EFFECT OF LEADING EDGE TUBERCLES ON AIRFOIL PERFORMANCE

By

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A Thesis submitted in fulfilment of the requirements for the
Degree of Doctor of Philosophy

SCHOOL OF MECHANICAL
ENGINEERING

THE UNIVERSITY
of ADELAIDE

July 2012

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Abstract of thesis

This thesis provides a detailed account of an experimental investigation into the effects of leading edge sinusoidal protrusions (tubercles) on the performance of airfoils. The leading edge geometry was inspired by the morphology of the Humpback whale flipper, which is a highly acrobatic species. The aim of this study is to investigate the potential advantages and disadvantages of incorporating tubercles into the leading edge of an airfoil. Specific parameters have been varied to identify an optimum tubercle configuration in terms of improved lift performance with minimal drag penalties.

The investigation has shown that for all tubercle arrangements investigated, increased lift performance in the post-stall regime comes at the expense of degraded lift performance in the pre-stall regime. However, it has also been noted that through optimizing the amplitude and wavelength of the tubercles, pre-stall lift performance approaches the values attained by the unmodified airfoil and post-stall performance is much improved. In general, the configuration which demonstrates the best performance in terms of maximum lift coefficient, maximum stall angle and minimum drag has the smallest amplitude and wavelength tubercles. A new alternative modification has also been explored, whereby sinusoidal surface waviness is incorporated into the airfoil, giving a spanwise variation in local attack angle. Results indicate that optimisation of this configuration leads to similar performance advantages as the best-performing tubercle configuration. It is believed that the flow mechanism responsible for performance variation is similar to tubercles.

The deterioration in pre-stall performance for airfoils with tubercles in the current study has been explained in terms of Reynolds number effects and also the relatively weak spanwise flow in the boundary layer. In swept and tapered wings such as the Humpback whale flipper, spanwise flow occurs along the entire span, so the effect of tubercles can be expected to be much larger.

Surface pressure measurements have indicated that the region of separation and reattachment for airfoils with tubercles is restricted to the trough between the tubercles rather than extending across the entire span. Hence, leading-edge separation is initiated at the troughs but occurs at a higher angle of attack for other locations, leading to a delayed overall stall for airfoils with tubercles. In addition, integration of the surface pressures along the airfoil chord has indicated that lift, and hence circulation, varies with spanwise position, providing suitable conditions for the formation of streamwise vorticity. A spanwise variation in circulation is also predicted for the wavy airfoil since the relative angle of attack varies along the span.

Counter-rotating streamwise vortices have been identified in the troughs between tubercles using particle image velocimetry in a series of cross-streamwise, cross-chordwise planes which have not been investigated previously using this technique. The associated peak primary vorticity and circulation have been found to increase with angle of attack for a given measurement plane. This provides an explanation for the effectiveness of tubercles post-stall since an increased primary vortex strength leads to a greater boundary layer momentum exchange. The results show that the magnitude of the circulation generally increases in the streamwise direction, except when there exist secondary vortex structures of opposite sign on the flow side of the primary vortices. A proposed mechanism for this increasing circulation of the primary vortices is the entrainment of secondary vorticity which is generated between the adjacent primary vortex and the airfoil surface. It is postulated that this process of entrainment alternates between the primary vortices in an unsteady fashion.

Leading edge tubercles have also been found to mitigate tonal noise associated with the NACA 0021 and the NACA 65-021 at all angles of attack in a novel investigation. Elimination of the tonal noise occurred for the majority of modified airfoils and in many cases the broadband noise level was also reduced for certain frequency ranges. It is believed that tonal noise elimination is facilitated by the presence of the streamwise vortices and that the spanwise variation in separation location is also an important factor. Both characteristics modify the stability characteristics of the boundary layer, altering the frequency of velocity fluctuations in the shear layer near the trailing edge. This affects the coherence of the vortex generation downstream of the trailing edge, hence leading to a decrease in trailing edge noise generation.

Statement of Originality

I, Kristy Lee Hansen certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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Kristy Lee Hansen
Date: January 2012

Acknowledgements

I would like to thank all who have helped me during my candidature. I am especially grateful to my supervisors Associate Professor Richard Kelso and Associate Professor Bassam Dally for giving me the opportunity to work on this project and for their contribution and advice. I am also sincerely grateful to my father, Professor Colin Hansen, who continually encouraged me and offered valuable technical support. I also appreciate the support of Associate Professor Con Doolan who made valuable contributions to this work.

