

Aerodynamic analysis and monitoring of the Vortec 7 diffuser-augmented wind turbine

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The Vortec 7 is the first full-scale diffuser-augmented wind turbine (DAWT) to be built. A DAWT has a duct which surrounds the wind turbine blades and increases in cross-sectional area farther downstream. The aerodynamics of a diffuser are such that more air flows through the blade plane, and more power can be generated compared to a "bare turbine" of the same rotor blade diameter. Research on using a diffuser to augment the power of a wind turbine had been directed by K.M. Foreman at Grumman Aerospace Corporation, and the design of the Vortec 7 is based on the best model as determined by wind tunnel tests on various DAWT options performed by Grumman in the 1970s and early 1980s.

It was found that a simplified theoretical analysis showed significant differences from computational fluid dynamic (CFD) results, but that the CFD agreed quite well with field measurements. Many of the field results also agreed with the Grumman measurements, including wind speed-up at inlet near the blade tips. Preliminary measurements showed that the speed-up across the blade plane was not uniform as assumed by Foreman, decreasing towards the hub, and hence the power output of a DAWT would be less than predicted by Foreman. Improvements to the inlet velocity profile were anticipated after retrofitting a bullnose to the primary diffuser slot and a parabolic nose cone ahead of the rotor hub. This performance optimisation work was guided by the CFD modelling and blade and diffuser performance codes.

Keywords: wind turbine - aerodynamic analysis - airflow diffuser - fluid dynamics

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1. Introduction

The Vortec 7 is the first full-scale diffuser-augmented wind turbine (DAWT) to be built. This technology demonstration unit, with a rotor blade diameter of 7.3 m, has been constructed by Vortec Energy Limited and is situated near the Franklin west coast, 120 km south of Auckland, New Zealand.

The Vortec 7 was developed from work performed by the Grumman Aerospace Corporation in the 1970s and early 1980s (see Bibliography). Although the idea of using a diffuser to augment the power of a wind turbine had been considered earlier,¹ the designs were not economically viable. The work performed at Grumman under K. M. Foreman explored the design of compact, short length-to-diameter diffusers, with large outlet-to-inlet area ratios. It is very difficult to keep the flow attached in a diffuser if its area increases rapidly, and Grumman cleverly used the high speed external flow to energise the boundary layer inside the duct by directing it through boundary layer control slots to prevent separation. Their optimal design employed two boundary layer control slots to prevent the flow within the duct from separating from the internal surface of the diffuser. They were able to achieve very short diffusers with large expansion angles.

A DAWT has a duct (diffuser) which surrounds the wind turbine blades and increases in cross-sectional area farther downstream. The mean velocity of the flow is decreased downstream in the diffuser with the increasing duct area from conservation of mass, and thus by Bernoulli's equation the static pressure must increase downstream for isentropic flow. The static pressure at the diffuser outlet can be expected to be slightly sub-atmospheric as it is at the leeward side of this obstruction to the flow, and this means that at the narrower inlet surrounding the blades, the pressure will be even lower. This low pressure at the inlet of the diffuser is expected to draw more air through the blade plane compared to a bare turbine, and thus the power output of a DAWT should be increased compared to a bare turbine. The anticipated effect on the stream-tube passing through the blade plane² can be seen in Figure 1 with an axi-symmetric cross-section of the Vortec 7 shown in Figure 2.

A considerable amount of wind tunnel testing and analytical work were used to establish the technology. However, an economical material could not be found at the time. It was the use of high-tensile wire-reinforced fibrous ferro-cement (HT Ferro) which enabled Vortec Energy Limited to acquire a licence from Grumman and begin construction of the first full-scale DAWT. An over-

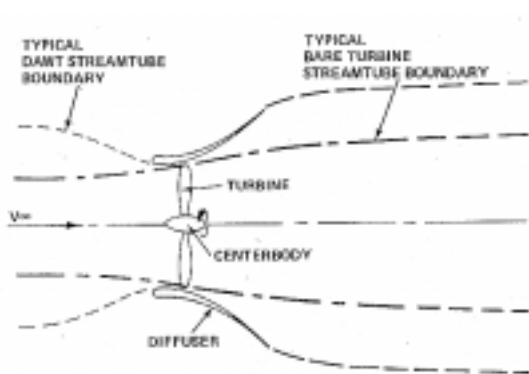


FIGURE 1. Effect of diffuser on stream-tube passing through blade plane (from Ref. 1).

view of the design and construction of the Vortec 7 is presented by Nash³.

