is shown in Fig. 5. where the two bladed case is shown to closely follow a curve representing two thirds of the skew in the three bladed case.

In addition to the above, it was found that the circulation shed from the blades of the turbine in yaw varied as a function of azimuth phase rotor angle and angle of yaw between the wind and turbine rotor. The initial formation of the vortex was seen to critically depend on the wake expansion angle, determined by the turbine rotor yaw angle and the blade orientation and geometry. As the vortex developed a significant interaction between the vortex sheet from the inboard blade trailing edge and the tip vortex was shown to take place in yaw. This had to do both with the orientation of the rotor in the wind and the additional circulation variation along the blade generated in the yawed configuration. This interaction was shown to produce significant changes in roll up and final form of the tip vortex. These features are fully described in Refs. [12-15] and a qualitative illustration is provided in Fig. 6.

Low Reynolds Number Aerofoil Tests

In a scale model test, it is relatively straightforward to match the tip speed ratio of larger machines. This, however, often introduces difficulties since the resulting blade chord Reynolds number on the test turbine will be considerably lower than that on the larger turbine at the same tip speed ratio. For modelling purposes, this is not a significant problem since a prediction can be made on the basis of either case provided the blade section characteristics at the particular Reynolds number are known. For this reason, a series of low Reynolds number tests were conducted on the aerofoil profile to be used for the turbine blade section. The particular section chosen for the test turbine was the NACA 4415 aerofoil. Although several datasets were already available for this aerofoil, they either did not cover the required Reynolds number range or were conducted in poor conditions.

Low Reynolds number tests, covering the chord Reynolds number range 100000 to 600000, were conducted in the 1.15m x 0.83m low speed wind tunnel of the University of Glasgow. The tunnel-spanning model had a chord length of 0.3m and consisted of a glass fibre skin filled with epoxy foam. The model had sixty surface pressure tappings distributed across the mid span which allowed the nominally two-dimensional surface pressure distribution to be obtained. Drag estimates were made using a ZOC electronic scanning module connected to a pitot rake mounted aft of the model on a two-dimensional traverse. By moving the pitot rake in small increments, it was possible to obtain high spatial resolution for these measurements. The traverse was controlled by a Macintosh Microcomputer via National Instruments LabView software. The results obtained in this part of the study provided the necessary blade sectional data input to the prescribed wake model to allow comparison with the model turbine tests to be made.

Wind Tunnel Tests at Glasgow

The objective of this part of the project was to measure the wake convection characteristics and blade surface pressures on an outboard section of the turbine blades in both head-on and yawed flow conditions. The test programme was conducted in the University of Glasgow 2.13 x 1.61m low speed wind tunnel. The turbine model, which was a two-bladed upwind design and had a rotor diameter of 1m, was specifically designed to maximise the available internal space for instrumentation. The NACA 4415 section blades were manufactured from carbon fibre and had a chord length of 0.1m. One blade was instrumented with sixteen miniature pressure transducers positioned at the 75% of chord location. The internal structure of the nacelle was constructed from aluminium and housed the rotating shaft of the turbine. On this shaft were located the necessary electronics to condition the signals from the pressure transducers prior to passing the signals through slip-rings located at the rear of the nacelle. The signals were then passed to a high speed data acquisition system capable of sampling at up to 50KHz per channel. The speed of rotation was controlled by an electronic braking system, similar to that used in the PIV proving tests, located below the wind tunnel floor and connected to the turbine shaft by a belt and pulley system. A schematic of this arrangement is illustrated in Fig. 7. The entire turbine arrangement could be rotated about the support shaft and locked at any required yaw angle.

During testing, seeding was introduced downstream of the model and allowed to convect around the tunnel circuit before entering the measurement plane. Each measurement encompassed approximately half of the width of the wake between the turbine and a downstream distance of approximately 1.5 rotor diameters. This

corresponded to a measurement area of 0.7m x 1.5m and was obtained by simultaneously firing two cameras fitted with wide angle lenses. Image distortion was removed by appropriate calibration. As before, illumination was provided by YAG lasers mounted on a platform at the side of the wind tunnel. By careful setting of the angle at which the laser beam entered the tunnel, these produced a horizontal light sheet which was of the necessary width to illuminate the measurement area. As originally envisaged, tests were conducted over a range of yaw angles and tip-speed ratios. The delay to the testing programme in the Glasgow tunnel has meant that detailed comparisons between the prescribed wake code and the wind tunnel measurements are only now being made. This work is being conducted by a University funded research student.

CONCLUDING REMARKS

As indicated above, the majority of activities proposed in the original workplan have been completed within the three year period. It has been possible to significantly enhance the prescribed wake code and to extensively validate it against field data during this project. In addition, the PIV studies carried out have been much more extensive than those originally proposed. These studies have provided new insight into the evolution of the turbine wake structure and the parameters which influence its development.