I would also like to thank the School's workshop staff, in particular Bill Finch for machining my airfoils with such perfection. I am also grateful to Dave Osborne for building by force measurement apparatus. In addition, I will never forget the workshop humour which always seemed to lift my spirits.

Thanks to my colleagues for their help and support both technically and emotionally. I'm especially grateful to those who engaged in complex intellectual discussions with me, which challenged my ideas and perceptions and broadened my understanding of the topic. I also appreciate those who listened to me asking a question, which I subsequently answered myself simply because I was given the opportunity to communicate my misunderstanding. In addition, I am thankful to those who passed on their knowledge of experimental apparatus, helping me to progress more efficiently.

Finally, thanks to my family and friends for being there for me and for believing in me. Especially to those who stopped asking me when I was going to finish and also expressed an interest in my topic. I also appreciate the encouragement of dear Damon Shokri who convinced me to publish despite my claims that my work was not ready for that. From this moment, I realised that the true value of my work could never be realised until I shared it with others.

Nomenclature

a_o	speed of sound = 343m/s
A	tubercle amplitude
b	airfoil span
c	airfoil chord
c	Pitot probe centreline
$\overline{c}$	mean airfoil chord
c_i	sensitivity coefficient
c_r	convection velocity of boundary layer instabilities
C	cross-sectional area of wind tunnel
C_{Cf}	chordwise component of form drag coefficient
C_D	drag coefficient
C_{Di}	induced drag coefficient
C_{Du}	uncorrected drag coefficient.
C_L	lift coefficient
C_{Lmax}	maximum lift coefficient
C_{Lu}	uncorrected lift coefficient
$\Delta C_{L,sc}$	change in lift coefficient due to streamline curvature
$C_{M_{1/4}}$	pitching moment coefficient at the quarter-chord position
$C_{M_{1/4}u}$	uncorrected pitching moment coefficient
C_N	normal coefficient
C_p	pressure coefficient
d	Pitot tube diameter
d_{diff}	diffraction limited image diameter
d_o	distance between object and image planes
d_p	particle diameter
d^+	non-dimensional Pitot diameter
D	drag
D_a	aperture diameter.
D_i	diagonal of camera sensor frame
D_o	diagonal of object plane

f	frequency
f	camera focal length
f_n	discrete frequency related to primary tonal peak
f_s	peak tonal frequency
$f_\#$	f-number
F_C	chordwise force
F_N	normal force
h_{eff}	effective tubercle height
h	height of wind tunnel test section
h_{max}	airfoil camber
H	shape factor
H	height of wind-tunnel jet
l_c	height or width of CCD array
L	lift
L	suitable length scale
L_c	characteristic length
L	length of aeroacoustic feedback loop
$(L/c)_p$	normalised length of separation bubble on pressure surface
$(L/c)_\mathrm{s}$	normalised length of separation bubble on suction surface
k	roughness height
k	coverage factor
M	magnification factor
n	total number of measurements
n_v	number of vectors across the diameter of a vortex
N_{IW}	number of interrogation windows across image
p	pressure at airfoil surface
p_∞	freestream statics pressure
q	dynamic pressure
s^+	spanwise spacing between riblets in wall units
s	spanwise spacing between riblets
r_i	residual
r_m	median residual
r_o	conversion factor between pixel units at CCD array to mm

r_0^*	normalised residual
R	half-width of wind tunnel.
Re	Reynolds number
Re_x	Reynolds number based on boundary layer development length
Re_{δ^*}	Reynolds number based on boundary layer displacement thickness
Re_θ	Reynolds number based on boundary layer momentum thickness
S	planform area
Stk	Stokes number
t	airfoil thickness
ΔT	time delay between laser pulses
Tu	turbulence intensity
u	velocity component in streamwise (x) direction
u_c	combined standard uncertainty
u_k	velocity of flow at top of roughness element
u_τ	frictional velocity
U	expanded uncertainty
U_c	characteristic velocity
U_i	uncertainty component
U_∞	freestream velocity
$\overline{u'}$	average fluctuating velocity component in streamwise (x) direction
v	velocity component in vertical (y) direction
v	degrees of freedom
v_{eff}	effective degrees of freedom
v_s	particle settling velocity
v_0'	estimated vector for outlier replacement
$\overline{v'}$	average fluctuating velocity component in vertical (y) direction
$\tilde{v}$	"smoothed" vector value determined using an adaptive Gaussian window
V	volts
$\vec{V}_m$	local median velocity vector
$\vec{V}_0$	central displacement vector
V_u	uncorrected velocity
ΔV	axial velocity due to doublet