The Vortec 7 was officially opened on 26 April 1997 and since then a considerable amount of commissioning work has been undertaken on the wind turbine and the monitoring systems as well as performance measurements. Several diffuser retrofits have been carried out in order to improve aerodynamic flows and diffuser efficiency. In addition some simple theoretical work has been undertaken as well as some investigative work using computational fluid dynamics (CFD). This paper presents some of the results of this ongoing work.

2. Project objectives

The primary focus of the test programme is to measure and optimise the demonstrator's power performance, in order to confirm the cost of energy from the Vortec design. Figure 3 shows Vortec 20 development as the end goal and the pre-requisite steps necessary in order to achieve that goal.

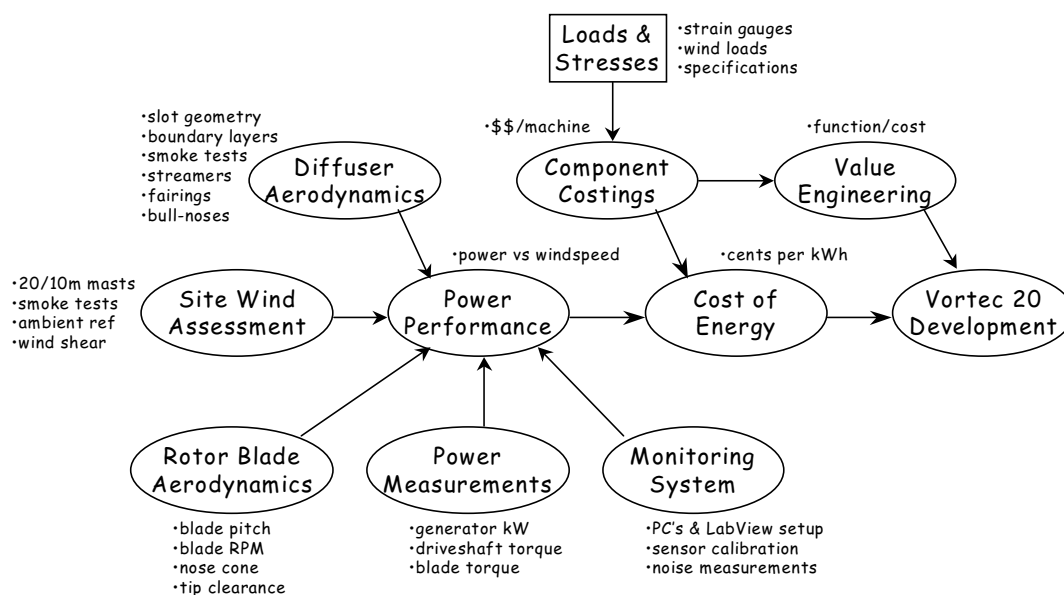


FIGURE 3. Testing the Vortec 7.

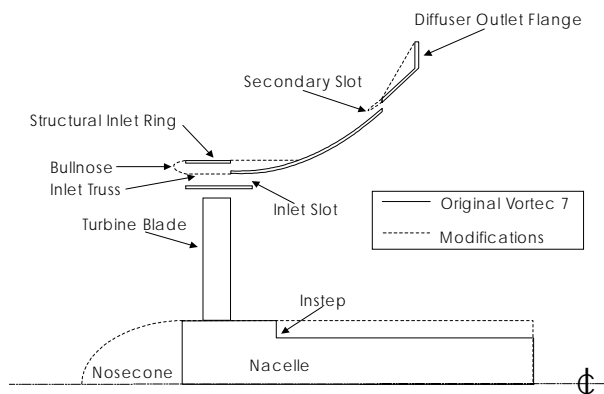


FIGURE 2. Axi-symmetric cross-section of the Vortec 7.

3. Vortec 7 test programme

The mutual dependence of rotor and diffuser aerodynamic behaviour requires a thorough and systematic test program. These tests involve varying one parameter at a time to assess the importance of each parameter, e.g. blade pitch, tip speed ratio, rotor solidity, tip clearance, etc. The results will determine the design configuration of the wind turbine that provides the greatest power output. Significant progress has been made on the test programme detailed in Table 1. Several diffuser retrofits have necessitated re-runs of tests # 3, 5, 6, 7, 8 and 9.

