DESIGN OF A DIFFUSER AUGMENTED WIND TURBINE

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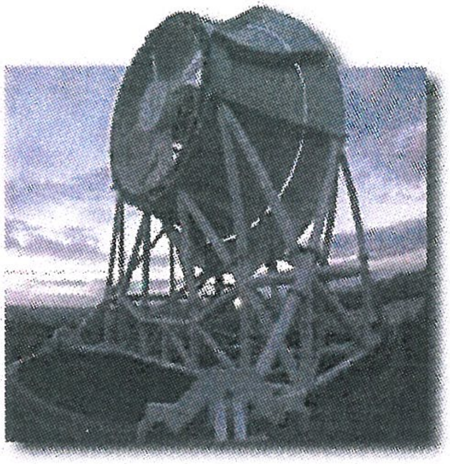

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INTRODUCTION

Our requirements for clean renewable energy and diversity of supply can be met by wind generated electricity. Worldwide there is now over 7000 MW of installed wind power plant, and annual rates of installation are steadily increasing. Wind Energy has come of age with participation by large technology & finance companies, reliable & robust wind turbine designs and public demand for 'green' electricity.

Wind turbine design has evolved rapidly over the last twenty years. Many of the design initiatives in the 70's and early 80's involved government funded multi-megawatt size turbines in the USA & Europe. However, the more successful technology path is considered by many as the incremental development from smaller (sub 100 kW) size machines to the 500 - 1500 kW turbines available commercially today.

Despite the apparent maturity of wind turbine technology, there is still a lack of consensus about the basic parameters of the optimum machine. The current contenders are the solid 'Danish' horizontal axis upwind 3-bladed designs. These compete for market share with teetered 2-bladed rotors, lightweight guyed tower designs, downwind coning rotors and vertical axis turbines. Many of these latter concepts are aimed at improving weight-effectiveness as a means of reducing cost. There is further differentiation according to pitch or stall power regulation, fixed vs. variable speed and use of a gearbox or direct drive. This design diversity indicates a continued evolution of wind turbine technology.

Vortec Energy Limited have designed and built the world's first field-size Diffuser Augmented Wind Turbine, the Vortec Seven. This technology demonstrator, with a rotor blade diameter of 7.3m, was installed at a site 110 km south of Auckland, New Zealand in early 1997.

Vortec Energy secured a license to develop & commercialise the DAWT technology from Northrop Grumman, following rights already secured by Vortec to a material technology suitable for the diffuser. The Vortec Seven design is based on the best model geometry determined by development work by Grumman Aerospace over a seven year period, including extensive wind tunnel model testing. A comprehensive monitoring & performance enhancement programme has been carried out by Vortec over the last 16 months on the Vortec Seven wind turbine.

This paper reports on the design & performance enhancement of the Vortec wind turbine, and discusses the Wind Engineering analysis tools used.

DIFFUSER AUGMENTATION

The Diffuser Augmented Wind Turbine (DAWT) has a long development history (Lilley et al, 1956). Although long conical concentrators or diffusers could readily augment flow through a turbine, such structures were large and offered little promise of a cost effective wind energy conversion system. Progress was made by Grumman Aerospace in the late 1970's and early 1980's when the concept of using additional flow injected through slots in the diffuser walls was shown to lead to a more compact and cost effective diffuser. This work involved extensive wind tunnel testing at Grumman (Foreman et al, March 1983).

The Grumman diffuser design comprises an annular ring (shroud) just clear of the blade tips, and an expanding airfoil shaped diffuser downwind of the blades. The shroud allows radial flow (tip loss) components to be exploited in addition to axial flow, and itself increases power available over a conventional (bare rotor) turbine. The diffuser augments the power available further by providing a low pressure area behind the rotor, which acts to increase the mass flow of air through the blades (Figure 1).

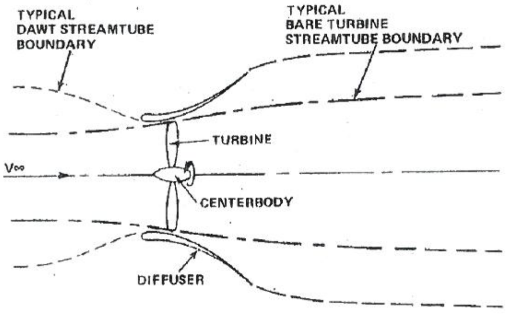

Figure 1: *Schematic of DAWT & bare turbine tip-stream boundaries.*

Boundary layer control is the key to the performance of the diffuser - inside wall flow attachment is maintained using two stages of air injection through slots. This provides a diffuser design with a length to exit diameter ratio of only 30%. Thus Grumman's DAWT development work provided a compact design requiring a minimum of diffuser material for the augmented power.