w	downwash velocity component
w	velocity component in spanwise (z) direction
$w_{i,j}$	weighting coefficient
$\overline{w'}$	average fluctuating velocity component in spanwise (z) direction
W	out-of-plane component of velocity
x	streamwise distance
$\overline{x}$	mean of data set
x_m	single measurement
x/c	non-dimensional chordwise distance
y	vertical distance
y_c	distance from wall to probe centreline
$\mathrm{y}+$	non-dimensional wall distance
Δy	streamline displacement correction
z	spanwise distance
Δz	light sheet thickness
ΔZ_0	light sheet thickness
α	angle of attack
α	non-dimensional velocity gradient
α_*	true angle of attack
$\Delta\alpha_{sc}$	change in attack angle due to streamline curvature
α'	actual angle of flow for finite-span airfoil
$\Delta\alpha$	angle induced by downwash from tip vortices
κ	Von Karman’s constant
δ	boundary layer thickness
δ	buffer to account for laser jitter
δ^*	boundary layer displacement thickness
$\delta_{\Delta D}$	uncertainty in displacement
δ_e	uncertainty in particle image diameter
δ_g	uncertainty due to velocity gradient
δ_m	magnification uncertainty
δ_N	uncertainty due to sub-optimal particle seeding
δ_p	actual position of the particle

δ_p	perspective uncertainty
δ_t	uncertainty due to laser “jitter”
δ_w	wall proximity correction
ε	angular misalignment of load cell axes
ε	compensating factor for normalised median test
$\varepsilon_{\Delta D}$	relative uncertainty in displacement
ε_e	relative uncertainty in particle image diameter
ε_g	relative uncertainty due to velocity gradient
ε_m	relative magnification uncertainty
ε_N	relative uncertainty due to sub-optimal particle seeding
ε_p	relative perspective uncertainty
ε_t	relative uncertainty due to laser “jitter”
ε_u	random velocity error
ε_{sb}	solid blockage of model in wind tunnel
ε_{wb}	wake blockage of model in wind tunnel
$\varepsilon_{\Gamma\text{-}random}$	random error in circulation
$\varepsilon_{\Gamma\text{-}bias}$	bias error in circulation
$\varepsilon_{\omega\text{-}bias}$	bias error in vorticity
$\varepsilon_{\omega\text{-}rand}$	random error in vorticity
Γ	circulation
λ	tubercle wavelength
λ	wavelength of illuminating light
λ_2	shape factor
λ_0	noise transmission ratio
μ	dynamic viscosity
ν	kinematic viscosity
θ	relative rotation angle between a trough and peak for wavy airfoil
θ	boundary layer momentum thickness
ρ , ρ_f	fluid density
ρ_p	particle density
σ	standard deviation

σ_s	uncertainty in particle displacement
τ	particle relaxation time
τ_w	wall shear stress
ω	vorticity
ω_t	vorticity threshold or contour
ζ	similarity variable
Δ	horizontal/vertical grid spacing
$\Delta_{f\text{-}q}$	flashlamp q-switch delay