4. 'Technology for Business Growth'

A 'Technology for Business Growth' (TBG) grant was awarded to Vortec Energy Limited for the monitoring and optimisation of the demonstrator unit with this work being performed in conjunction with Industrial Research Limited and the University of Auckland. This work encompasses three areas - aerodynamic analysis, turbine conversion, and structural analysis.

The objective of the aerodynamic analysis is to design and construct appropriate instrumentation to enable suit-

TABLE 1. Vortec test programme.

#	Test	Objectives and comments
1	Data Acquisition system set-up	Computers, DAQ cards, LabView software, Sensor selection and fitting.
2	Sensor checks and calibration	Ensure data quality through sensor calibration and installed system calibrations.
3	Flow visualisation tests	Smoke and ribbons used to demonstrate diffuser aerodynamics. Video recording for review.
4	Site wind survey	For ambient reference (20 m and 10 m masts)
5	Basic power performance measurements	Preliminary power curve, measure pressure drop across blades.
6	Power performance optimisation (1/2)	Understand behaviour, effect of pitch
7	Diffuser inlet wind speed assessment	Understand wind at blades and speed-up, compare with Grumman method
8	Rotor thrust assessment	Calculate by Dpressure through rotor blades
9	Base pressure coefficient (Cp4)	Measure diffuser efficiency and compare with Grumman results
10	Power performance optimisation (2/2)	Maximise power delivery, effect of 3 blades
11	Structural frequency tests (1/2)	Blade modal tests, structure natural frequency tests. Speed exclusion zones.
12	Noise testing	Measure noise output.
13	Rotor blade loads	Understand for production blade design
14	Structural frequency tests (2/2)	Fatigue and vibration assessment

able field measurements to be taken. The macroscopic aerodynamic characteristics of the airflow through the turbine will then be determined. For example the effectiveness of the boundary layer control slots is being assessed, and the acceleration of the wind into the diffuser inlet is also being measured.

The interaction between the aerodynamic parameters and the turbine power conversion is being investigated. This area was highlighted in the work performed at Grumman and showed an inter-relationship between the blade loading and the efficiency of the diffuser. This work will provide power conversion characteristics and the sensitivity of the diffuser performance to variations in turbine settings.

The structural analysis will be used to assess the demonstrator and to correlate measured wind forces on the structure with theoretical predictions. This will provide information for the design of future production machines. Correlation of the aerodynamic analysis with the turbine and structural results will be performed to provide a complete assessment of the Vortec 7 and the optimal operating configuration.

5. Instrumentation and monitoring

The work performed by Grumman showed that three parameters were necessary to characterise the aerodynamic performance of the Vortec 7. These were the velocity speed-up into the diffuser, the turbine thrust coefficient, and the base or exit pressure coefficient. Sensors that can cope with swirl, and converging and diverging streamlines have been developed by IRL to measure wind speeds and pressures at the inlet and base of the diffuser. Measurement of the thrust coefficient is achieved by measuring the pressure in planes up- and down-stream of the blades. The hilly nature of the test site has also made the determination of a reference wind speed somewhat difficult. Calibrations of the sensors have been carried out in an AU wind tunnel. The sensor locations on the front face boom are shown in Figure 4.

