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An Investigation on
Diffuser Augmented Wind Turbine Design

Derek Grant Phillips

A thesis submitted in partial fulfilment of the requirements for the degree of
Doctor of Philosophy in Engineering

Supervised by
Professor Richard G. J. Flay
&
Associate Professor Peter J. Richards

Department of Mechanical Engineering
School of Engineering
The University of Auckland 2003

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Always there, their unfailing support and encouragement too often goes without the
acknowledgement it deserves.
Sarah, Ma, Pa and Sis; it is with you I share this achievement and
to you I dedicate this work.

Abstract

Diffuser Augmented Wind Turbines (DAWTs) are one of many concepts to have been proposed to reduce the cost of renewable energy. As the most commercially viable, they have been the focus of numerous theoretical, computational, and experimental investigations. Although intimated in these studies to be able to augment the power output of a wind turbine, the extent of this power increase, or augmentation, the factors influencing DAWT performance, the optimal geometric form and their economical benefit remained unanswered. It is these issues that have been addressed in this investigation.

In reviewing historic investigations on DAWTs it has been identified that excessive wind tunnel blockage, inappropriate measurement technique, varied definitions of augmentation, and the inclusion of predicted performance based on incorrect assumptions have in general led to the overstatement of DAWT performance in those studies. In reassessing the performance of the most advanced of those DAWT designs, Grumman's DAWT 45, it has been calculated that the actual performance figures for the 2.62 exit-area-ratio and 0.488 length-to-diameter ratio DAWT were an available augmentation of 2.02, a shaft augmentation of 0.64 and a diffuser efficiency of 56%.

By contrast, the development of the Mo multi-slotted DAWT in this investigation has yielded a design whose shaft augmentation of 1.38 was achieved by a diffuser with exit-area-ratio of only 2.22 and overall length-to-diameter ratio of 0.35.

Such performance improvement has been obtained by gaining both an understanding of the flow characteristics of DAWTs and the geometric influences. More specifically it has been shown that: the velocity across the blade-plane is greater than the free-stream velocity and increases towards the rotor periphery; that the rotor thrust or disc loading impacts upon diffuser performance by altering the flow behaviour through it; and that DAWTs are able to maintain an exit pressure coefficient more negative than that attainable by a conventional bare turbine. The net result is that DAWTs encourage a greater overall mass-flow as well as extract more energy per unit of mass-flow passing through the blade-plane than a conventional bare turbine.

The major drivers of DAWT performance have been shown to be the ability of the design to maximise diffuser efficiency and produce the most sub-atmospheric exit pressure possible. Parametric investigation of the various DAWT geometric components has shown peak performance to be obtained when: the external flow is directed radially outward by maximising the included angle of the external surface in conjunction with a radially orientated exit flap; by applying boundary-layer control to a trumpet shaped diffuser via a pressurised cavity within the double-skin design of the multi-slotted DAWT; having an exit-area-ratio of the order of 2.22; and by employing an inlet contraction with inlet-area-ratio matched to the mass-flow passing through the DAWT under peak operating conditions.

To translate the available augmentation into shaft power a modified blade element method has been developed using an empirically-derived axial velocity equation. The resulting blade designs whose efficiencies reached 77%, twice those of Grumman, highlight the accuracy of the modified blade element method in calculating the flow conditions at the blade-plane of the multi-slotted DAWT. It was also noted that the rotor efficiencies remain below 'best practice' and therefore offer the potential for further increases in shaft augmentation. However, in order to achieve such gains, a number of limitations present in the current method must be addressed.

In assessing the likely commercial suitability of the multi-slotted DAWT a number of real-world influences have been examined. Shown to have little if any effect on DAWT performance were Reynolds number, ground proximity and wind shear. Turbulence in the onset flow on the other hand had the beneficial effect of reducing separation within the diffuser. Finally, DAWT performance was assessed under yaw misalignment where it was shown that the multi-slotted DAWT performed favourably in comparison to that associated with a conventional bare turbine.

The major drawback identified in the DAWT concept by this investigation was its drag loading and the fact that drag and augmentation were interdependent. The result is that the cost of a conventional DAWT is dictated by the necessity to withstand an extreme wind event despite the fact that augmentation is only required up to the rated wind speed. The overall conclusion drawn was that in order to optimise a DAWT design economically, and therefore make the DAWT concept a commercial reality, a creative solution that minimises drag under an extreme wind event would be required.

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Contents

Abstract *v*

Acknowledgements *vii*

Contents *ix*

Nomenclature *xvii*

English Symbols xvii

Subscripts xviii

Greek Symbols xix

Abbreviations and Acronyms xix

List of Figures *xxi*

List of Tables *xli*

Chapter 1 Introduction *1*

1.1 Development of the wind turbine industry 2

1.2 Scope of the current study 4
- 1.2.1 A Review of Wind Turbine Augmentation 4
- 1.2.2 Principal Investigations into Diffuser Augmented Wind Turbines 4
- 1.2.3 Theoretical Analysis of DAWTs 4
- 1.2.4 Development of a Generic Diffuser Geometry 5
- 1.2.5 The Design & Performance of a DAWT Rotor 5
- 1.2.6 The Influence of Real-World Conditions 5

1.2.7 Analysis of Diffuser Geometric Features 6
1.2.8 Drag & its Impact on DAWT Cost of Energy 6
1.2.9 Conclusions and recommendations 6
1.3 Original contributions 6

Chapter 2 *A Review of Wind Turbine Augmentation* 7

2.1 Augmentation of a wind turbine 7
2.2 Factors influencing the cost of energy 9
2.3 Augmented wind turbine concepts 10
2.3.1 Augmentation derived from Vortex type systems 14
2.3.1.1 Vortex Augmented Turbines 14
2.3.1.2 Wing Tip Vortex Concentrator 15
2.3.1.3 Tornado Turbine 15
2.3.2 Augmentation derived from a Nearby Obstruction 16
2.3.2.1 Cylindrical Obstruction Concentrator 16
2.3.2.2 Toroidal Accelerator Rotor Platform 16
2.3.3 Augmentation derived from a Diffuser Effect 17
2.3.3.1 Tip-Vanes 17
2.3.3.2 Diffuser Augmented Wind Turbines (DAWTs) 19
2.4 Summary 22

Chapter 3 *Principal Investigations into Diffuser Augmented Wind Turbines* 23

3.1 A review of historical DAWT research 23
3.2 The beginning of DAWT geometry evolution 27
3.3 The exploration of compact diffuser designs 29
3.3.1 Igra's first step towards compact shrouds 29
3.3.2 The third generation design by Igra 30
3.3.3 Initial exploration at Grumman Aerospace 32
3.3.3.1 Selection of the Grumman Baseline geometry 34
3.3.3.2 Parameters underlying the Baseline DAWT performance 36
3.3.3.3 Evaluation of real-world influences - ground proximity, shear flow & drag 40
3.3.4 Refinement of the Baseline geometry 42
3.4 The development of rotor designs 45