Table of Contents

Abstract of thesis....i
Statement of Originality.... iii
Acknowledgements....v
Nomenclature....vii
Table of Contents.... xiii
List of figures....xvii
List of tables....xxv
Chapter 1 Introduction to Flow Control....1
  1.1 Introduction....1
  1.2 Background....2
  1.3 Flow Control....3
  1.4 History and Development of Flow Control....4
  1.5 Classifications of Flow Control....6
  1.6 Passive Techniques....7
    1.6.1 Lift Enhancement....7
    1.6.2 Drag Reduction....14
  1.7 Active Techniques....16
    1.7.1 Lift Enhancement....17
    1.7.2 Drag Reduction....24
    1.7.3 Manipulation of Near Wall Viscosity....24
  1.8 Summary and Discussion of Passive/Active Techniques....25
  1.9 Purpose of Tubercles on Humpback Whale Flipper....27
  1.10 Potential Applications for Engineered Devices....29
Chapter 2 Review of Literature and Associated Patents....35
  2.1 Introduction....35
  2.2 Research into Tubercles....35
    2.2.1 Quantification of Performance Enhancement....36
    2.2.2 Influence of Tubercle Configuration on Airfoil Performance....39
    2.2.3 Finite Span Compared with Semi-Infinite Span Results....39
    2.2.4 Reynolds Number Effects....40
    2.2.5 Flow Patterns....41
    2.2.6 Mechanism of Flow Control....46
  2.3 Airfoil Tonal Noise....49
  2.4 Existing Patents....53
    2.4.1 Scalloped Wing Leading edge....53
    2.4.2 Scalloped Leading edge Advancements....53
    2.4.3 Scalloped Trailing Edge....54
    2.4.4 Turbine/Compressor Rotor with Leading edge Tubercles....55
    2.4.5 Spoked Bicycle Wheel....56
  2.5 Summary and Discussion....57
  2.6 Aims and objectives of current research....59
  2.7 Remainder of Thesis....62
  2.8 New Work in this Thesis....63
Chapter 3 Experimental Equipment and Methodology....65
  3.1 Introduction....65
  3.2 Airfoil Design....65

3.3 Force Measurements 72
3.3.1 Wind Tunnel 72
3.3.2 Boundary Layer Profile 73
3.3.3 Turbulence Intensity 79
3.3.4 Experimental Method for Force Measurements 80
3.3.5 Collection and Processing 82
3.3.6 Angular Misalignment Correction 83
3.3.7 Conversion of Rig to Test Half-Span Models 84
3.3.8 Boundary Layer Trip Design 85
3.3.9 Corrections of Wind Tunnel Effects for a Full-Span Model 86
3.3.10 Corrections of Wind Tunnel Effects for a Finite-Span Model 89
3.3.11 Force Measurement Uncertainty Analysis 94
3.4 Surface Pressure Measurements 98
3.4.1 Pressure Taps 99
3.4.2 Scanivalve 100
3.4.3 Pressure Tap Locations 101
3.4.4 Determining Lift and Form Drag From Pressure Distributions 103
3.4.5 Pressure Tap Uncertainty Analysis 104
3.5 Hydrogen Bubble Visualisation 105
3.5.1 Water Channel 105
3.5.2 Hydrogen Bubble Method 107
3.6 Particle Image Velocimetry 109
3.6.1 Specific Considerations for Airfoils with Tubercles 110
3.6.2 Thebarton Water Channel 112
3.6.3 Tracer Particles 114
3.6.4 Particle Image Size 116
3.6.5 Lasers 117
3.6.6 Light Sheet Optics 118
3.6.7 Time Delay Calculations 119
3.6.8 Timing and Synchronisation 120
3.6.9 Imaging System 121
3.6.10 PIV Image Processing 122
3.6.11 Post-Processing Techniques 124
3.6.12 Dynamic Velocity Range 127
3.6.13 Dynamic Spatial Range 128
3.6.14 Vorticity Estimation 128
3.6.15 Circulation Estimation 129
3.6.16 PIV Uncertainty Analysis 130
3.6.17 Summary 131
3.7 Acoustic Measurements 132
3.7.1 Anechoic Wind Tunnel Measurements 133
3.7.2 Acoustic Measurement Uncertainty Analysis 135
3.8 Airfoil Structural Resonance Frequency Measurements 136
Chapter 4 Lift and Drag Forces 141
4.1 Introduction 141
4.2 Full-Span Airfoils 142
4.2.1 Comparison with Published Data 142
4.2.2 Negative Lift Characteristic of the NACA 65-021 Airfoil 143
4.2.3 Comparison of Airfoils and Effects of Tubercles 147
4.2.4 Performance Effects of Variation in Tubercle Amplitude 148

