Chapter 11

Conclusion

Darrieus turbines with fixed blades are characterised by low or even negative torque at tip speed ratios below that at which they are designed to run (greater than approximately three). This feature prevents or greatly inhibits the ability of such turbines to self-start. It also significantly affects total energy capture in a turbulent wind. The use of passive variable-pitch blade mechanisms to improve this aspect of performance of straight-bladed vertical axis wind turbines is the subject of this thesis. A momentum theory mathematical model and a vortex theory mathematical model have been developed as part of this work to predict the performance of different designs of passive variable-pitch turbine. Wind tunnel testing of a prototype turbine featuring two new design concepts has also been undertaken.

Evaluation of existing designs

A review of existing passive variable-pitch vertical axis wind turbine designs has been performed. The provision of some form of 'restoring moment' acting independently on each blade is a common feature of almost all the design concepts found in the literature. This moment may be produced by elastic means or by the inertial loads on the blade. Insight into the operation of passive variable-pitch turbines and a basis for systematic selection of design parameter values has been gained through use of Pro/MECHANICA and the momentum model. It is concluded that greatest torque at all tip speed ratios is achieved if the magnitude of this restoring moment increases with the square of turbine speed. Inertial-type designs inherently produce such a moment.

A theoretical basis for the selection of parameters governing the strength of the restoring moment has been developed. Treatment of the pitching blade as a spring/mass/damper system excited by a harmonic driving force indicates that the natural frequency is a function of turbine speed and that the frequency ratio is therefore a constant function of design parameters. This ratio must be less than one to ensure that the blade motion is not too far out of phase with the aerodynamic driving force and that positive torque is produced.

Potential of new designs

Elastomeric blade mounting component concept - A design concept featuring elastomeric blade mounting components has been proposed. The aim is to produce an elastic restoring moment on the blades that increases with centrifugal load.

The turbine using the particular design of flexible elastomeric components tested in the wind tunnel did not perform well. The combination of geometry and material that was chosen proved to be excessively stiff in torsion, preventing the blade from pitching sufficiently. A different geometry could be selected to reduce this stiffness, however it is likely that the tensile stiffness of the component would then be reduced. It appears that it would be difficult to find a suitable compromise between these two constraints.

A further potential difficulty is that if an appropriate combination of part geometry and material properties could be found to produce the desired relationship between torsional stiffness and radial force, the properties of the material may change with time. This may result from fatigue, moisture absorption or temperature. Given the sensitivity of blade pitch response and turbine performance to the torsional stiffness of the blade connection, this may prove to be a significant issue.

Rolling profile concept - A design concept that produces restoring moment from inertial loads using a component in rolling contact with the rotor has been proposed. Mathematical modelling, using both the momentum and vortex mathematical models has indicated the potential of the concept. The design allows greater control over restoring moment than is available with other inertial type passive variable-pitch designs. It also reduces the mass moment of inertia of the blades, allowing smaller aerodynamic moment arms to be used and producing faster blade response.

Wind tunnel testing of a prototype turbine has been conducted and the rolling profile concept was demonstrated to enable self-starting. Further refinement of the design is required to reduce the effects of friction and parasitic drag. The compressibility of the components used for testing is thought to have affected performance significantly.

The ‘pendulum’ design of Sicard (1977) and Kentfield (1978) is probably the simplest design of passive variable-pitch VAWT and its predicted performance is not greatly different from that of the rolling profile concept. The conceptual advantages of the new design - of reduced blade mass moment of inertia and greater control over restoring moment - will be of little value if the turbine is significantly less reliable or more expensive. Further development of the detailed design is required before the concept can be judged as successful.

Development of a blade pitch response measurement technique

A significant part of the present thesis has been the development of a technique for the measurement of the pattern of blade pitch angle variation when the turbine is in operation. A photogrammetric technique using long exposures to record the trajectories of light emitting diodes mounted on one of the blades was adopted. A computer program has been written to extract the pitch angle history from the digital camera images. This method has been used successfully to measure the pitch response patterns of the prototype turbine operating in the wind tunnel.