3.4.1 Rotor design options 45
3.4.2 Development of blade designs 46
3.4.3 Experimental investigation of Igra's axial flow turbine 49
3.4.4 Experimental investigation of a multi-bladed rotor by Lewis et al 51
3.4.5 Experimental investigation of Grumman's rotor design 54

3.5 The impact of drag - structural considerations 65

3.6 The final generation of DAWT designs 68
3.6.1 Development of boundary-layer control by Igra 68
3.6.2 Advancement of DAWT design at Grumman Aerospace 72

3.7 Summary 78
3.7.1 Diffuser development and performance 79
3.7.2 Geometric influences on DAWT performance 81
3.7.3 The influence of flow characteristics and operational parameters on DAWT performance 83
3.7.4 The impact of real-world effects 85
3.7.5 The design of rotors and their influence on DAWT performance 86
3.7.6 Factors in wind tunnel testing that influence DAWT performance 87
3.7.7 Recommendations for further DAWT development presented in the research to date 87

Chapter 4 Theoretical Analysis of DAWTs ***89***

4.1 One-dimensional analysis of a conventional bare wind turbine 89
4.1.1 Energy balance 91
4.1.2 Axial momentum balance 91

4.2 One-dimensional analysis of a DAWT 94
4.2.1 Energy balance 95
4.2.2 Axial momentum balance 97

4.3 The relationships between geometric, operational and flow parameters 100

4.4 Summary 104

Chapter 5 Development of a Generic Diffuser Geometry ***107***

5.1 Analysis of the Vortec 7 107
5.1.1 Full-scale testing of the Vortec 7 109
5.1.2 Computational fluid dynamic modelling of DAWTs 110
5.1.3 Performance of the Vortec 7 110
5.1.4 Flow behaviour associated with the Vortec 7 geometry 113

5.2 Enhancement of the Vortec 7 geometry 116

5.3 Exploration of a second generation of diffuser geometry 123

5.4 Development and performance of a third generation DAWT - the multi-slotted DAWT 128

 5.4.1 Performance of the multi-slotted DAWT using gauze screens having a uniform local disc loading 133

 5.4.2 Performance of the multi-slotted DAWT using gauze screens having a radial variation in local disc loading 135

5.5 Flow phenomenon and operational characteristics of DAWTs 137

 5.5.1 Distribution of velocity across the blade-plane 137

 5.5.2 The influence of disc loading on DAWT flow 141

 5.5.3 Factors Influencing DAWT exit pressure 149

5.6 Summary 154

Chapter 6 The Design & Performance of a DAWT Rotor 159

6.1 Development of a rotor design method for DAWTs 159

 6.1.1 The blade-element method 160

 6.1.2 Implications of a diffuser - the modified-blade-element method 161

 6.1.3 Blade design methodology 165

 6.1.4 Blade profiles and lift & drag data 166

 6.1.5 Blade production 168

6.2 Performance of the multi-slotted DAWT under rotor operation 169

 6.2.1 Instrumentation validation 169

 6.2.2 Performance of the multi-slotted DAWT under rotor operation at the design pitch 171

 6.2.3 Performance of the multi-slotted DAWT under rotor operation at off-design pitch angles 174

6.3 The influence of an operating rotor on DAWT performance 175

6.4 Evaluation of the modified blade-element method 183

 6.4.1 Modelling error introduced through lift and drag data 188

 6.4.2 Modelling error introduced by the empirical velocity speed-up equation 191

6.5 Summary 193

Chapter 7 The Influence of Real-World Conditions 195

7.1 Reynolds number, turbulence intensity and scaling 195

7.2 Yaw 204

7.3 Ground proximity and boundary-layer influence 208

7.4 Unsteady loading due to environmental conditions 211

7.5 Summary 212

Chapter 8 Analysis of Diffuser Geometric Features 213

8.1 External surface geometry 213

8.1.1 Experimental investigation 214

8.2 Inner surface geometry and slot performance 223

8.2.1 Background to diffuser design and performance 223

8.2.2 Diffuser geometry 224

8.2.3 Boundary-layer control for DAWTs 227

8.2.4 Blowing for boundary-layer control 227

8.2.5 Annular jets for boundary-layer control 228

8.2.6 Effectiveness of the multi-slotted DAWT's boundary-layer control 229

8.3 Exit-area-ratio 235

8.4 Inlet contraction 244

8.5 Centrebody configuration 246

8.6 The impact of structures within the diffuser flow 249

8.7 Performance of a fourth generation DAWT - Mo 252

8.8 Summary 256

Chapter 9 Drag & its Impact on DAWT Cost of Energy 259

9.1 Experimental investigation 259

9.2 DAWT lift and drag characteristics 260

9.3 The interrelationship between drag and augmentation 267

9.4 The cost of energy of DAWTs 270

9.5 Summary 272

Chapter 10 Principal Conclusions of the Investigation 273

10.1 Background and historical review 273
10.2 Theoretical analysis 274
10.3 DAWT performance and augmentation 274
10.4 Flow characteristics 275
10.5 Rotor design and performance 277
10.6 Real-world influences 279
10.7 Geometric influences 280
10.8 Economic considerations 282
10.9 Summary 283

Chapter 11 Recommendations for Further Research 285

11.1 DAWT drag loading 285
11.2 DAWT performance 285
11.3 DAWT blade design and modelling 286
11.4 Real-world considerations 287

References 289

Appendix A Computational Fluid Dynamic Modelling 303

A.1 Computational fluid dynamic modelling of the rotor 303
  A.1.1 Validation of the CFD rotor model 305
A.2 CFD modelling of DAWTs 307
  A.2.1 CFD modelling of the Vortec 7 308
  A.2.2 Refinement of the CFD model 309

Appendix B Investigation of the Multi-Slotted DAWT: Models, Instrumentation and Test Facilities 311

B.1 Test model description 311
  B.1.1 Blades 312
  B.1.2 Diffuser 313
  B.1.3 Centrebody 314
    B.1.3.1 Wind tunnel multi-slotted DAWT 314