4.2.5 Performance Effects of Variation in Tubercle Wavelength........................149
4.2.6 Wavy Airfoil Comparison........................151
4.2.7 Amplitude-to-wavelength Ratio (A/λ)........................152
4.2.8 Effective Device Height to Boundary Layer Thickness (heff/λ) Ratio........................153
4.3 Half-Span Airfoils........................155
4.3.1 Comparison of Results for Variation in Tubercle Amplitude........................158
4.3.2 Comparison of Results for Variation in Tubercle Wavelength........................161
4.3.3 Finite Effects on Wavy Airfoil Models........................162
4.4 Quantification of Three-Dimensional Effects........................163
4.5 Analysis of the Uncertainty Associated with Force Measurements........................165
4.6 Summary........................169
Chapter 5 Surface Pressure Characteristics........................173
5.1 Introduction........................173
5.2 Unmodified NACA 0021 Airfoil........................175
5.2.1 Analysis of Pressure Distribution........................175
5.2.2 Lift Coefficient Calculated from Pressure Distribution Data........................180
5.2.3 Pressure Contours as a Function of Chordwise Position and Angle of Attack 182
5.3 Unmodified NACA 65-021 Airfoil........................183
5.3.1 Analysis of Pressure Distribution........................183
5.3.2 Explanation for Negative Lift Phenomenon........................188
5.3.3 Lift Coefficient Calculated from Pressure Distribution Data........................190
5.3.4 Pressure Contours as a Function of Chordwise Position and Angle of Attack 191
5.4 NACA 0021 with A8λ30 Leading Edge Tubercle Configuration........................192
5.4.1 Analysis of Pressure Distribution........................192
5.4.2 Lift Coefficient Calculated from Pressure Distribution Data........................195
5.4.3 Pressure Contours as a Function of Chordwise Position and Angle of Attack 197
5.5 Analysis of the Uncertainty Associated with Pressure Measurements........................198
5.6 Summary........................203
Chapter 6 Analysis of Flow Patterns........................207
6.1 Introduction........................207
6.2 Hydrogen Bubble Visualisation........................208
6.3 Airfoil Selection for Particle Image Velocimetry (PIV)........................210
6.4 Suitability of Ensemble Averaging........................211
6.5 Vorticity........................212
6.5.1 Summary of Vorticity Characteristics........................218
6.6 Circulation........................219
6.7 Discussion of Circulation........................223
6.8 PIV Uncertainty Analysis........................225
6.8.1 Estimation of Systematic Uncertainty in Particle Displacement........................225
6.8.2 Estimation of Random Uncertainty in Particle Displacement........................226
6.8.3 Uncertainties in Vorticity Estimation........................229
6.8.4 Uncertainties in circulation estimation........................230
6.9 Summary........................231
Chapter 7 Acoustic Measurements........................233
7.1 Introduction........................233
7.2 Calibration........................233
7.3 Acoustic Measurements in Hard-Walled Wind Tunnel........................234

    7.3.1 Noise Levels Associated with NACA 0021 Airfoil 235
    7.3.2 Noise Levels Associated with NACA 65-021 Airfoil 239
  7.4 Acoustic Measurements in Anechoic Wind Tunnel 241
    7.4.1 Verification of the choice of frequency range 242
    7.4.2 Noise Measurements for NACA 0021 Airfoil 242
    7.4.3 Noise Measurements for NACA 65-021 Airfoil 245
    7.4.4 Aeroacoustic Feedback Loop 246
  7.5 Summary 248
Chapter 8 Conclusions 253
Chapter 9 Recommendations for Future Work 263
References 267
Appendix A – Verification of force transducer calibration 285
Appendix B – Efficiency Plots for Force Measurements 287
Appendix C – Surface pressure measurement feasibility study 289
  C1 Expected pressure forces 289
  C2 Complexity 290
  C3 Difficulty in interpreting images 291
Appendix D – Airfoil structural resonance frequency measurements 293
Appendix E – Proposed Flow Topology for a Tubercle 297

List of figures

Figure 1.1 - Humpback whale calf with tubercles visible on flipper leading edge (http://www.oceanwideimages.com). 2

Figure 1.2 – (a) Co-rotating vortex generator configuration, (b) counter-rotating vortex generator configuration (Adapted from Godard & Stanislas, 2006). 9

Figure 1.3 – Leading edge serrations (Soderman, 1972). 10

Figure 1.4 – Dye flow visualisation showing leading edge extensions and associated flow pattern (Adapted from Thompson, 1997). 10

Figure 1.5 – (a) Conventional trip strip turbulator, (b) Zig-zag trip strip turbulator. 11

Figure 1.6 – Oil flow visualisation showing the flow pattern and associated interpretation for a wavy wing at $\alpha = 0^\circ$ (Adapted from Zverkov & Zanin, 2009). The waviness is created by extending the grooves and humps of tubercles along the entire chord length. 12