Performance of mathematical models

Each of the mathematical models was able to produce results that are in general agreement with torque coefficient data measured from the wind tunnel experiments with the prototype turbine. The difference in results from the two models is surprisingly small given the different approaches to calculation of the velocity field. Both models failed to reproduce the higher tip speed ratio performance observed for a number of variations of the rolling profile design, potentially due to the effect of blockage. The pitch response patterns produced by both models were reasonably close to those measured over a range of tip speed ratios once adjustments to friction and restoring moment values had been made.

The difference in performance predicted by the momentum and vortex models was not great, despite the greater complexity of the vortex model. It is concluded that for general design analysis and parameter selection the faster momentum model is adequate. The much greater computational expense of the vortex model appears only to be justified for the study of turbulent wind performance, which momentum methods cannot handle.

Turbulent wind performance

The vortex model has been used to simulate turbulent wind performance of a number of passive variable-pitch turbines. The results indicate that significant reductions in average efficiency occur in unsteady conditions. Well-designed passive variable-pitch turbines are predicted to suffer losses in efficiency of around 10% in typical wind conditions. A standard Darrieus turbine is predicted to lose approximately 28% of its steady-state efficiency. The results indicate the importance of a 'flat' turbine power coefficient curve and the ability of passive variable-pitch turbines to achieve this. Rotor and blade mass moment of inertia also influence turbulent wind efficiency, though to a lesser extent. The results indicate that a major advantage of variable-pitch turbines is improved total energy capture, not just self-starting ability.

11.1 Summary of Research outcomes

The key outcomes of the research are:

- Development and wind tunnel testing of two new design concepts for passive variable-pitch turbines. These are the use of a specially designed elastomeric component to produce a connection whose torsional stiffness increases with centrifugal force; and the use of a rolling profile component whose shape determines the relationship between pitch angle and the restoring moment arising from inertial force. Refer to Chapters 3 and 10.
- Extension of the Double Multiple Streamtube type mathematical model to include the full inertia effects of pitching blades, as well as different passive variable-pitch designs. Refer to Chapter 5.

- Development of a free vortex wake mathematical model for passive variable-pitch Darrieus turbines, allowing modelling of unsteady performance. Refer to Chapter 6.
- Development of a parameter selection strategy for passive variable-pitch turbines based on a frequency response analysis of the blade pitching. Refer to Chapter 7.
- Investigation of the turbulent wind performance of VAWTs, indicating the ability of passive variable-pitch turbines to achieve significantly greater average efficiency than the corresponding fixed-bladed turbine. Refer to Chapter 8.
- Development of a simple, non-invasive method for measuring the blade pitch response of a turbine in operation in the wind tunnel. Refer to Section 9.4.3.
- Modification of the semi-empirical MIT dynamic stall method to allow it to be used in the modelling of the starting performance of Darrieus turbines. Refer to Section 5.1 and Appendix B.

11.2 Conclusion and Recommendations for Further Work

This thesis has identified a logical basis for the design and selection of key parameters for passive variable-pitch vertical axis wind turbines. This knowledge enables specious ideas to be identified amongst the variety of possible design concepts and provides guidance for blind trial and error optimisation processes. A range of design paths remain open for passive variable-pitch turbines and the question of which, or if any, of these can lead to an economical and reliable self-starting VAWT remains to be answered. The most critical hurdles may lie in the detailed design and materials selection to produce a simple, economical, reliable machine with adequate fatigue life. Before these issues are tackled however a sound design concept must be selected and confidence must exist that the effect of different parameter selections on performance can be adequately predicted. Continued development of mathematical models and experimental validation is therefore required. A number of specific areas warrant further attention:

- The greatest area of weakness of all mathematical models of Darrieus turbines is the prediction of unsteady aerodynamic forces, including dynamic stall. The complexity of the phenomenon places upper limits on the ability of semi-empirical techniques to accurately predict unsteady forces by modifying static lift, drag and pitching moment coefficients. While greater accuracy may be obtained by using computational fluid dynamics techniques, greater computing power will be required to make their use practical.
- Further testing of a passive variable-pitch turbine using metal rolling profile components is needed to further assess the potential of this concept.
- Outdoor testing of this turbine is needed to assess the effect of constraint of the turbine wake in the wind tunnel.

Such work may ultimately allow passive variable-pitch vertical axis wind turbines to be widely used as a decentralised, renewable and economical energy source.