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Experimental Verification of a Mathematical Model for Predicting the Performance of a Self-Acting Variable Pitch Vertical Axis Wind Turbine

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ABSTRACT

A mathematical model has been developed to predict the performance of self-acting variable pitch vertical axis wind turbines (SAVPVAWTs) and hence to select optimum settings for pitch control parameters for any desired performance characteristic. This mathematical model predicts that an optimised SAVPVAWT will far outperform fixed pitch VAWTs and that its performance will be comparable with that of very much more complex giromills. Experimental evidence is presented to support these predictions.

INTRODUCTION

Mathematical Model Predictions

An extended double multiple stream tube model has been developed which models the performance of any straight blade vertical axis wind turbine (1,2,3). In particular, it is able to model pitch variations caused by aerodynamic and inertial forces on variable pitch blades.

This model has been used to predict the performance of a SAVPVAWT and hence to optimise geometrical parameters for various optimum performance criteria (2,3). For example, generators and centrifugal pumps require a small starting torque to overcome friction in the drive train, bearings, seals etc., plus a torque-speed characteristic increasing roughly with the square of the angular velocity. A positive displacement pump, on the other hand, requires a high starting torque almost equal to the torque required at full speed.

The model shows that by modifying the wind turbine pitch control parameters it is possible to achieve a torque-speed curve suitable for most generator and centrifugal pump applications with a peak efficiency some 25% higher than that of a corresponding fixed pitch turbine (1). Using different pitch control settings on a turbine of the same solidity it is possible to increase starting and low speed torque to over half the peak torque (2), but at the expense of some peak efficiency. Thus settings may be selected for a known load characteristic to ensure that the system will start at the desired wind speed and will operate near its peak efficiency in a steady wind.

This mathematical model has also been used to compare the predicted performance of SAVPVAWTs not only with that of fixed pitch VAWTs but also with that of giromills or cycloturbines in which pitch varies according to a pedetermined schedule (3). These predictions suggest that the SAVPVAWT could achieve a performance comparable with that of the giromill, while its mechanical simplicity should enable it to be built much more cheaply.

COMPARISON OF MATHEMATICAL PREDICTIONS WITH EXPERIMENTAL DATA

Kentfield (4,5) has published experimental performance curves showing good agreement with mathematical predictions for a cyclogiro with freely hinged blades, which is in some ways similar to the SAVPVAWT being considered at present.

The present mathematical model has been used to predict VAWT and giromill performance (1,2,3), but experimental performance data for the present SAVPVAWT design have not hitherto been available. This paper presents and compares wind tunnel test data with mathematical model predictions for various pitch-control settings on a SAVPVAWT.

TESTING FACILITY

Wind turbine performance measurements in natural wind are at best difficult to interpret, at worst meaningless, due to the fluctuation in wind velocity (6,7).

Attempts have been made (8,9,10) to overcome this problem and create a steady wind velocity without the use of a wind tunnel by mounting a model on a vehicle which is then driven at a steady speed in still air. The data from such tests have again been difficult to interpret due to fluctuations in vehicle speed and the fact that even light airs of 1 m/s or less create large relative changes in wind velocity when vehicle speed is only of the order of 10 m/s.

Thus it was considered essential that tests be done in a wind tunnel. The wind tunnel facility in the Civil Engineering Department at the University of Queensland was used for the tests reported here. It has a working section 2 m high and 3 m wide with a maximum wind velocity of 18 m/s.

EXPERIMENTAL MODEL GEOMETRY

Reynolds Number Considerations

The proposed full size turbine has 3 blades 4 m long with 0.4 m chord length and a diameter of 8 m, giving solidity $\sigma = 0.3$ and blade aspect ratio 10. This turbine is expected to operate at up to about 80 RPM in a 10 m/s wind, giving blade chord Reynolds numbers up to approximately 10^6.