Figure 1.7 – Schematic of movable flaps showing (a) attached flow at a low angle of attack and (b) separated flow at a high angle of attack (Meyer & Bechert, 1999). 13

Figure 1.8 – Various models and aircraft with wing fences used in the experiments by Williams (2009). 14

Figure 1.9 – Experimental investigation by Gaster to determine the response of compliant coatings to the Tollmien-Schlichting waves generated by a disturbance input (Gaster, 1987). 14

Figure 1.10 – Schematic showing scalloped groove riblets with associated velocity profiles (Bechert *et al.*, 2000). 15

Figure 1.11 – Sketch of airfoil-shaped large-eddy breakup devices in tandem in a turbulent boundary layer (Gad-el-Hak, 1990). 16

Figure 1.12 - The position of the leading edge flaps and slats on an airliner (Airbus A-300). In this picture, both devices are extended (Wikipedia, 2010). 17

Figure 1.13 - Krueger flap, an example of leading edge flap device (Swatton, 2011). 18

Figure 1.14 – Instantaneous image of Gurney flap showing vortex formation as well as upwards deflection of the flow (Carpenter & Houghton, 2003). 19

Figure 1.15 - Schematic of zero net mass flux jet with acoustic actuator (adapted from Gillaranz *et al.*, 2002). 20

Figure 1.16 - Flow visualisation of the uncontrolled (left) and controlled (right) NACA 0015 airfoil at $\alpha = 18^\circ$ (Tuck and Soria, 2004). 21

Figure 1.17 – Leading edge slots (Dingle & Tooley, 2005). 21

Figure 1.18 – Schematic of vortex generator jet actuator showing pitch angle of 30° and a rotatable plug to vary the skew angle (Khan & Johnson, 2000). 22

Figure 1.19 – Flow visualisation for NACA 0015 airfoil at $\alpha = 12^\circ$ showing separation in the absence of flow control (left) and flow reattachment with plasma (right) (Roth, 2003). 24

Figure 1.20 – Typical Reynolds number range for various applications (Adapted from Lissaman, 1983). 29

Figure 1.21- Surfboard fin with leading edge tubercles (Stafford, 2010) 32

Figure 1.22 - Altra-Air Fan 2.4m with leading edge tubercles (Fanmaster, 2011). 33

Figure 2.1 – (a) Experimental models, (b) Lift Coefficient vs. angle of attack and (c) Lift/drag ratio. Solid lines: unmodified airfoil, triangles: modified airfoil (Miklosovic *et al.*, 2004). 37

Figure 2.2 – (a) Model whale flippers, sweep angles of 15° & 30°, (b) Lift plots, sweep angle = 15° (Murray *et al.,* 2005). 37

Figure 2.3 - Panel method simulation of flow over a finite span wing at $\alpha = 10^\circ$ with straight leading edge (*left*) and leading edge tubercles (*right*). Colours represent the pressure differences on the wing. (Watts & Fish, 2001). 42

Figure 2.4 - Streamlines at the edge of the boundary layer (Watts & Fish, 2001). 42

Figure 2.5 – Pressure contours and streamlines for NACA 63-021 with and without tubercles (Fish and Lauder, 2006). 43

Figure 2.6 – Dye flow visualisation showing formation of streamwise vortices at $\alpha = 24^\circ$ after stall. (a) Unmodified airfoil and (b) Airfoil with tubercles, $\lambda = 0.05\ c$ and $A = 0.12\ c$ (right). (Custodio, 2008). 44

Figure 2.7 – (a) Instantaneous vorticity magnitude slices in span-wise direction for $a = 15^\circ$ and (b) Averaged shear-stress lines for $\alpha = 15^\circ$, $Re = 500{,}000$ (Pedro & Kobayashi, 2008). 45