B.1.3.2 V2 2 m diameter truck-testing-prototype 314

B.2 Wind tunnel testing 315

B.3 Runway testing of the V2 2 m diameter truck-testing-prototype 320

B.4 Field testing 322

B.5 Instrumentation selection and design 323

B.5.1 Pressure probes 324

B.5.2 Surface pressure tappings 327

B.5.3 Hotwire anemometry 329

B.5.4 Gauze screen calibration 329

Appendix C Calculation of DAWT Performance Variables ***331***

C.1 Wind tunnel instrumentation 331

C.2 Wind tunnel performance parameter definitions 332

Nomenclature

English Symbols

A	Area
a	Axial flow interference factor
a'	Tangential induction factor
B	Number of blades
c	Blade chord
C_L	Lift coefficient
C_D	Drag coefficient
Ct_∞	Disc loading coefficient relative to the free-stream dynamic pressure $\frac{\Delta P_{2-3}}{q_\infty}$
Ct_2	Disc loading coefficient relative to the local dynamic pressure $\frac{\Delta P_{2-3}}{q_2}$
Cp_{air}	Available power coefficient $\frac{\Delta P_{2-3} A_r V_2}{\frac{1}{2}\rho V_\infty^3 A_r}$
Cp_{sh}	Shaft power coefficient $\frac{T\varpi}{\frac{1}{2}\rho V_\infty^3 A_r}$
Cp_4	Exit pressure coefficient $\frac{\Delta P_{\infty-4}}{q_\infty}$
D	Drag force
F	Force
g	Acceleration due to gravity
H	Energy

k	Screen loss coefficient
L	Lift force
$\dot{m}$	Mass-flow rate
P	Power
p	Pressure
Q	Volume flow rate
q	Dynamic pressure
R_{tip}	Tip radius of the rotor
r	Local radius of the rotor
r_{air}	Available augmentation $\frac{Cp_{air}}{0.593}$
r_{sh}	Shaft augmentation $\frac{Cp_{sh}}{0.593}$
Re	Reynolds number
T	Torque
V	Velocity
W	Resultant velocity
x	Distance in axial direction from DAWT inlet
z	Height above ground

Subscripts

cb	Quantities evaluated at/related to the centre body
diff	Quantities evaluated at/related to the diffuser
r	Quantities evaluated at rotor blade-plane/related to the rotor
∞	Station in ambient free-stream
1	Station at DAWT inlet
2	Station immediately upstream of blade-plane
3	Station immediately downstream of blade-plane
4	Station at diffuser exit-plane
5	Station well downstream of turbine

Greek Symbols

α	Angle of attack
ϕ	Resultant flow angle
θ	Local pitch angle
ε	Velocity speed-up $\frac{V_2}{V_\infty}$
η	Efficiency
λ	Reciprocal of the diffuser exit-area-ratio $\frac{1}{\left(\frac{A_4}{A_3}\right)}$
μ	Dynamic viscosity
σ	Rotor solidity
ν	Kinematic viscosity
ρ	Density
ω	Rotational speed of rotor

Abbreviations and Acronyms

DAWT	Diffuser Augmented Wind Turbine
EAR	Exit-area-ratio $\frac{A_4}{A_3}$
HAWT	Horizontal-Axis Wind Turbine
TSR	Tip-speed ratio

List of Figures

Figure 2.1: Conventional wind energy extraction process [9]....8

Figure 2.2: Diffuser process of augmentation [9]....8

Figure 2.3: Ejector process of augmentation [9]....8

Figure 2.4: Various innovative wind energy conversion systems (WECS) as presented by Weisbrich [13]....11

Figure 2.5: Various innovative wind energy conversion systems (WECS) as presented by Weisbrich [13]....12

Figure 2.6: Various innovative wind energy conversion systems (WECS) as presented by Weisbrich [13]....13

Figure 2.7: Photograph of a prototype Vortex Augmenter Concept turbine during testing [14]....15

Figure 2.8: The streamline of a conventional bare turbine (a) [9] compared with that incorporating tip-vanes (b) [18] as sketched in (c) [18]....18

Figure 2.9: The Grumman Aerospace [19] diffuser augmented wind turbine....19

Figure 3.1: The Vortec 7 diffuser augmented wind turbine....24

Figure 3.2: Layout of the first generation shroud researched Kogan & Seginer at Ben-Gurion University of the Negev, Israel as presented by Igra in [22]....28

Figure 3.3: Layout of Igra's [24] Model A showing location of the three aerofoil ring-shaped flaps or ring-wings....29

Figure 3.4: Igra's third generation models with NACA cross-section [24]....30

Figure 3.5: Various boundary-layer control diffusers from the first phase experiments at Grumman Aerospace. Included angles of 40°, 60° and 80° with an exit-area-ratio of 2.78 are shown left to right [25]. 33

Figure 3.6: Grumman Baseline configuration: 60° included angle diffuser with exit-area-ratio of 2.78 and 0.37 local disc loading coefficient screen installed [25]. 33

Figure 3.7: Effect of boundary-layer control slots in preventing separation within a DAWT as illustrated in [19].........................35

Figure 3.8: Variation in static pressure, and therefore velocity, measured across the blade-plane of the Grumman Baseline boundary-layer diffuser [25]. Each line shows the static pressure from the inlet of the DAWT downstream across the blade-plane and through the diffuser. 37

Figure 3.9: Exit-plane pressure distributions for the Grumman Baseline boundary-layer diffuser [25].........................38

Figure 3.10: Exit-plane pressure coefficient for various Grumman boundary-layer control diffuser half angles as a function of exit-area-ratio [25]. 39

Figure 3.11: Exit-plane pressure coefficient for various Grumman boundary-layer control diffuser half angles as a function of local disc loading [25]. 40

Figure 3.12: Grumman phase two diffuser model performance with screen simulation of a turbine [27]. 43

Figure 3.13: Schematic layout of the wind tunnel model used by Igra [23] for turbine testing. 49

Figure 3.14: Front view of Igra's [24] prototype wind turbine with electrical power curve. 51

Figure 3.15: The two duct geometries (i) of Lewis et al [40]: (a) Theoretical duct - the small-scale gauze screen duct, and (b) Experimental duct - the larger-scale rotor duct. Shown in (ii) is the 11 bladed rotor.........................52

Figure 3.16: The Baseline model (a) and simple cylindrical duct (b) from the third phase of Grumman Aerospace wind tunnel testing [19]. 54

Figure 3.17: Schematic diagram showing the three effects causing overestimation of the blade-plane velocity measurement on the Baseline DAWT: (1) increased velocity towards rotor periphery, (2) slot flow accelerated by pressure drop across blade-plane and (3) separation or low pressure over inlet leading edge due to contraction of flow into the blade-plane [91]......58

Figure 3.18: Comparison of Grumman Baseline diffuser wind tunnel test data with operating rotor and simulation by gauze screens [27]......65

Figure 3.19: Grumman conical frustrum drag model showing the location of the static pressure taps and drag results......66

Figure 3.20: Schematic diagram of Igra's [22, 24] boundary-layer control models showing inlet holes 1, 2 & 3 and discharge holes A, B, C & D......69

Figure 3.21: Variation in available power coefficient (a) and turbine efficiency (b) with tip-speed ratio for the DAWT 45 operating at 28° pitch [32]. Shown are the measured data, Grumman's trend line (solid) and the present author's interpretation of the average performance of each (dashed line)......75