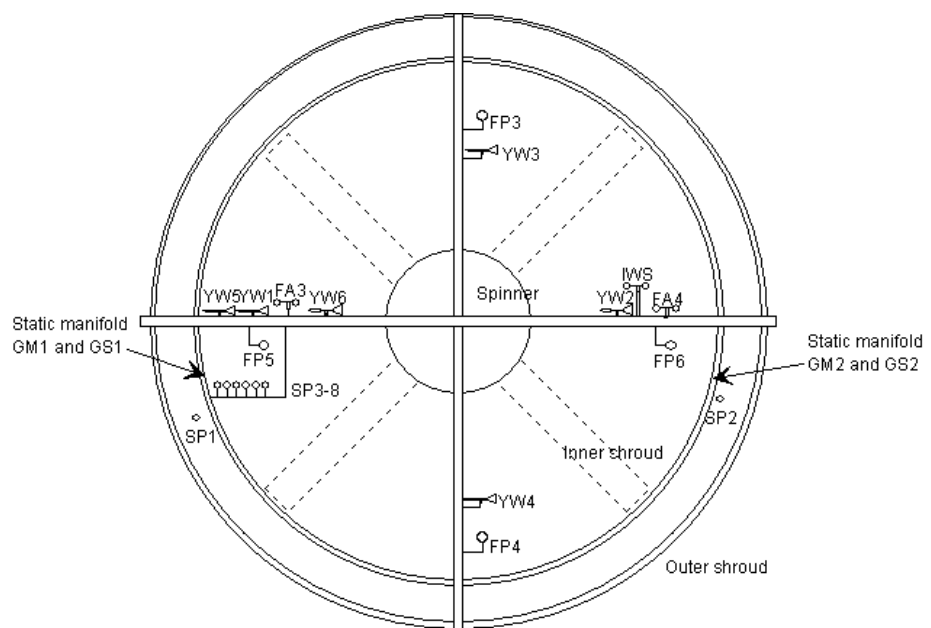


FIGURE 4. View of diffuser front face (inlet plane) with sensor locations shown.

Legend: FP Directional front pitot tubes
 SP Fixed-position pitot tubes in shroud
 YW Yaw error wind vanes
 FA and IWS Cup anemometers
 GM and GS Static manifold per Grumman method

Site wind shear and turbulence is assessed using anemometry mounted at four levels on a 20 m tower. Strain gauges on the blade roots, drive-shaft and yaw bogies provide a measurement of applied loads. Pressure transducers mounted on a radial boom across the rotor inlet and immediately downstream provide an assessment of mass flow through and pressure drop across the rotor. Sensors mounted at the exit measure C_{p4} , the exit base pressure coefficient, for use in the DAWT semi-empirical theory (developed by Grumman Aerospace) and to assess performance of the diffuser. A noise assessment will be carried out when the operation of the rotor is matched to the diffuser.

The 20 m instrumented tower collects site wind data using 4 cup and 2 vane anemometers. Weather data - temperature, barometric pressure, and the reference static pressure - are also collected routinely. Two movable 10 m towers (hub height of the Vortec 7) are used for site wind surveys and velocity measurements in front of and around the Vortec 7. Typical locations of these masts are shown in Figure 5.

The locations of the measurement booms are shown in Figure 6. Note that there are booms at 3 axial positions. A 'cherry picker' has been used for easy access to the anemometers and pressure sensors. Static taps have been fitted into the diffuser wall, and these will be used to determine the symmetry of the axial static pressure gradient within the diffuser.

6. Optimisation of the Vortec 7

The Vortec 7 has a wide-band variable speed power electronics system that allows for very flexible operation of the turbine in wind conditions within its operating range. The control system enables the Vortec 7 to be operated at either a specified rotational speed or a set tip speed ratio. Series of runs are being undertaken to measure the power curve at a range of tip speeds and blade pitches, over the 20 degree adjustment range, to find the optimal operating conditions. Preliminary results have been obtained and example plots are shown below. Figure 7 shows the power curve compared with tip speed ratio with the variation in velocity profile across the blade plane shown in Figure 8 (legend shown in data order).

Optimisation of diffuser performance has involved several modifications to diffuser slot and step geometry, streamlining of shroud and slot entry sections, and the support structure. Testing and assessment of these modifications, using flow streamers fitted to the diffuser inside wall and smoke visualisation techniques, measurements of shaft power and local pressures and velocities, have confirmed the benefit of these modifications. The intermittent separation initially shown on the inner wall of the secondary diffuser has been eliminated with the modifications to the boundary layer control slot. The bull nose added to the primary diffuser has increased the velocity through the inlet slot with nearly a doubling of the ambient wind speed being achieved.