Figure 2.8 – (a) Leading edge sheet cavitation and tip vortex cavitation on the smooth rudder, $\alpha = 17.0^\circ$ and (b) Cloud cavitation in troughs between tubercles and tip vortex cavitation on

modified rudder, α = 15.8°. Re = 786,000 (Weber *et al.*, 2010). Cavitation is highlighted by black arrows...46
Figure 2.9 – Schematic showing movement of vortices towards troughs as predicted using the method of images (Custodio, 2008). Image vortices shown in red are adapted....48
Figure 2.10 - Schematic of tonal noise generating mechanism as portrayed by Desquenses (2007)....52
Figure 2.11 – Cross-sectional view taken from the leading edge of a tubercle to the trailing edge (Watts & Fish, 2006)....54
Figure 2.12 – An illustrative perspective view portraying the invention (Presz Jr. *et al.*, 1989)....55
Figure 2.13 – (a) Yacht with invention incorporated on the sail, keel and rudder (b) Gas turbine with external casings taking the form of the invention (c) Stator vane with the invention included on the trailing edge (Presz Jr. *et al.*, 1989)....55
Figure 2.14 –Bicycle wheel with tubercles on leading edge of spokes (Zibkoff, 2009)....56
Figure 3.1 – Process used to construct model airfoils with tubercles....66
Figure 3.2 – Associated whale flipper (Fish & Battle, 1995)....68
Figure 3.3 - Section view of airfoil with tubercles (a) 3D view, (b) Plan view with characteristic dimensions....70
Figure 3.4 – Set of NACA 0021 and NACA 65-021 airfoils with tubercles (left and right respectively)....70
Figure 3.5 - Process used to model wavy airfoils....71
Figure 3.6 – Sections of wavy models with labels, (a) $\theta 4\lambda 15$, (b) $\theta 4\lambda 30$ and (c) $\theta 2\lambda 30$....71
Figure 3.7 – Schematic of the wind tunnel used for force and pressure tapping measurements....73
Figure 3.8 – Velocity profile at wind-tunnel contraction exit normalised with respect to mean velocity....73
Figure 3.9 – Plot of boundary layer profile, Re = 120,000....75
Figure 3.10 – Schematic of displacement correction....76
Figure 3.11 – Schematic of wall proximity correction....76
Figure 3.12 – Velocity distribution for a turbulent boundary layer....78
Figure 3.13 - Plot of output voltage against freestream velocity for hot-wire calibration....80
Figure 3.14 – Load cell arrangement....81
Figure 3.15 – Experimental set-up....81
Figure 3.16 - Lift and Drag Forces....83
Figure 3.17 – Schematic of airfoil showing relative force transducer axes, F_x and F_y and misalignment, ε....84
Figure 3.18 – Modified mount for analysis of three-dimensional effects, (a) original frame (b) modified lowered frame, (c) structure used to gain height and block hole in test section....85
Figure 3.19 – Schematic showing method of images used to simulate three-dimensional model....90
Figure 3.20 – Relative contribution of various sources of drag (Barlow et al., 1999)....91
Figure 3.21 – Image system for a three-dimensional model in a closed rectangular test section (Barlow *et al.*, 1999). Note that the model in the current study is mounted vertically....92
Figure 3.22 – Image vortex locations for a closed round jet (Barlow *et al.*, 1999)....93
Figure 3.23 - Block diagram of Scanivalve pressure multiplexer and associated hardware, (a) data logger, (b) Scanivalve controller, (c) Scanivalve and (d) Baratron pressure transducer....101
Figure 3.24 – Timing diagram in reference frame of controller....101
Figure 3.25 – Pressure tap locations for unmodified airfoils....102
Figure 3.26 – Modified airfoil showing three rows of pressure taps....102
Figure 3.27 – Coordinate system and stress definitions....104
Figure 3.28 – Water tunnel facility used for hydrogen bubble visualisation....106
Figure 3.29 – Independent dye visualisation and particle image velocimetry (PIV) for water tunnel calibration (ER Hassan 2011, personal communication)....107
Figure 3.30 – Mount used in water tunnel for hydrogen bubble visualisation experiments....108
Figure 3.31 – Examples of generic hydrogen bubble wire designs, (a) horizontal wire probe, (b) vertical wire probe (Smits & Lim, 2000)....109
Figure 3.32 – Section of airfoil at $\alpha = 5°$ with tubercles showing particle image velocimetry measurement planes from a perspective viewpoint....111
Figure 3.33 – Typical field of view for PIV experiments....112
Figure 3.34 – Thebarton water tunnel used for PIV experiments....113
Figure 3.35 – Particle image velocimetry calibration for Thebarton water tunnel....114
Figure 3.36 – Histogram of PIV data showing the "peak-locking" effect (Raffel *et al.*, 1998)....116
Figure 3.37 – Energy output from laser cavity as a function of Flash lamp – Q switch delay....118
Figure 3.38 – Optics set-up for particle image velocimetry experiments (not to scale)....119