Figure 3.22: Calculation of shaft power coefficient from available power coefficient and turbine efficiency. The curves represent this author's best fit line to Grumman's [32] data shown in Figure 3.21......76

Figure 4.1: Illustration of the streamtube passing through a conventional bare turbine. Atmospheric pressure exists at stations ∞ and 5, well up and downstream of the rotor respectively......90

Figure 4.2: Illustration of the streamtube passing through a ducted turbine rotor. Atmospheric pressure exists at stations ∞ and *5*, well up- and downstream of the rotor. Stations *1* and *4* correspond to the duct inlet and exit respectively......94

Figure 4.3: Influence of diffuser efficiency on DAWT augmentation over a range of local disc loading coefficients......101

Figure 4.4: Influence of diffuser efficiency on augmentation, velocity speed-up, free-stream and local disc loading coefficients......102

Figure 4.5: Influence of exit-area-ratio on augmentation, velocity speed-up, free-stream and local disc loading coefficients.......102

Figure 4.6: Influence of exit pressure coefficient on augmentation, velocity speed-up, free-stream and local disc loading coefficients.......103

Figure 4.7: Effect of relative changes of the parameters governing DAWT performance [95].......104

Figure 5.1: The Vortec 7. Flow is from left to right. The structural inlet ring and triangular truss are visible at the inlet on the left with the curved boundary-layer slot seen near the outlet on the right.......108

Figure 5.2: Axi-symmetric cross-section of the original Vortec 7.......108

Figure 5.3: Instrumentation booms at the inlet (a) and exit (b) of the Vortec 7 showing the various pieces of anemometry equipment used to assess its performance.......109

Figure 5.4: Summary of the full-scale Vortec 7 performance and CFD prediction. Area weighted averages have been used for all variables except for the Vortec 7 velocity speed-up which corresponds to the value at 0.72 of the tip radius.......111

Figure 5.5: CFD predicted radial variation of the velocity speed-up across the blade-plane of the Vortec 7 for various local disc loading coefficients.......112

Figure 5.6: CFD streamline plot for the original Vortec 7 design showing flow reversal through the inlet truss, separation adjacent to the primary and secondary diffusers as well as along the centrebody, for a local disc loading coefficient of 0.15.......113

Figure 5.7: Flow visualisation showing flow reversal around the inlet structural ring and into the inlet boundary-layer control slot on the Vortec 7. Modifications to give directional stability to the slot flow are evident on the secondary boundary-layer control slot.......114

Figure 5.8: Schematic diagram indicating separation generated from the cylindrical inlet ring on the Vortec 7 as a result of yaw misalignment or large-scale turbulence.......114

Figure 5.9: CFD streamline plot showing flow separation from the nacelle of the original Vortec 7 at a local disc loading coefficient of 0.3. 115

Figure 5.10: Schematic diagram of the modifications made to the Vortec 7 geometry. 117

Figure 5.11: The full-scale modified Vortec 7 with nosecone, streamlined centrebody, inlet and secondary boundary-layer control slot modifications. 117

Figure 5.12: Comparison of available augmentation for the original Vortec 7, the subsequent modifications predicted from CFD modelling and the one-dimensional theoretical calculation using average exit pressure coefficients taken from the respective CFD predictions..................................118

Figure 5.13: CFD predicted radial variation of the velocity speed-up across the blade-plane for the Vortec 7 and the Vortec 7 with elliptical nosecone for various local disc loading coefficients. 119

Figure 5.14: CFD streamlines through the Vortec 7 with elliptical nosecone and fairing of the inlet and secondary boundary-layer control slots at a local disc loading coefficient of 0.5. 120

Figure 5.15: CFD streamlines through the Vortec 7 with elliptical nosecone and fairing of the inlet and secondary boundary-layer control slots at a local disc loading coefficient of 0.7. 120

Figure 5.16: CFD streamline plot for the fully modified Vortec 7 with a local disc loading coefficient of 1.3. 121

Figure 5.17: CFD predicted radial variation of the velocity speed-up across the blade-plane for the Vortec 7 and the fully modified Vortec 7 for various local disc loading coefficients...122

Figure 5.18: Schematic cross-section of the second generation DAWT. 123

Figure 5.19: Predicted augmentation of the second generation DAWT. Comparison is made with the predicted performance of the modified Vortec 7 and one-dimensional theory. 124

Figure 5.20: CFD streamline plot of the second generation DAWT showing controlled contraction of the flow into the blade-plane at the throat of

the DAWT and through the secondary boundary-layer control slot at a local disc loading coefficient of 0.3. 125

Figure 5.21: Schematic diagram of the second generation DAWT boundary-layer control slot highlighting the contraction of flow through the slot and direction of slot flow towards and tangentially along the inner surface of the secondary diffuser 125

Figure 5.22: Available augmentation comparison for the original CFD model, the refined CFD model and wind tunnel data for the second generation DAWT 126

Figure 5.23: Streamline plot for the refined CFD model of the second generation DAWT at a local disc loading coefficient of 0.7. 127

Figure 5.24: Velocity vector plot for the refined CFD model of the second generation DAWT at a local disc loading coefficient of 0.5. 127

Figure 5.25: Schematic diagram showing the generic flow behaviour through the multi-slotted DAWT 129

Figure 5.26: CFD velocity plot of the third generation multi-slotted diffuser concept. 130

Figure 5.27: Wind tunnel model of the multi-slotted DAWT shown with a gauze screen having a local disc loading coefficient of 1.0. 131

Figure 5.28: The V2 2 m diameter truck-testing-prototype of the multi-slotted DAWT. A gauze screen having a local disc loading coefficient of 1.0 is shown. The measurement boom mounted at the 180° position from the rear of the centrebody is also visible 131

Figure 5.29: Gauze screen having a radial distribution in local disc loading coefficient. Screen S2 which uses 5 annular rings to approximate a linear variation in local disc loading coefficient from 1.5 at the centrebody to 0.5 at the screen periphery is shown 132

Figure 5.30: Augmentation of the multi-slotted DAWT with uniform local disc loading gauze screens, together with one-dimensional theoretical predictions using the area weighted average exit pressure coefficient measured under peak augmentation conditions. The V2 2 m diameter

truck-testing-prototype data has been offset from the 1.0 disc loading coefficient examined to aid clarity.......133

Figure 5.31: Velocity speed-up distribution across the blade-plane of the multi-slotted DAWT operating under a uniform local disc loading coefficient of 1.0.......134

Figure 5.32: The augmentation obtained for three different non-uniform disc loading distributions. The distributions from root to tip are 1.24-0.9, 1.5-0.5 and 0.5-1.5 for screens S1, S2 and S3 respectively. The non-uniform screen data has been offset from their average local disc loading coefficient of 1.0 in order to aid clarity.......136