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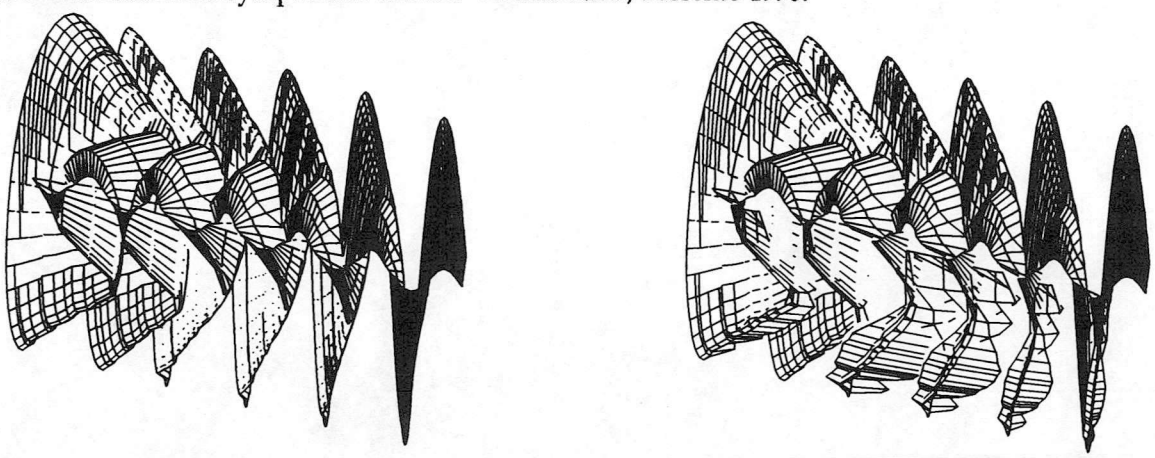

(a). without tower shadow (b). with tower shadow

Fig. 1. Typical yawed flow wind turbine wakes with and without tower shadow

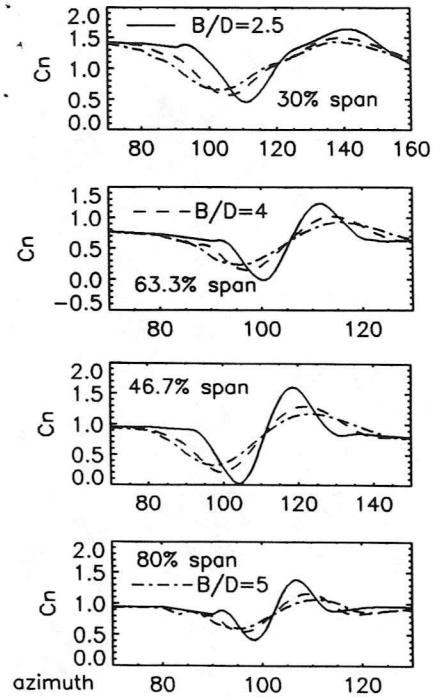

Fig. 2. Effect of tower shadow width (B=Tower shadow width) (D=Tower diameter)

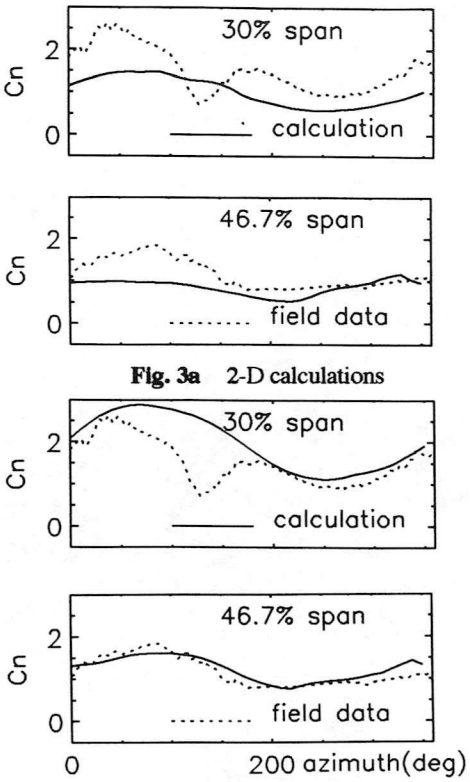

Fig. 3a 2-D calculations

Fig. 3b. Influence of 3-D effects at two span stations.