VORTEC SEVEN DESIGN

Ken Foreman, the team leader at Grumman during the DAWT project, was engaged as a consultant to Vortec Energy. He specified the key aspects of diffuser geometry and drive-train sizing. Foreman's predictions for power output were 5.5 times the power of a bare turbine of the same rotor diameter, resulting from a uniform velocity speed-up of 2 across the blade inlet plane.

Design & manufacture of the Vortec Seven demonstrator components took place in 1996. Various New Zealand and International consultants & contractors were engaged for the project.

The diffuser was fabricated from high tensile fibre-reinforced ferro-cement, a material used previously in vessel hull, pontoon & onshore tank structures. The drive-train was designed with a conventional layout of a fail-safe brake on the low speed shaft, a single stage gearbox coupled to a synchronous generator. Blade pitch was altered manually on the Vortec Seven, between test runs.

Full band variable speed operation is provided by rectification & line commutated inverter connection to the grid. However while testing, generator power is dissipated to a resistor bank for smooth electrical loading. Further design & construction details are provided by Nash (1997).

The parameters of interest which characterise the performance of the DAWT are the velocity speed up at the turbine plane, the diffuser exit pressure coefficient and the rotor disc loading. These parameters together determine the power performance of a DAWT. The completed Vortec Seven demonstrator is shown below (Figure 2).

Figure 2: *Vortec Seven with instrumentation*

WIND ENGINEERING TOOLS

Wind Engineering analysis tools are used extensively in wind turbine design. Turbine site selection involves careful assessment of wind strength, direction, shear, gust factors and the incidence of vertical components.

Wind turbine aerodynamic design includes load case definition, selection of blade profile & twist/taper, and dynamic design of rotor, nacelle & tower assembly. Fatigue loading spectra for critical components can be obtained from analysis of measured (strain-gauged) data, or alternatively derived from a von Karman cycle analysis.

Computational Fluid Dynamics (CFD) and Wind Tunnel modelling are useful tools for power curve prediction & optimization of new designs such as the Vortec. Power performance assessment of a prototype wind turbine requires an accurate measure of ambient wind conditions (strength, direction & shear) in addition to shaft power.

Windfarm energy yield prediction requires an annual distribution of wind speeds. This wind availability is usually measured for at least 12 months at the intended site, although it can be derived synthetically using a Weibull distribution with the site specific shape & scale factors applied.

Individual turbine energy yields may be reduced by wake effects from other turbines in the windfarm. Turbine noise assessment involves an understanding of propagation effects of wind & topography.

Computational analysis techniques involve digitized topographical mapping and extrapolation of measured data from an anemometry station which may be some distance away. For example the WAsP software, available from Riso Laboratories in Denmark, will generate energy resource maps for a proposed site.

Integrated software packages, available from the Natural Power Company, UK (WINDOPS), or Garrad Hassan & Partners, provide a graphically interactive wind farm optimisation and design tool. This software allows a determination of the optimum turbine layout for a wind farm which will deliver the maximum potential energy yield, while minimising noise, visual and other environmental effects (Figure 3).

Figure 3: Sample windfarm layout map used in energy yield & noise optimisation software.

Further elements of wind engineering include the design of materials & protection systems. This involves a knowledge of wind borne particles such as salt or soil, in addition to temperature & humidity effects. Provision for blade anti-icing is necessary at some wind turbine sites.

Properties of the ambient wind are of particular interest in DAWT design due to the sensitivity of diffuser performance to changes in wind strength, direction & turbulence. Significant attention of the Vortec Seven monitoring installation has been given to wind flow & pressure instrumentation on and upstream of the diffuser (Figure 4).