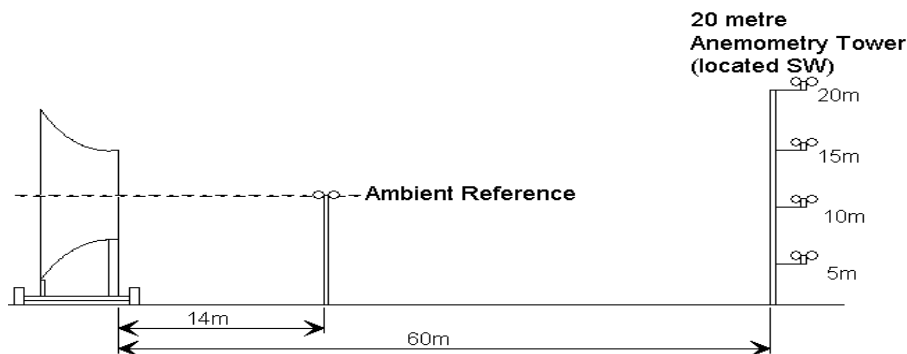


FIGURE 5. Typical location of anemometry towers.

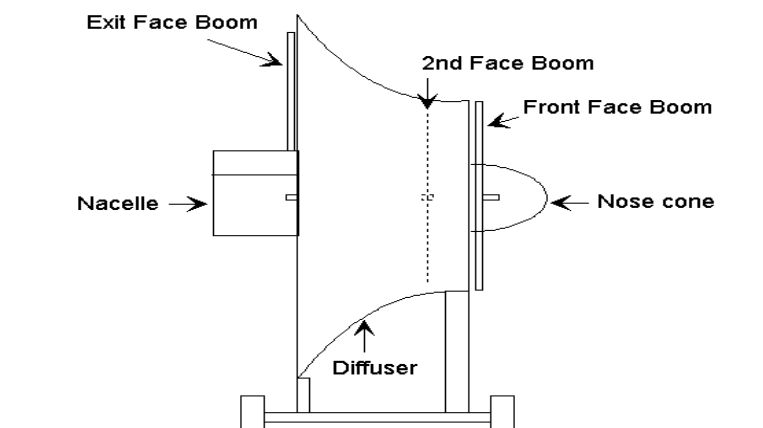


FIGURE 6. Side view of Vortec 7 showing location of instrumentation.
(Note that wind enters turbine from right-hand side.)

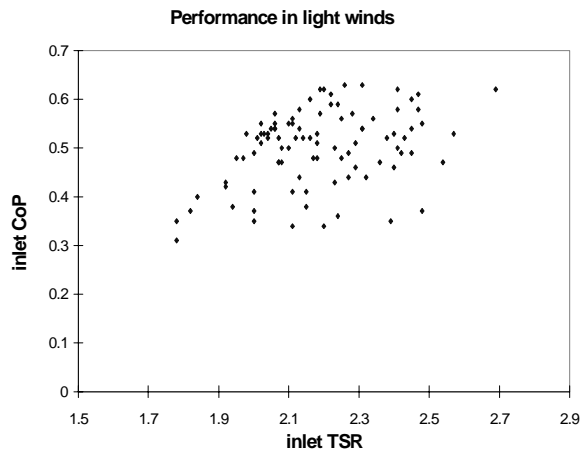


FIGURE 7. Local power coefficient v. tip speed ratio.

7. Aerodynamic analysis

The aerodynamic analysis has several different prongs in its attack. A simplified one-dimensional theory has been developed to investigate trends; CFD is being used to model the as-built Vortec 7 to investigate the effectiveness of various changes; flow visualisation using smoke has been used to quickly ascertain the nature of the flow through the full-size demonstrator; a wind survey of the entire site has been performed to validate proposed wind tunnel testing of a topographical model.

7.1 One-dimensional analysis

A simple one-dimensional model has been developed in conjunction with this research. It consists of a free isentropic contraction into the diffuser inlet, a specified pressure drop coefficient (analogous to a screen) which replaces the blades, a specified diffuser efficiency, and a specified base pressure coefficient. This is solved to find the wind speed at the diffuser inlet, and by multiplying by the blade pressure drop coefficient, i.e. the air power, the potential power for turning wind turbine blades, can also be determined.

Figure 9 shows the effect of varying the base pressure coefficient with diffuser efficiency fixed at 0.95. Clearly the power augmentation compared to the ideal Betz limit for a bare turbine is maximised when the base pressure coefficient is lowest. Maximum power is also obtained when the turbine thrust coefficient is around 0.2–0.4. This simplified theory would lead us to expect power augmentations of about 4.

Figure 10 shows the speed-up into the diffuser inlet. The effect of base pressure with fixed diffuser efficiency is illustrated. Clearly low disc loadings give the highest speed-up as expected. The speed-ups are quite healthy at about 2 for disc loading coefficients in the range 0.2–0.4 and according to these results, the diffuser augmentation idea looks promising.