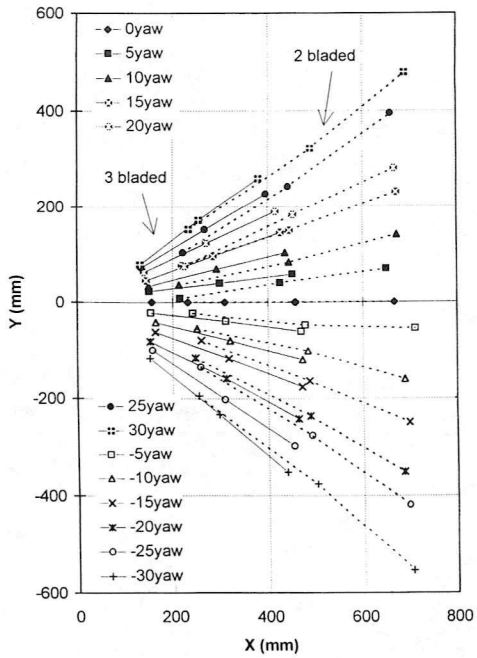

Fig. 4. The Position of the intersection of the trailing vortex tube with the illuminating light sheet as a function of yaw angle seen from the frame of reference of the turbine

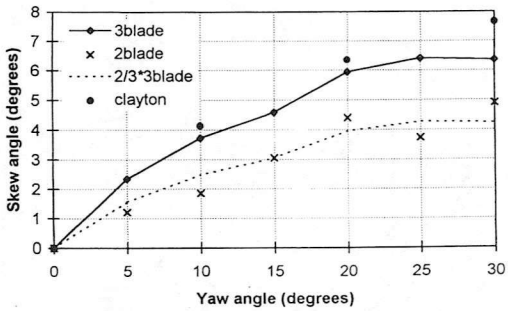

Fig. 5. The wake skew angle of the two and three blade turbine configurations as a function of yaw angle

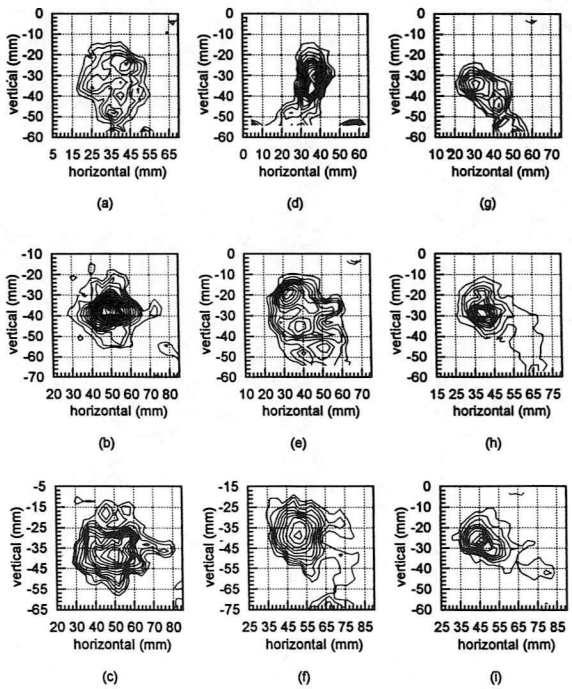

Fig. 6 Vorticity contour plots for the vortex trailing from the turbine as a function of yaw angle and azimuth phase position, flow from right to left;

0° yaw	(a) phase angle 18°;	(b) phase angle 90°;	(c) phase angle 156°;
-30° yaw	(d) phase angle 18°;	(e) phase angle 90°;	(f) phase angle 156°;
30° yaw	(g) phase angle 18°;	(h) phase angle 90°;	(i) phase angle 156°.

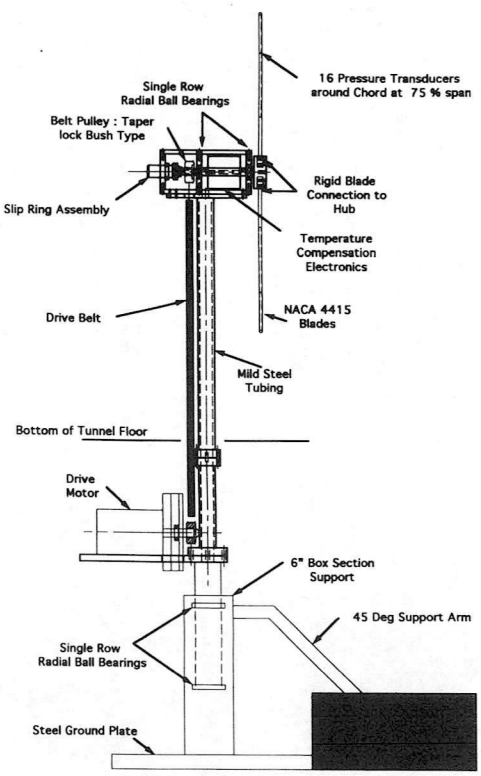

Fig. 7. Wind turbine model used in Glasgow tests

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Department of Aerospace Engineering
University of Glasgow
GLASGOW
G12 8QQ

I.Grant
Dept. of Civil and Offshore Eng.
Heriot-Watt University
EDINBURGH
EH14 4AS

LIST OF PUBLICATIONS

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Also departmental data reports on wind tunnel tests in preparation