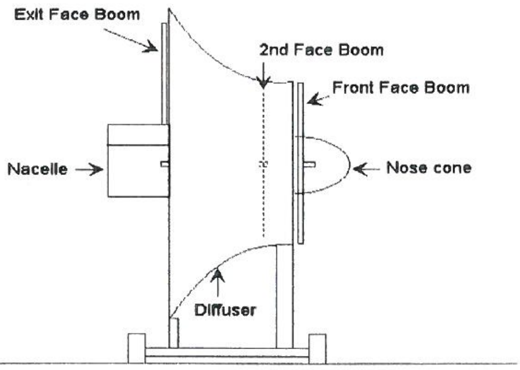

Figure 4: Side view of Vortec Seven showing location of instrumentation. (Note that wind enters turbine from right hand side)

VORTEC SEVEN MONITORING

A Technology for Business Growth (TBG) grant was awarded to Vortec Energy Limited in conjunction with the University of Auckland and Industrial Research Limited. This provided for a comprehensive monitoring and performance enhancement programme on the Vortec Seven project.

Monitoring of ambient conditions was achieved by several anemometry masts - a 20m tall fixed reference mast measured wind strength, direction & shear profile. Other relocatable 10m masts were positioned for each test according to wind direction.

Two LabView configured data acquisition cards formed the heart of the monitoring system. Structural booms (Figures 5 & 6), mounted to the entry & exit faces of the diffuser, support a variety of commercially available and custom made sensors. These measured local wind speed, direction & air pressure components at various radial & axial positions throughout the diffuser.

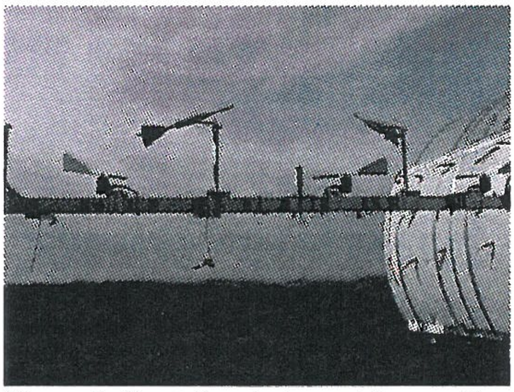

Figure 5: *Front face instrument boom with a static pressure probe, three wind-vanes & two self-aligning (2-axis) pitot probes shown.*

Figure 6: *Rear face instrumentation boom*

Flow visualisation was performed using spinnaker cloth ribbon tufts, and smoke testing sequences were video recorded for later analysis. Boundary layer attachment was monitored using pitot rakes mounted to the inside wall of the diffuser (Figure 7).

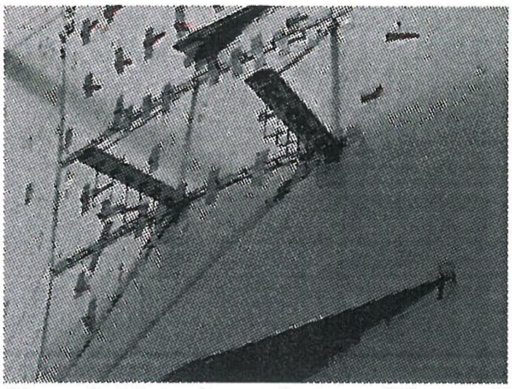

Figure 7: *Pitot rakes on the inner diffuser wall monitor boundary layer flow attachment.*

SENSOR BEHAVIOUR & DATA ANALYSIS

Various sensor types were used to monitor flows & pressures around the diffuser for assessment of speed-up, disc loading, exit pressure & flow attachment.

The commercially available sensors fitted, include:

- Cup anemometers
- Direction windvanes
- Fixed pitot tubes

The custom made sensors included:

- Static pressure probes
- Self-aligning pitot "vane" - single pivot
- Self-aligning pitot "dart" - dual axis pivot
- Pitot rakes

The cup anemometers gave reliable & consistent measurements providing the flow was not oblique to the rotor cup plane. The wind-vanes mounted near the Vortec Seven rotor experienced some oscillation, but this was able to be filtered.

The pitot tubes gave reliable data only when correctly aligned with the flow. Regular cleaning out of salt residue & water was necessary with the pitot tubing. Blockages in the tubing were detected by regular check calibrations of the pitot sensors.

The static pressure probes were fabricated from aluminium, machined then anodised for field conditions, before calibration in a wind tunnel. These sensors worked well in the field and were little affected by varying flow directions.

The single axis self-aligning pitot sensors performed well near the Vortec Seven rotor, where oscillating flow directions were experienced (Figure 8). The dual axis sensors required balancing and did not perform well in the pitch axis.