Figure 5.33: Comparison of the relative velocity speed-up distribution across the blade-plane for CFD prediction of the second generation DAWT and modified Vortec 7 along with wind tunnel data for the multi-slotted DAWT at local disc loading coefficients corresponding to peak augmentation of each geometry.......138

Figure 5.34: Averaged velocity speed-up across the blade-plane of the wind tunnel multi-slotted DAWT for all uniform disc loading screens wind tunnel tested.......139

Figure 5.35: Effect of different variable disc loading distributions on radial velocity speed-up for the wind tunnel multi-slotted DAWT.......140

Figure 5.36: Flow visualisation at the exit-plane of the Vortec 7 under low disc loading indicating separation from the diffuser wall and a recirculation zone at the centrebody.......142

Figure 5.37: Flow visualisation at the exit-plane of the Vortec 7 under high disc loading indicating a strong radial flow component at the diffuser exit with no separation in the vicinity of the diffuser wall and a pronounced recirculation zone at the centrebody.......142

Figure 5.38: Static pressure distribution along the inner surface of the wind tunnel multi-slotted DAWT with no screen.......143

Figure 5.39: Static pressure distribution along the inner surface of the wind tunnel multi-slotted DAWT under a local disc loading coefficient of 0.68.......144

Figure 5.40: Static pressure distribution along the inner surface of the wind tunnel multi-slotted DAWT under a local disc loading coefficient of 1.0. 144

Figure 5.41: Static pressure distribution along the inner surface of the wind tunnel multi-slotted DAWT under a local disc loading coefficient of 2.3. 145

Figure 5.42: The local velocity adjacent to the diffuser wall of the wind tunnel multi-slotted DAWT for various disc loading coefficients relative to the average velocity across the blade-plane. 146

Figure 5.43: Static pressure distribution of the wind tunnel multi-slotted DAWT immediately downstream of the gauze screen for various uniform disc loading coefficients. 147

Figure 5.44: The influence of disc loading on the average velocity speed-up through the blade-plane of the multi-slotted DAWT. 148

Figure 5.45: Available augmentation ratio to mass-flow ratio of the wind tunnel multi-slotted DAWT. 149

Figure 5.46: Area weighted average exit pressure coefficients for the wind tunnel multi-slotted DAWT under gauze screen testing for various disc loading coefficients. 150

Figure 5.47: The relationship between the diffuser exit pressure coefficient and exit velocity ratio squared for the wind tunnel multi-slotted DAWT at various local disc loading coefficients. 151

Figure 5.48: Influence of wind tunnel wall interference and blockage on the average diffuser exit pressure coefficient for the second generation DAWT wind tunnel model and CFD predictions at various local disc loading coefficients. 153

Figure 5.49: Influence of wind tunnel wall interference and blockage on the average augmentation for the second generation DAWT wind tunnel model at various local disc loading coefficients. 153

Figure 6.1: Velocities and local forces acting on a blade-element. 160

Figure 6.2: Comparison of the empirically-derived velocity speed-up for various disc loading coefficients with wind tunnel data for the multi-slotted DAWT. 163

Figure 6.3: Comparison of the augmentation derived from the empirical velocity speed-up equation with data obtained from wind tunnel testing using uniform disc loading gauze screens over a range of local disc loading coefficients for the multi-slotted DAWT. 163

Figure 6.4: Comparison of the empirically-derived velocity speed-up against wind tunnel data for the multi-slotted DAWT with non-uniform disc loading screens. 164

Figure 6.5: Lift and drag data for the SELIG S-3021-095-84 profile using the Viterna-Corrigan [109] model extrapolation for post-stall data for a Reynolds number of 1 x 10^5. 167

Figure 6.6: Three-dimensional CAD model of the DAWT wind tunnel blade....................168

Figure 6.7: Variation in shaft power coefficient with tip-speed ratio for the wind tunnel DAWT rotor operating as a conventional bare turbine at 6.7° pitch. 169

Figure 6.8: Radial variation in the velocity speed-up immediately downstream of the DAWT rotor operating as a conventional bare turbine at 4.7° pitch. 170

Figure 6.9: Radial variation in the local disc loading coefficient across the blade-plane of the DAWT rotor operating as a conventional bare turbine at 4.7° pitch....................170

Figure 6.10: Variation in shaft augmentation with tip-speed ratio for the wind tunnel multi-slotted DAWT at 6.7° pitch for free-stream wind speeds ranging from 7.5 m/s to 9.5 m/s. 171

Figure 6.11: Variation in shaft augmentation with tip-speed ratio for the V2 2 m diameter truck-testing-prototype multi-slotted DAWT at 7.0° pitch at a free-stream wind speed of 12 m/s. 172

Figure 6.12: Variation in available augmentation with tip-speed ratio for the wind tunnel multi-slotted DAWT at 6.7° pitch for free-stream wind speeds ranging from 7.5 m/s to 9.5 m/s. 173

Figure 6.13: Variation in available augmentation with tip-speed ratio for the V2 2 m diameter truck-testing-prototype multi-slotted DAWT at 7.0° pitch at a free-stream wind speed of 12 m/s. 173

Figure 6.14: Variation in shaft augmentation with tip-speed ratio for pitch angles ranging from 4.7° to 29.7° on the wind tunnel multi-slotted DAWT. 174

Figure 6.15: Variation in shaft augmentation with tip-speed ratio for pitch angles ranging from 0.5° to 15.0° on the V2 2 m diameter truck-testing-prototype............175

Figure 6.16: Comparison of the available augmentation for the wind tunnel multi-slotted DAWT under rotor operation at the design pitch angle of 6.7° and under gauze screen simulation. 176

Figure 6.17: Available augmentation ratio to mass-flow ratio of the multi-slotted DAWT wind tunnel data and ideal conventional bare turbine calculation. 177

Figure 6.18: Comparison of the static pressure distribution along the inner surface of the multi-slotted DAWT under rotor operation at 6.7° pitch and with gauze screen simulation............177

Figure 6.19: Variation in shaft torque divided by the local velocity squared (swirl) with local disc loading coefficient for the wind tunnel multi-slotted DAWT at 6.7° pitch at various free-stream wind velocities............178

Figure 6.20: Variation in the average local disc loading coefficient with tip-speed ratio for the wind tunnel multi-slotted DAWT at 6.7° pitch............179

Figure 6.21: Variation in local disc loading distribution across the rotor blade-plane of the wind tunnel multi-slotted DAWT for various tip-speed ratios. Tip-speed ratios of 4.5, 6 and 8 correspond to average local disc loading coefficients of 0.70, 1.0 and 1.3 respectively. 181

Figure 6.22: Comparison of the exit velocity distributions of the wind tunnel multi-slotted DAWT under gauze screen simulation and rotor operation at 6.7° pitch. 182