The wind tunnel working section imposed a model size limit of 2 m diameter and 1 m blade length (11). If the solidity and aspect ratio of the model were to be kept the same as the full size turbine, blade chord length would be 0.1 m and maximum Reynolds number would be below 0.5×10^6, even at the maximum wind speed available in the tunnel. Although these Reynolds numbers would be representative of those on the full size turbine in light winds, such a scenario would pose three problems:

1. Reynolds number and laminar separation effects

According to Ref. 12:

> *"The distinguishing characteristic of an airfoil operated a low chord Reynolds numbers ($R_e < 5.0 \times 10^5$) is the formation of an extensive laminar separation bubble. ... Laminar separation bubbles not only increase airfoil drag but also cause hysteresis in both lift and drag with angle of attack."*

The model would be operating in just this region. Its performance would be sensitive to Reynolds number and lift, drag and moment coefficients would be subject to hysteresis and thus would be difficult to predict. Even if they could be reliably predicted the performance would not be representative of the full range of operating conditions of the full size turbine.

Although the mathematical model incorporates Reynolds number effects, its predictions can only be as good as the reliability and repeatability of the aerofoil data used. For Reynolds numbers below 0.5×10^6 these data are sparse and not always consistent. Modelling based on these data will inevitably be less reliable than that based on data at higher Reynolds numbers.

2. Accuracy of Aerofoil profile

It has been suggested (12) that:

> *"if the error in surface contour is greater than 0.2% of chord, the performance will be affected."*

Ref. 13 also refers to the sensitivity of the airfoil boundary layer to model contour accuracy.

On a 100 mm chord, 0.2% of chord represents a maximum tolerance of 0.2 mm. It is difficult to build a blade to this tolerance without machining it out of solid metal, which was not acceptable for the present investigation because blade inertia affects its pitching behaviour and must be kept within limits. A solid metal blade would be unacceptably heavy. The best accuracy we could get for laser-cut ribs or templates for a FRP mould was 0.4 mm.

5. Centripetal Acceleration and Inertial Loading on Blades

For a chord Reynolds number approaching 0.5×10^6 on this sized model, centripetal acceleration would be of the order of 700 g and blade stresses would be enormous.

For thes reasons, it was decided to compromise on geometrical similarity between model and prototype and use a blade chord of 200 mm. The solidity was now doubled to 0.6 and aspect ratio halved to 5. These variables can be accommodated by the mathematical model, although there is a tendency for mathematical models to break down at high solidity and high tipspeed ratio. Also the radial arms, located 20% of span from each end, tend to inhibit spanwise flow so that the effective aspect ratio is greater than 5.

Having increased blade chord to 0.2 m, dimensional tolerances on the profile were now less critical (0.4 mm – achievable with a laser cutter) and it was hoped to reach Reynolds numbers around 0.8×10^6 at 600 RPM, approaching those encountered in the full size turbine, with centripetal acceleration limited to 400 g.

TURBINE CONSTRUCTION

The complete model turbine is shown in Figure 1. Blades are mounted on needle roller bearings housed in the outer ends of radial arms where the pitch control mechanism is located. These radial arms are fixed to two taperlock hubs mounted on a 30 mm diameter K1040 steel shaft which runs in bearings housed in a steel tube cantilevered up from the floor of the wind tunnel.