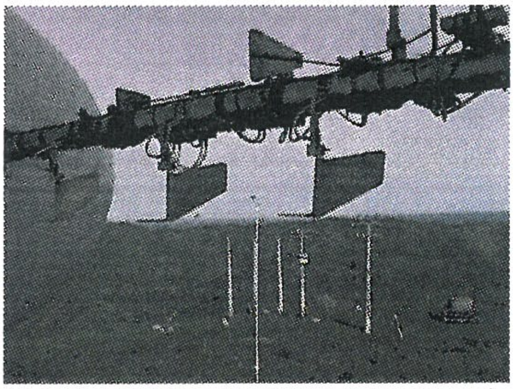

Figure 8: Three single axis pitot sensors on the underside of the front instrument boom.

Early analysis of the Vortec Seven inlet speed up revealed that the profile was not uniform across the rotor blade as Foreman (June 1983) had assumed. Instead, the rotor inlet flow was slowest near the hub, increased radially outward along the blades and was highest outboard of the blade tip in the accelerated primary slot flow (Figure 9).

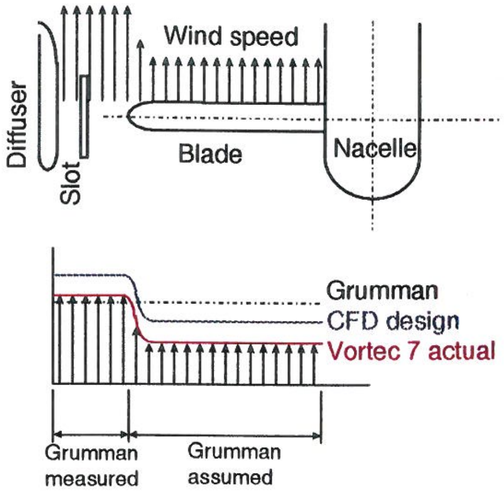

***Figure 9** : Schematic comparison of rotor inlet profiles.*

This observation led to significantly reduced power expectations from the Grumman diffuser upon which the Vortec Seven was designed. With this in mind, Vortec embarked on a programme of performance improvement, involving both the as-built Vortec Seven and design of new advanced diffuser models.

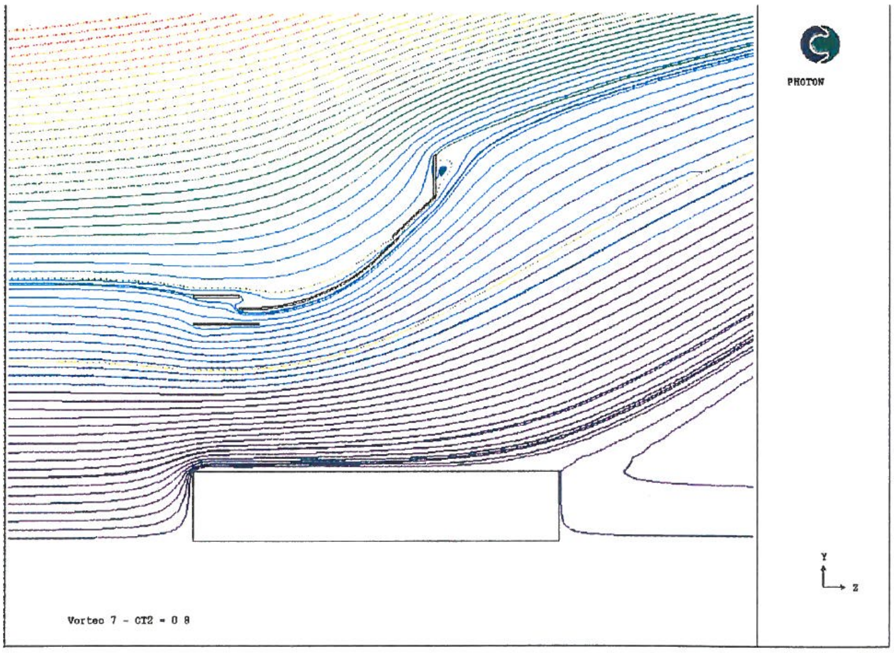

***Figure 10:** CFD streamline model of as-built Vortec Seven showing flow reversal through structural inlet collar & downstream of nacelle.*

VORTEC SEVEN PERFORMANCE ENHANCEMENT

It was found that flow visualisation techniques provided an effective means of diagnosing areas of poor diffuser performance (Phillips et al, February 1998). Video recording of generated smoke emitted from a mobile wand was a particularly useful technique. Spinnaker cloth ribbon tufts attached to external surfaces of diffuser & centrebody were also very instructive.