Figure 6.23: Comparison of the area weighted average exit pressure coefficients for the wind tunnel multi-slotted DAWT under rotor operation at 6.7° pitch with those obtained under uniform gauze screen simulation. 183

Figure 6.24: Comparison of the shaft augmentation for the modified blade-element prediction and wind tunnel data for the multi-slotted DAWT at the design pitch of 6.7°. 184

Figure 6.25: Comparison of the shaft augmentation for the modified blade-element prediction and V2 2 m diameter truck-testing-prototype at the design pitch of 7.0°. 185

Figure 6.26: Comparison of the shaft augmentation for the modified blade-element prediction and wind tunnel data for the multi-slotted DAWT at the finer pitch of 4.7°. 186

Figure 6.27: Comparison of the shaft augmentation for the modified blade-element prediction and wind tunnel data for the multi-slotted DAWT at the coarser pitch of 10.7° 186

Figure 6.28: Comparison of the shaft augmentation for the modified blade-element prediction and V2 2 m diameter truck-testing-prototype at the finer pitch of 5.0°. 187

Figure 6.29: Comparison of the shaft augmentation for the modified blade-element prediction and V2 2 m diameter truck-testing-prototype at the coarser pitch of 10.0°. 187

Figure 6.30: Comparison of shaft augmentation for the wind tunnel DAWT rotor operating as a conventional bare turbine at 6.7° pitch against the standard blade-element prediction using lift and drag data from Simons [108] (Figure 6.5). 188

Figure 6.31: Comparison of the original and modified lift and drag data for the SELIG S-3021-095-84 profile. The modified data assumes an earlier onset of stall. Extrapolation of the post-stall data has been made following the Viterna-Corrigan model. 189

Figure 6.32: Comparison of shaft augmentation for the wind tunnel DAWT rotor operating as a conventional bare turbine at 6.7° pitch against the standard blade-element prediction using the modified lift and drag data presented in (Figure 6.31). 190

Figure 6.33: Comparison of the predicted shaft augmentation for the modified blade-element method using modified lift and drag data against results from the wind tunnel testing of the multi-slotted DAWT at 6.7° pitch. 191

Figure 6.34: Comparison of the velocity speed-up across the blade-plane of the wind tunnel multi-slotted DAWT at pitch angles of 4.7°, 6.7° and 10.7°. 192

Figure 6.35: Comparison of the exit velocity ratios for the wind tunnel multi-slotted DAWT at pitch angles of 4.7°, 6.7° and 10.7°..192

Figure 7.1: Influence of Reynolds number on the peak average available and shaft augmentations for the wind tunnel multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio. 197

Figure 7.2: Influence of Reynolds number on the peak average shaft augmentation for the wind tunnel multi-slotted DAWT and V2 2 m diameter truck-testing-prototype under rotor operation at the optimal pitch and tip-speed ratio..197

Figure 7.3: Influence of Reynolds number on the pressure coefficient on the inner surface of the wind tunnel multi-slotted DAWT with no screen or rotor present in the diffuser. 198

Figure 7.4: Influence of Reynolds number on the pressure coefficient on the inner surface of the wind tunnel multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio. 198

Figure 7.5: Influence of Reynolds number on the exit pressure coefficient for the wind tunnel multi-slotted DAWT and V2 2 m diameter truck-testing-prototype under rotor operation at their respective optimal pitch and tip-speed ratio. 199

Figure 7.6: Influence of turbulence intensity on the pressure coefficient on the inner surface of the wind tunnel multi-slotted DAWT with no screen or rotor present within the diffuser. 201

Figure 7.7: Influence of turbulence intensity on the velocity speed-up through the wind tunnel multi-slotted DAWT with no screen or rotor present within the diffuser..201

Figure 7.8: Influence of turbulence intensity on the pressure coefficient on the inner surface of the wind tunnel multi-slotted DAWT under gauze screen simulation at a local disc loading coefficient of 1.0. 202

Figure 7.9: Influence of turbulence intensity on the pressure coefficient on the inner surface of the wind tunnel multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio. 202

Figure 7.10: Influence of turbulence intensity on the exit pressure coefficient for the wind tunnel multi-slotted DAWT under both gauze screen simulation and rotor operation at the optimal pitch and tip-speed ratio............................203

Figure 7.11: Comparison of the relative shaft augmentation for the wind tunnel multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio for yaw angles between ±60° with 2% turbulence intensity against the cosine-cubed relation for a conventional bare turbine..................205

Figure 7.12: Comparison of the relative shaft augmentation for the wind tunnel multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio for yaw angles between ±40° with 15% turbulence intensity against the cosine-cubed relation for a conventional bare turbine..................205

Figure 7.13: Comparison of the relative shaft augmentation for the wind tunnel multi-slotted DAWT with 15% turbulence intensity in the onset flow and the V2 2 m diameter truck-testing-prototype under rotor operation at the optimal pitch and tip-speed ratio for yaw angles between ±40° against the cosine-cubed relation for a conventional bare turbine..................206

Figure 7.14: Comparison of pressure coefficients at various azimuths on the inner surface, within the diffuser cavity and on the external surface of the wind tunnel multi-slotted DAWT at 0° yaw under rotor operation at the optimal pitch and tip-speed ratio. 207

Figure 7.15: Comparison of pressure coefficients at various azimuths on the inner surface, within the diffuser cavity and on the external surface of the wind tunnel multi-slotted DAWT at 15° yaw under rotor operation at the optimal pitch and tip-speed ratio..207

Figure 7.16: Comparison of pressure coefficients at the leeward (91°) and windward (271°) azimuthal sectors on the inner surface, within the diffuser cavity and on the external surface of the wind tunnel multi-slotted DAWT at 45° yaw under rotor operation at the optimal pitch and tip-speed ratio...208

Figure 7.17: Influence of ground proximity on the peak average shaft augmentation for the wind tunnel multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio for both a uniform onset flow with 2% turbulence intensity and a boundary-layer profile with 15% nominal turbulence intensity...210

Figure 8.1: Various external surface geometries examined on the wind tunnel multi-slotted DAWT....215

Figure 8.2: An example of a radial exit flap incorporated onto the wind tunnel multi-slotted DAWT....215

Figure 8.3: Comparison of exit pressure coefficient with variation in external surface geometry on the wind tunnel multi-slotted DAWT under gauze screen simulation and rotor operation at the optimal pitch and tip-speed ratio....216

Figure 8.4: Comparison of augmentation with variation in external surface geometry on the wind tunnel multi-slotted DAWT under gauze screen simulation and rotor operation at the optimal pitch and tip-speed ratio....217

Figure 8.5: Influence of external surface geometry on the pressure coefficient on the inner surface of the wind tunnel multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio....217