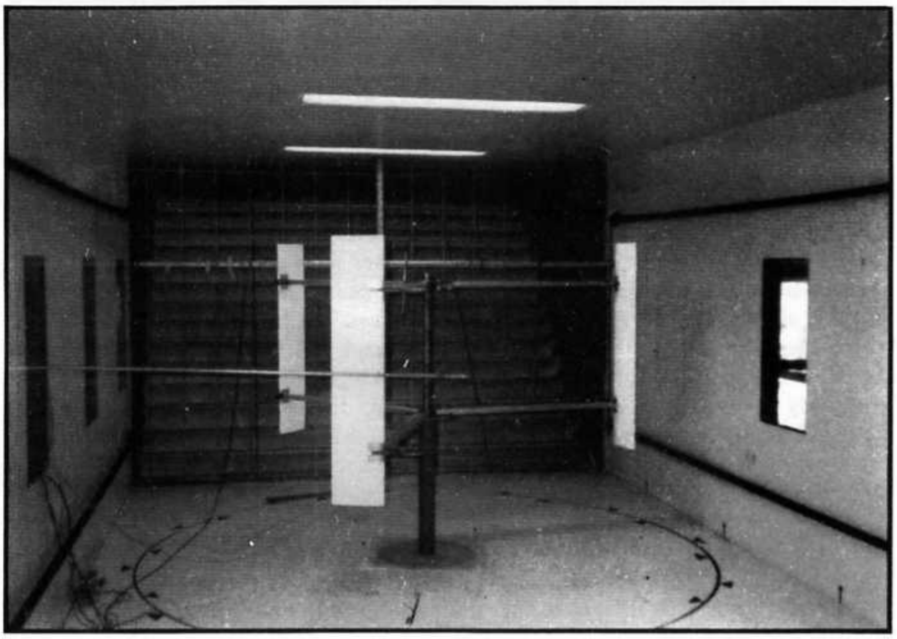

Figure 1. Complete model turbine.

Radial Arms

Two radial arms per blade were used to reduce blade stresses. Ideally, these radial arms should combine maximum mechanical strength and stiffness with minimum drag. An Eppler E862 non-lifting section was considered ideal for this purpose (14), but rather than fabricating this complete section, an off-the-shelf extrusion of aluminium alloy used for struts on light planes was used. It was found to have a profile closely approximating the E862 except at the trailing edge where it has a large radius which would produce unacceptable drag. This trailing edge profile was modified by folding a piece of 0.3 mm sheet aluminium and pop riveting and gluing it to the extrusion to form a sharp trailing edge (Figure 2).

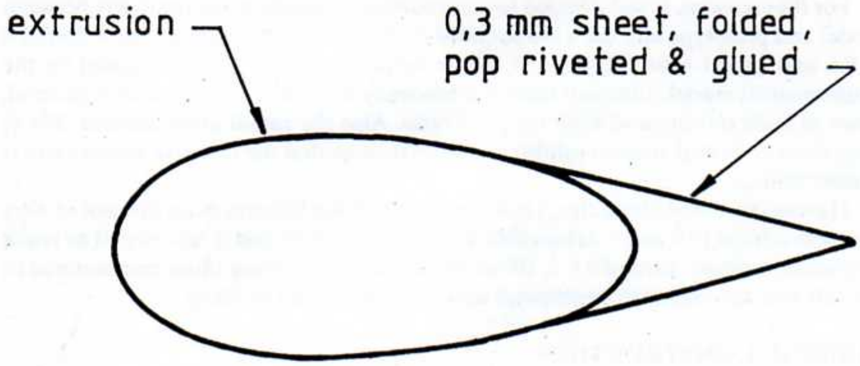

Figure 2. Radial arm profile.

Blades

NACA0018 profile was selected since it is a thick section permitting mechanical strength, its characteristics are relatively well known, and its performance is suitable (15).

Blade skins were constructed of FRP laminate consisting of 3 layers of 180 GSM bidirectional carbon fibre cloth bonded with vinyl ester resin. The outer and inner layers were set at 0 and 90° to the span and the middle layer at 45° to give adequate strength in all directions to cope with torsion as well as spanwise and chordwise bending (16).

A PVC foam core was then stuck in each half skin to give it extra rigidity and the halves were stuck together with epoxy adhesive. This gave a very stiff and strong blade construction, but weight was significantly higher than the design weight due to absorbtion of epoxy by the foam core. Calculations indicated that the turbine could still run at up to 500 RPM without excessive stress.

To check on actual blade bending strength, each individual blade was statically loaded in a Vega compression testing machine using foam plastic pads to give a load uniformly distributed over the span. Load was also distributed over the chord so that the load intensity was greater where profile thickness is greatest (Figure 3). This gave a close approximation of the actual distribution of aerodynamic and inertial loads. A load 50% higher than that expected in the wind tunnel was applied.

TESTING TECHNIQUE

The model turbine was allowed to accelerate from rest against its own rotational inertia in a uniform wind.

Wind velocity was measured just upstream of the turbine using a Betz micromanometer.

A slotted wheel was mounted on the turbine shaft below the wind tunnel floor, with an infra red LED on one side and a phototransistor on the other, so that 24 pulses per