Flow separation was observed downstream of the nacelle and on the exit face of the diffuser outlet flange. Another important observation was the reversal of flow around the structural inlet collar of the Vortec Seven (Figure 10).

Vortec Energy Limited modified the Vortec Seven with an elliptical nosecone, a bull-nose fitted to the inlet slot to prevent the flow reversal observed initially, and modified the secondary inlet slot and diffuser to direct flow tangential to the secondary diffuser wall These modifications are shown in Figure 11.

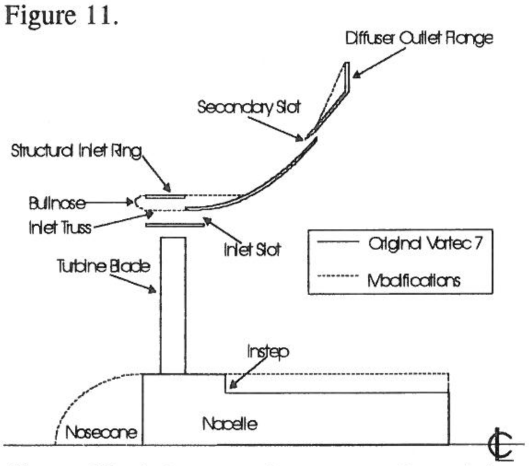

Figure 11: *Axi-symmetric cross-section of the Vortec Seven showing modifications made.*

Subsequent flow visualisation showed regions of separation downstream of the spinner along the nacelle. While the initial retrofits had improved flow attachment, intermittent separation was still observed on the trailing third of the primary diffuser. Vortex generators were installed to remedy this problem (Figure 12). Meanwhile, the strong secondary slot flow adhered well to the secondary diffuser wall.

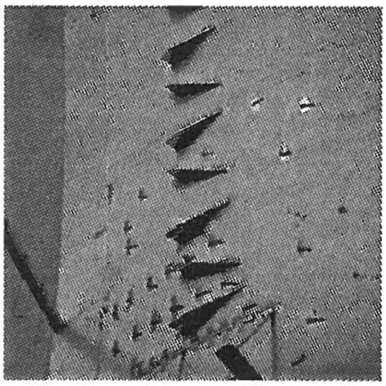

Figure 12: *View of inner diffuser wall towards exit face. Vortex generators mix the boundary layer & assist flow attachment.*

The separated centrebody flow was improved by better surface streamlining with foam sections fitted along the centrebody wall. However, the high costs of modifications to improve the Vortec Seven performance was a disincentive to proceed further with retrofits. With the CFD model well validated with Vortec Seven data, the Vortec development moved focus to CFD & wind tunnel modelling.

COMPUTATIONAL FLUID DYNAMIC (CFD) MODELLING

CFD models of the Vortec wind turbine were written & developed at the University of Auckland, in parallel to the Vortec Seven site testing. The fully viscid, finite volume code PHOENICS was used (Phillips et al, July 1998).

Initially, qualitative results from a CFD model of the 'as-built' Vortec Seven turbine, were compared with observations from flow visualisation work at site. The CFD model correctly predicted separation on the nacelle, on the diffuser outlet flange and the reversal of flow about the structural inlet collar. The model also predicted the high velocity through the inlet slot and the radial variation of flow speed across the blade plane as observed on site.

The effect of the disc loading was studied and showed that at high disc loading the flow was forced out toward the diffuser and reduced the separated region on the diffuser's internal wall.

This effect was observed with the Vortec Seven by varying the rotational speed of the turbine. Velocity and directional anemometry sensors located on a boom at the diffuser exit (Figure 6), clearly showed the separated region next to the nacelle and the high diffusion angles outside that region. These observations confirmed the streamline plots obtained with the CFD model.

ADVANCED DIFFUSER DESIGNS

The development of the geometry for advanced diffuser designs was achieved using CFD modelling. Validation of the model with Vortec Seven data was the starting point for this work. The effects of the inlet slot, diffuser outlet flange, nacelle shape & size were examined using the original diffuser exit area ratio and angle.

A new design was developed which introduced controlled contraction of the flow into the blade plane (Figure 13 & 14). The primary diffuser was extended upstream and the diffuser exit flange removed. Significant increases in power were achieved over the original Grumman diffuser design.