Figure 8.6: Comparison of exit pressure coefficient with variation in exit flap width for the 0° radial flaps on the wind tunnel multi-slotted DAWT under gauze screen simulation and rotor operation at the optimal pitch and tip-speed ratio....219

Figure 8.7: Comparison of augmentation with variation in exit flap width for the 0° radial flaps on the wind tunnel multi-slotted DAWT under gauze screen simulation and rotor operation at the optimal pitch and tip-speed ratio....219

Figure 8.8: Influence of exit flap width for the 0° radial flaps on the pressure coefficient on the inner surface of the wind tunnel multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio....220

Figure 8.9: Comparison of augmentation with variation in exit flap width and orientation on the wind tunnel multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio....221

Figure 8.10: The four simple diffuser wall shapes: (a) straight, (b) bell-shaped, (c) trumpet-shaped and (d) inflected-wall....225

Figure 8.11: Comparison of the theoretical static pressure distribution for the multi-slotted DAWT diffuser with the ideal linear distribution of a trumpet-shaped diffuser....226

Figure 8.12: Influence of boundary-layer control using blowing on the pressure coefficient on the inner surface of the wind tunnel multi-slotted DAWT with no screen or rotor present. 230

Figure 8.13: Influence of boundary-layer control using blowing on the pressure coefficient on the inner surface of the wind tunnel multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio. 230

Figure 8.14: Impact of boundary-layer control on the exit velocity profiles of the wind tunnel multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio. 231

Figure 8.15: Impact of boundary-layer control on the velocity speed-up profiles across the blade-plane of the wind tunnel multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio. 231

Figure 8.16: Impact of boundary-layer control on the shaft augmentation of the wind tunnel multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio. 232

Figure 8.17: Variation in peak shaft augmentation for 3 mm, 6 mm and 9 mm boundary-layer control slot heights on the V2 2 m diameter truck-testing-prototype under rotor operation at the optimal pitch and tip-speed ratio. 233

Figure 8.18: Schematic diagram depicting the flow pattern observed on the multi-slotted DAWT where the slot flow remains attached to the diffuser wall whilst the core flow forms a jet-type flow with stalled or recirculating flow in between. 234

Figure 8.19: Schematic diagram of the multi-slotted DAWT cross-sectional geometry for the original exit-area-ratio of 3.0 and the truncated exit-area-ratios of 1.42, 1.83 and 2.5. 236

Figure 8.20: Variation in available augmentation with overall DAWT exit-area-ratio for the various wind tunnel multi-slotted DAWTs and flap combinations in terms of diffuser exit-area-ratio under rotor operation at the optimal pitch and tip-speed ratio. 237

Figure 8.21: Variation in available augmentation with overall DAWT exit-area-ratio for the various wind tunnel multi-slotted DAWTs and flap

combinations in terms of flap width under rotor operation at the optimal pitch and tip-speed ratio. 238

Figure 8.22: Variation in exit pressure coefficient with overall DAWT exit-area-ratio for the various wind tunnel multi-slotted DAWTs and flap combinations in terms of diffuser exit-area-ratio under rotor operation at the optimal pitch and tip-speed ratio. 239

Figure 8.23: Influence of diffuser exit-area-ratio on the pressure coefficient on the inner surface of the wind tunnel multi-slotted DAWT with 5% exit flap under rotor operation at the optimal pitch and tip-speed ratio. 240

Figure 8.24: Influence of flap width on the pressure coefficient on the inner surface of the wind tunnel multi-slotted DAWT with diffuser exit-area-ratio of 1.83 under rotor operation at the optimal pitch and tip-speed ratio. 240

Figure 8.25: Variation in average velocity speed-up with overall DAWT exit-area-ratio for the various wind tunnel multi-slotted DAWTs and flap combinations in terms of diffuser exit-area-ratio under rotor operation at the optimal pitch and tip-speed ratio. 241

Figure 8.26: Influence of diffuser exit-area-ratio on the velocity speed-up distribution across the blade-plane of the wind tunnel multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio. 242

Figure 8.27: Influence of flap width on the velocity speed-up distribution across the blade-plane of the wind tunnel multi-slotted DAWT with diffuser exit-area-ratio of 3.0 under rotor operation at the optimal pitch and tip-speed ratio. 242

Figure 8.28: Influence of flap width on the velocity speed-up distribution across the blade-plane of the wind tunnel multi-slotted DAWT with diffuser exit-area-ratio of 1.42 under rotor operation at the optimal pitch and tip-speed ratio. 243

Figure 8.29: The standard NACA0024 centrebody used on the multi-slotted DAWT (a), the slotted centrebody (b) and the large diameter Joukowski profiled centrebody (c). 247

Figure 8.30: Comparison of the velocity speed-up profiles in the multi-slotted DAWT for different centrebody geometries. 248

Figure 8.31: Wind tunnel model of the second generation DAWT showing initial mounting with central column and three aerodynamically profiled internal struts (a) and the subsequent mounting using external supports (b). 249

Figure 8.32: Comparison of diffuser performance when mounted with streamlined supports located within the diffuser flow against the performance with the diffuser mounted via external supports. 250

Figure 8.33: Comparison of the velocity speed-up distribution across the blade-plane for the 0° and 180° sectors of the V2 2 m diameter truck-testing-prototype under a uniform local disc loading coefficient of 1.0. 251

Figure 8.34: Schematic diagram comparing the Mo multi-slotted DAWT geometry with that of the original multi-slotted DAWT. 252

Figure 8.35: Comparison of the pressure recovery through the wind tunnel Mo multi-slotted DAWT and the original multi-slotted DAWT with no screen or rotor present. 253

Figure 8.36: Comparison of the pressure coefficient on the inner surface of the wind tunnel Mo multi-slotted DAWT and the original multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio. 254

Figure 8.37: Comparison of the shaft power augmentation of the wind tunnel Mo multi-slotted DAWT and the original multi-slotted DAWT under rotor operation at the optimal pitch. 255

Figure 8.38: Comparison of the radial variation in velocity speed-up across the blade-plane of the wind tunnel Mo multi-slotted DAWT and the original multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio. 255

Figure 8.39: Comparison of the radial variation in the local disc loading coefficient across the blade-plane of the wind tunnel Mo multi-slotted DAWT and the original multi-slotted DAWT under rotor operation at the optimal pitch and tip-speed ratio. 256

Figure 9.1: Schematic diagram of The University of Auckland Twisted Flow Wind Tunnel showing the location of the model, reference instrumentation and naming definitions for yaw, lift (or side) force and drag forces. 260

Figure 9.2: Variation in drag coefficient with yaw angle for the wind tunnel multi-slotted DAWT under non-operating conditions. 261

Figure 9.3: Variation in lift force coefficient with yaw angle for the wind tunnel multi-slotted DAWT under non-operating conditions. 261