7.2 Site wind survey

It is necessary to know the ambient wind conditions at the Vortec 7 to calculate its performance. However, this can-

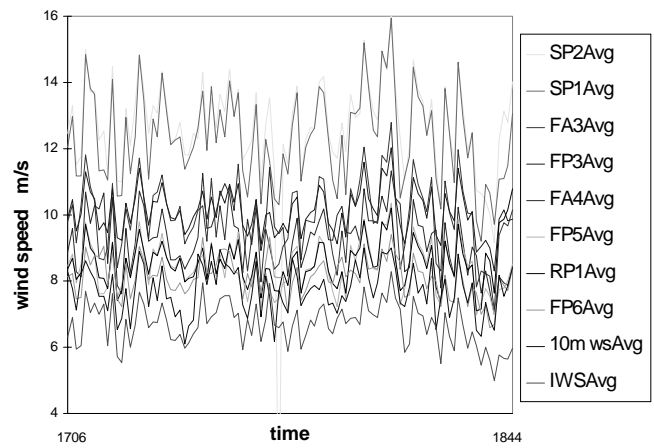


FIGURE 8. Time series of windspeeds from various sensors across the rotor blade plane.

not be measured once the wind turbine is in place because it affects any sensor located nearby. Ideally an anemometer would be placed at hub height at the proposed wind turbine location, and a reference anemometer at an adjacent location, and both monitored simultaneously for say one year prior to installation. This was not conducted in the present project since foundation works commenced shortly after site selection. Instead, the 20 m tower is used to measure reference wind conditions, and two movable 10 m towers are positioned at various locations around the site and used to determine local velocities at hub height.

It is intended that this information will be used in conjunction with a wind tunnel model to calculate the velocity field for all wind directions. A 1:500 wind tunnel model

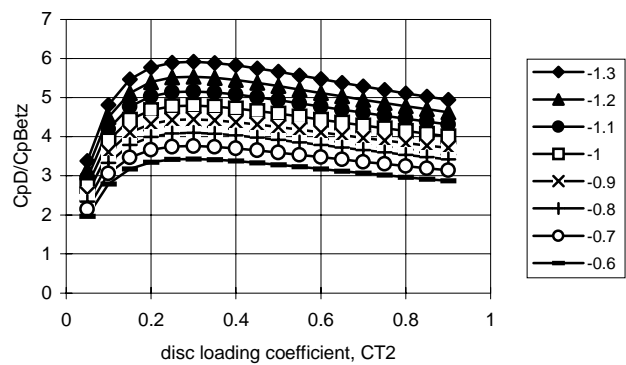


FIGURE 9. Effect of base pressure coefficient on power augmentation.

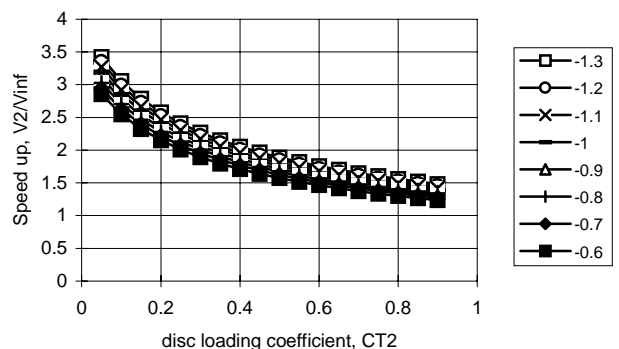


FIGURE 10. Effect of base pressure coefficient on speed-up.

will be built, and global positioning and aerial photography used to create a digital model to allow cutting the physical terrain model on the University's numerically controlled milling machine. This work will enable an accurate assessment of the Vortec 7's performance to be determined, and give useful information on the velocity variation at the top of a hill in complex terrain.

7.3 Computational fluid dynamic analysis

A computational fluid dynamic (CFD) model of the Vortec 7 has been developed using the finite volume, fully viscid program Phoenix. A parametric study has been used to show the effects of the diffuser shape and boundary layer control slots. The model is axi-symmetric with specified inlet boundary conditions. The turbine is modelled as a momentum sink with a specified pressure drop across the blade plane. The inlet truss has been modelled by a shear stress acting in both the axial and radial directions over the cells in the inlet boundary layer control slot. The shear stress accounts for the triangular nature of the truss with a modified area ratio to match the model to the Vortec 7.