Power coefficients of up to 1.9 were predicted by CFD modelling of the advanced diffuser geometries. This is equivalent to an augmentation of around 4.5 times the power output of a bare rotor turbine with the same blade diameter.

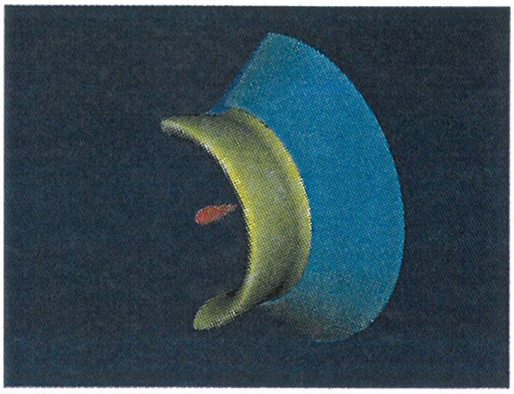

Figure 13: Advanced diffuser design developed by CFD work at Auckland University

Meanwhile, under a technical collaboration between Vortec, Kawasaki Heavy Industries & the Gifu Technical Institute in Japan, further advanced diffuser designs were proposed. CFD modelling at Kawasaki/Gifu, in parallel to the Auckland University work, provided a smaller diffuser design with a predicted power coefficient around 1.5.

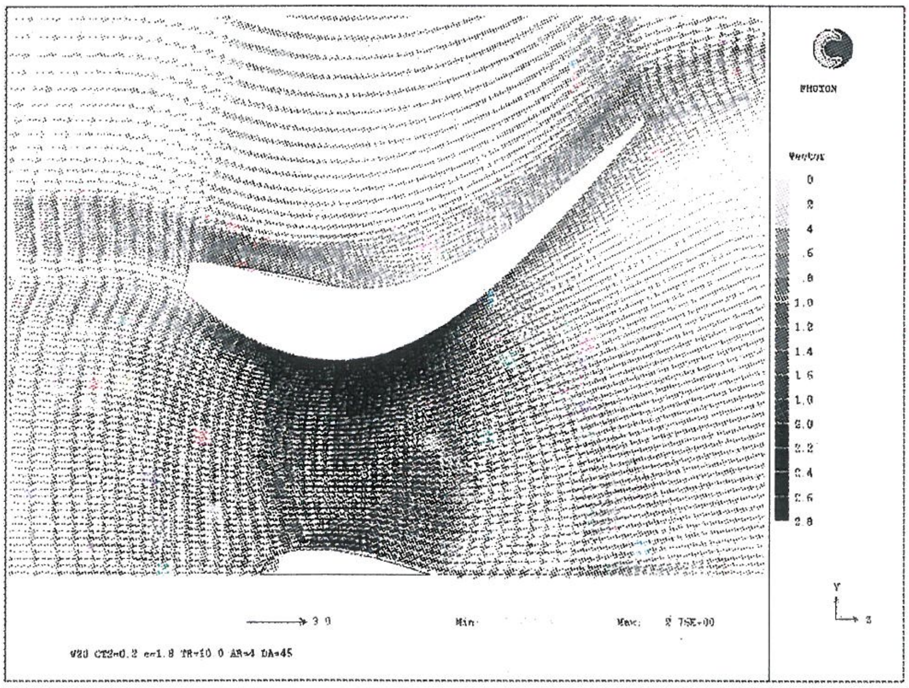

Figure 14: Velocity vector plot of advanced diffuser, with the geometry hidden

COMPARISON WITH ONE DIMENSIONAL ANALYSIS

A simple one dimensional model was developed in conjunction with the CFD research. It consists of a free isentropic contraction into the diffuser inlet, a specified pressure drop coefficient at the blade plane (analogous to the CFD turbine model), a specified diffuser efficiency, and a specified base pressure coefficient. This model was solved to determine the air power available for processing by the wind turbine blades.

Comparison of the CFD results for the as-built Vortec Seven with the one dimensional analysis showed considerable difference in both the magnitude of the speed-up, the corresponding power coefficient, and the local disc loading at which optimal power was achieved. This comparison is shown in Figure 15. This chart gives the one dimensional (1 D) data at two area ratios (3.1 & 4), the advanced diffuser design at two CFD turbulence levels (Adv1 & 2) and the benchmark Grumman & modified Vortec Seven designs.