Figure 9.4: Three-dimensional bodies analogous to the multi-slotted DAWT when yawed from 0° to 180° relative to the onset flow. Shown in relation to the onset flow are: a washer (a), a three-dimensional cone (b), a cylinder in cross-flow (c) and a hemispherical cup (d)....263

Figure 9.5: Comparison of overall drag coefficient for the wind tunnel multi-slotted DAWT for non-operating and operating conditions using gauze screens to simulate the presence of an operating turbine....264

Figure 9.6: Variation in diffuser-only drag coefficient with disc loading coefficient for the wind tunnel multi-slotted DAWT under gauze screen simulation. 265

Figure 9.7: Comparison of exit pressure coefficient and diffuser-only drag coefficient for the wind tunnel multi-slotted DAWT under gauze screen simulation at various disc loading coefficients. 265

Figure 9.8: Comparison of the pressure coefficient on the inner surface of the wind tunnel multi-slotted DAWT under non-operating conditions and operation at the optimal pitch and tip-speed ratio. 266

Figure 9.9: Comparison of diffuser-only drag coefficient, average velocity speed-up and exit pressure coefficient against local disc loading coefficient for the wind tunnel multi-slotted DAWT under gauze screen simulation....267

Figure 9.10: Comparison of drag coefficient in terms of rotor area against exit-area-ratio with augmentation overlaid for the multi-slotted DAWT under non-operating conditions. 268

Figure 9.11: Variation in drag coefficient with yaw angle for the wind tunnel multi-slotted DAWT and the Mo multi-slotted DAWT under non-operating conditions....269

Figure 9.12: Variation in drag coefficient with yaw angle for the wind tunnel multi-slotted DAWT and the Mo multi-slotted DAWT under operating conditions....269

Figure 9.13: Variation in DAWT cost of energy with exit-area-ratio for the multi-slotted DAWT under peak operating conditions. 271

Figure 9.14: Variation in DAWT cost of energy with exit-area-ratio for the multi-slotted DAWT under peak operating conditions assuming the drag coefficient is reduced to one-fifth at the extreme loading condition. 271

Figure A.1: Comparison of available air power coefficient against turbine pressure drop coefficient for the CFD of a conventional bare turbine model and the one-dimensional actuator disc theory. 306

Figure B.2: Plan view (a) showing chord distribution and rear view (b) showing the twist distribution of the V2 2 m diameter truck-testing-prototype blade. 312

Figure B.3: Schematic diagram of the double-skinned multi-slotted diffuser geometry showing the main geometric features. 314

Figure B.4: V2 2 m diameter truck-testing-prototype drive-train and instrumentation assembly. Rotor, hub, torque and thrust components are visible in (a) with alternator and instrumentation unit in (b). 315

Figure B.5: Example of grid to generate uniform turbulence in wind tunnel. 316

Figure B.6: Wind tunnel set-up showing trip-board and roughness elements for generation of a boundary-layer profile 316

Figure B.7: Schematic diagram of The University of Auckland Twisted Flow Wind Tunnel showing the location of the model, reference instrumentation and naming definitions. 317

Figure B.8: Turbulence spectrum of the bare tunnel configuration indicating a turbulence intensity of 1.75% and a length scale of 0.146 m 318

Figure B.9: Turbulence spectrum of the uniform grid generated turbulence tunnel configuration indicating a turbulence intensity of 15.04% and a length scale of 0.206 m. 319

Figure B.10: Velocity profile for Terrain Category 2 and wind tunnel comparison. 319

Figure B.11: Turbulence intensity profile for Terrain Category 2 and wind tunnel comparison. 320

Figure B.12: Testing of the V2 2 m diameter truck-testing-prototype showing the three sets of reference anemometry and RF link in (a) with the truck and trailer testing in (b). 321

Figure B.13: Field testing of the V2 2 m diameter multi-slotted DAWT prototype. 322

Figure B.14: Schematic diagram showing definition of diffuser reference positions. 323

Figure B.15: Total and static pressure probe pairs shown in (a) & (b) mounted on the V2 2 m diameter truck-testing-prototype. Schematic diagrams of the total (c) and static (d) pressure probe designs used to measure the swirling flow within the multi-slotted DAWT. 325

Figure B.16: Error in velocity for yaw and pitch offset calculated for each total and static probe pair 326

Figure B.17: Schematic diagram of hotwire and pressure probe locations together with pressure transducer pneumatic connection. 326

Figure B.18: Diffuser cross-section showing surface static pressure tap locations and nomenclature 327

Figure B.19: Rear view of diffuser showing azimuthal location of surface static pressure taps 328

Figure B.20: Alignment of surface static pressure taps in the streamwise direction. 328

Figure B.21: Wind tunnel set-up for gauze screen calibration. 330

Figure B.22: Test section showing partially removed gauze screen. 330

List of Tables

Table 1.1: World Market Growth rates 1995-2002....2

Table 1.2: Growth rates in the top-10 markets by installed capacity. 3

Table 3.1: Theoretical investigations into Diffuser Augmented Wind Turbines....25

Table 3.2: Computational investigations on Diffuser Augmented Wind Turbines. 25

Table 3.3: Experimental investigations on Diffuser Augmented Wind Turbines. 26

Table 3.4: Theoretical performance parameters for an augmentation of 7 by a DAWT with exit-area-ratio of 2.78. 65

Table 3.5: Summary of Experimental Results and Optimal Configurations obtained by Igra, Lewis et al and Grumman. Included are the author's reinterpretations of Grumman's Baseline DAWT and DAWT 45 based on averaged data and correction for the inlet velocity measurement error. Table headings are: length-to-diameter ratio, exit-area-ratio, available augmentation, shaft power augmentation, diffuser efficiency, rotor efficiency, exit pressure coefficient, local disc loading coefficient, free-stream disc loading coefficient and velocity speed-up. 80

Table 5.1: Comparison of the experimental results of Igra, Lewis et al and Grumman with those of the multi-slotted DAWT. Included is the author's interpretations for Grumman's DAWT 45 based on averaged data and correction for the inlet velocity measurement error. Table headings are: length-to-diameter ratio, exit-area-ratio, available augmentation, diffuser efficiency, exit pressure coefficient, local disc loading coefficient, free-stream disc loading coefficient and velocity speed-up....154

Table 6.1: Blade geometries investigated on the 0.48 m diameter wind tunnel multi-slotted DAWT and the V2 2 m diameter truck-testing-prototype. The table headings, t/c and Ct_2 are the section thickness-to-chord ratio and local disc loading coefficient respectively. 166

Table 8.1: Description of centrebody configurations 247

Table B.1: Blade geometries investigated on the 0.48 m diameter wind tunnel multi-slotted DAWT and the V2 2 m diameter truck-test-prototype. 313