Wall friction has been applied to all geometric features. The inlet boundary conditions assume a steady flow with a turbulence intensity chosen for the Vortec site. The geometry of the Vortec 7 results in the use of a body fitted grid. Modifications can be made to the model to allow for further optimisation of the DAWT design. Figure 11 is an example of the results obtained from the CFD model and shows the convergence of streamlines into the diffuser and the continued divergence beyond the diffuser exit.

Initial results from testing show good agreement with the CFD model for the inlet velocity and flow within the first

inlet slot. However, this work yields lower power predictions than the one-dimensional analysis.

7.4 Flow visualisation

To visualise the flow behaviour through the Vortec 7 two methods have been used. Spinnaker cloth tufts have been attached to the diffuser wall with tape. The flow behaviour can be clearly seen by the movement of the tufts. This has been particularly effective in visualising the effect of modifications to the boundary layer control slots. Modifications to the second boundary layer control slot have eliminated the intermittent separation caused by the turbulent onset flow evident in the as-built diffuser configuration and the flow now remains attached to the inner wall of the diffuser along its entire length.

Smoke visualisation has also been used to study the flow. It was especially useful when the machine was first run. The use of smoke has enabled the complex flow into the inlet slot to be determined, and was not as expected. However, the observed streamline behaviour shows close agreement with CFD results.

8. Conclusions

- The diffuser is expected to draw more air through the blade plane, thus allowing it to produce more power than a "bare turbine" of the same rotor size.
- Simplified one-dimensional arguments lead to predictions of speed-ups of about 2 and power augmentations of about 4, but such power levels have not been observed to date.
- Smoke was used successfully to visualise flow into and through the DAWT.

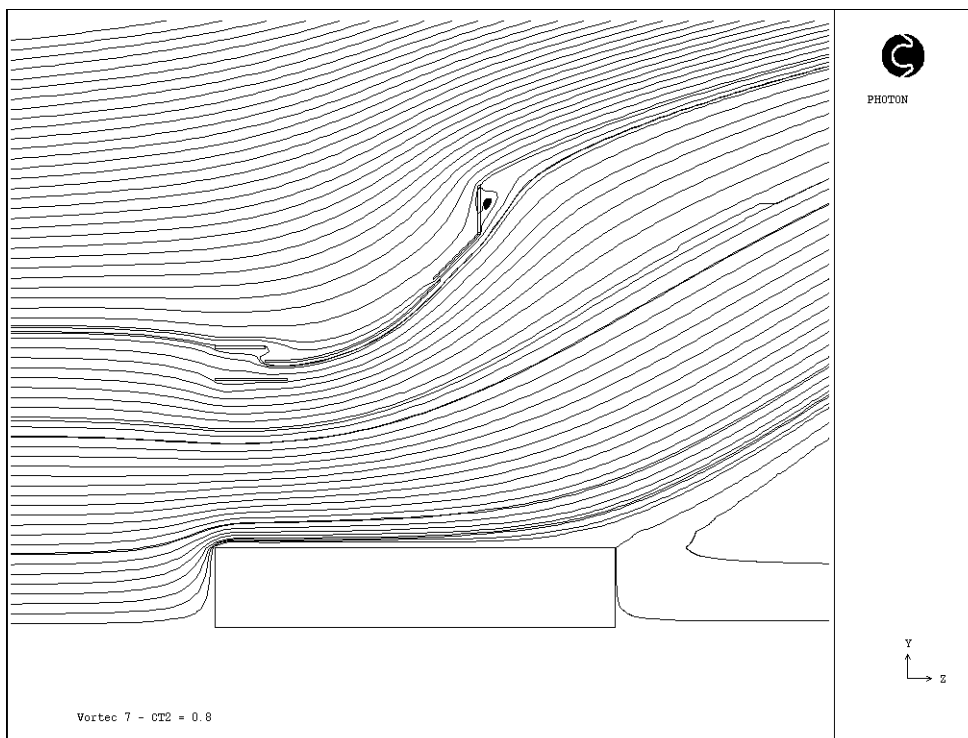


FIGURE 11. Streamlines through axi-symmetric CFD model of the Vortec 7.