The CFD model of the Vortec Seven geometry predicts an optimal power coefficient of approximately 1.3 at a local disc loading between 0.8 and 1.0 Meanwhile, the one dimensional theory for an equivalent area ratio diffuser, predicted an optimal power coefficient around 2.0. This is obtained with a local disc loading coefficient between 0.3 and 0.4 for the one dimensional theory assuming a diffuser efficiency of 95% and base pressure coefficient, Cp4 of -0.6.

The advanced diffuser geometry, with controlled inlet contraction, displayed similar trends to those predicted by the one dimensional analysis. Much larger inlet speed-ups were predicted for the advanced diffuser geometry than the Grumman / Vortec Seven diffuser design, with the optimal power coefficient of around 1.9 occurring at a local disc loading between 0.3 and 0.4. This compares to the one dimensional power coefficient prediction of 2.3 for the same exit area ratio of 4.

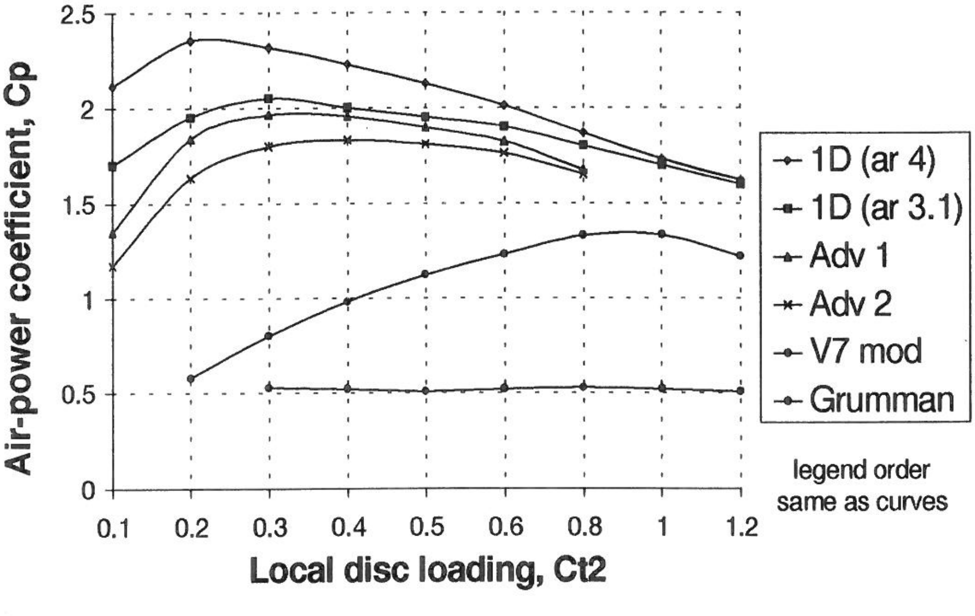

Figure 15: Comparison of CFD results with one dimensional analysis

WIND TUNNEL MODELLING

With the original CFD models validated using Vortec Seven site data, wind tunnel modelling was then used to verify the advanced CFD diffuser designs. Wind tunnel models were constructed on two advanced diffuser designs, one from Auckland University CFD work (Figure 16) & one from Kawasaki.

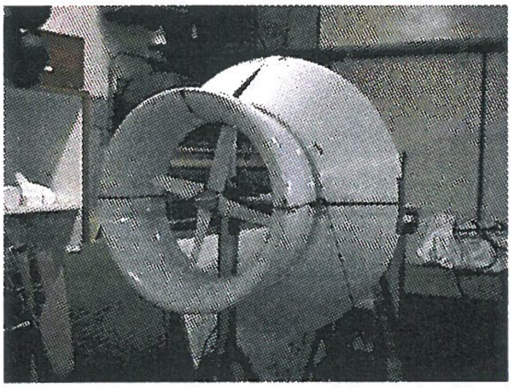

***Figure 16**: Wind tunnel model of Auckland University CFD advanced diffuser design.*

Both models were sized for a 457 mm diameter rotor blade, matching the size of the last Grumman test model, and which had been acquired by Vortec. A proposal to use the large wind tunnel at the Tamaki Campus of the University of Auckland was changed when the facility was closed for repair work to a fan. Preliminary set-up was carried out at the Auckland City Campus facility before relocating the models to Melbourne. Wind tunnel testing commenced at the Vipac Wind Engineering facility in late August. The results from this testing will be covered in the presentation.

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