- Spinnaker cloth tufts showed improved flow after modifications of the boundary layer slots.
- Preliminary results showed good qualitative agreement between CFD and full-scale results
- The velocity profile across the blade plane showed lower speeds closer to the hub, and a high speed region beyond the blade tips. As a consequence, preliminary power measurements were not as high as predicted by Foreman, who assumed uniform velocity across the blade plane as measured beyond the blade tips.
- Improvements to the inlet velocity profile are anticipated by the retrofit of a bullnose to the primary diffuser and a parabolic nose cone in front of the rotor hub.
- The CFD modelling work, blade and diffuser performance codes are important tools for optimising the performance of the DAWT.

9. Acknowledgements

The Vortec 7 design was specified by K.M. Foreman, consultant to Vortec and Head of Fluid Dynamics at Grumman Aerospace Corp. during their DAWT research programme. The diffuser geometry is based on Grumman's optimum design developed from scores of wind tunnel tests.

A Technology for Business Growth (TBG) grant was awarded by the Foundation for Research, Science and Technology to Vortec Energy Limited for the monitoring and optimisation of the demonstrator unit with this work being performed in conjunction with Industrial Research Limited and the University of Auckland.

10. References

1. Lilley, G. M., Rainbird, W. J. 1956. A preliminary report on the design and performance of ducted windmills. CoA Report No. 102.
2. Foreman, K. M. 1979. Cost analysis of DAWT innovative wind energy systems. Research Department Report RE-626AJ, Grumman Aerospace Corp.
3. Nash, T.A. 1997. Design and construction of the Vortec 7. New Zealand Wind Energy Association, First Annual Conference, Wellington, June 1997.

10. Bibliography

- Fletcher, C.A.J. 1981. Computational analysis of diffuser-augmented wind turbines. *Energy Conversion and Management* 21: 175–183.
- Foreman, K.M., Gilbert, B.L. 1979. Further investigations of diffuser augmented wind turbines. Part 1 Executive summary. US Dept of Energy Report C00-2616-2 UC-60, Grumman Aerospace Corp. Bethpage, New York.
- Foreman, K.M., Gilbert, B.L. 1979. Technical development of the diffuser augmented wind turbine concept. *Wind Engineering* 3 (3): 153–166.
- Foreman, K.M., Gilbert, B.L. 1983. Experiments with a diffuser-augmented model wind turbine. *Journal of Energy Resources Technology, Transactions ASME* 105 (3/83): 46–53.
- Foreman, K.M., Gilbert, B.L. 1979. Experimental demonstration of the diffuser-augmented wind turbine concept. *Journal of Energy* 3 (4).
- Foreman, K.M., Gilbert, B.L., Maciulaitis, A. 1983. Performance predictions and recent data for advanced DAWT models. ASME Solar Energy Division, Grumman Aerospace Corp., Bethpage, New York.
- Foreman, K.M. 1980. The diffuser augmented wind turbine (DAWT): A cost competitive-innovative energy conversion system. Systems Conference, Colorado Springs, 1980.
- Foreman, K.M. 1983. Size effects in DAWT innovative wind energy system design. *Journal of Solar Energy Engineering* 105: 401–407.
- Gilbert, B.L., Oman, R.A., Foreman, K.M. 1978. Fluid dynamics of diffuser-augmented wind turbines. *Journal of Energy* 2 (6): 368–374.
- Igra, Ozer. 1976. Compact shrouds for wind turbines. *Energy Conversion* 16: 149–157.
- Igra, Ozer. 1977. The shrouded aerogenerator. *Energy Conversion* 2: 429–439.
- Loeffler Jr, A.L. 1981. Flow field analysis and performance of wind turbines employing slotted diffusers. *Journal of Solar Energy Engineering* 103: 17–22.
- Loeffler Jr, A.L., Steinhoff, J.S. 1984. Computation of wind tunnel wall effects in ducted rotor experiments. AIAA, Jan 9–12, 1984, pp 1–6.
- North, P. 1976. The suppression of flow separation by sequential wall jets. *Journal of Fluids Engineering*: 447–454.
- Reigler, G. 1983. Principles of energy extraction from a free stream by means of wind turbines. *Wind Engineering* 7 (2): 115–126.