Figure 3.39 – Timing diagram for laser/camera synchronisation. 121
Figure 3.40 – Schematic of perspective error (not to scale). 131
Figure 3.41 – Schematic of microphone positions. 133
Figure 3.42 – Anechoic wind tunnel facility. 134
Figure 3.43 - Mount for anechoic wind tunnel. 134
Figure 3.44 – Schematic showing accelerometer positions for vertical mount (left) and horizontal mount (right). 138
Figure 3.45 – Structural resonance frequency measurements for unmodified NACA 0021 airfoil. (a) Vertical mount (b) horizontal mount. 140
Figure 3.46 - Structural resonance frequency measurements for NACA 0021 airfoil with $A2\lambda7.5$ tubercle configuration. (a) Vertical mount (b) horizontal mount. 140
Figure 4.1 - Lift coefficient vs. angle of attack for NACA 0021 compared with experimental data for NACA 0020 (Miklosovic, 2007). 142
Figure 4.2 - Drag coefficient vs. angle of attack for NACA 0021 compared with experimental data for NACA 0020 (Miklosovic, 2007). 142
Figure 4.3 - Repeatability and influence of gap on lift coefficient for NACA 0021, ... 143
Figure 4.4 - Repeatability and influence of gap on drag coefficient for NACA 0021, ... 143
Figure 4.5 - Lift coefficient plotted against angle of attack for NACA 65-021, ... 144
Figure 4.6 – Drag coefficient plotted against angle of attack for NACA 65-021, ... 144
Figure 4.7 – Effect of trip height on lift coefficient for NACA 65-021 (d = 5mm), ... 145
Figure 4.8 – Effect of trip height on drag coefficient for NACA 65-021 (*d* = 5mm), *Re* = 120,000. 145
Figure 4.9 – Effect of trip position on lift coefficient for NACA 65-021 (*k* = 0.4mm), ... 146
Figure 4.10 – Effect of trip position on drag coefficient for NACA 65-021 (*k* = 0.4mm), ... 146
Figure 4.11 - Tripped lift coefficient plotted against angle of attack for NACA 65-021, ... 146
Figure 4.12 - Tripped drag coefficient plotted against angle of attack for NACA 65-021, ... 146
Figure 4.13 - Tubercle amplitude variation and the effect on lift coefficient for NACA 0021, *Re* = 120,000. 147
Figure 4.14 - Tubercle amplitude variation and the effect on drag coefficient for NACA 0021, *Re* = 120,000. 147
Figure 4.15 - Further amplitude reduction and the effect on lift coefficient for NACA 0021, *Re* = 120,000. 149
Figure 4.16 - Further amplitude reduction and the effect on drag coefficient for NACA 0021, *Re* = 120,000. 149
Figure 4.17 - Tubercle wavelength variation and the effect on lift coefficient for 150
Figure 4.18 - Tubercle wavelength variation and the effect on drag coefficient for NACA 0021, *Re* = 120,000. 150
Figure 4.19 - Lift coefficient plot for various wavy airfoil configurations and comparison with the most successful tubercle configuration, *Re* = 120,000. 151
Figure 4.20 - Drag coefficient plot for various wavy airfoil configurations and comparison with the most successful tubercle configuration, *Re* = 120,000. 151
Figure 4.21 - Tubercle A/λ ratio and the effect on lift coefficient for NACA 0021, ... 152
Figure 4.22 - Tubercle A/λ ratio and the effect on drag coefficient for NACA 0021, ... 152
Figure 4.23 - The effect of amplitude-to-wavelength ratio on maximum lift coefficient, *Re* = 120,000. 153
Figure 4.24 - The effect of amplitude-to-wavelength ratio on stall angle, ... 153
Figure 4.25 - The effect of amplitude-to-wavelength ratio on maximum lift to drag ratio, *Re* = 120,000. 153
Figure 4.26 - Maximum lift coefficient and associated normalised effective tubercle height, *Re* = 120,000. 154
Figure 4.27 - Stall angle and associated normalised effective tubercle height, ... 154
Figure 4.28 – Maximum lift-to-drag ratio and associated normalised effective tubercle height, ... 155
Figure 4.29 – Comparison of lift coefficient for full-span and half-span NACA 0021 airfoils, *Re* = 120,000. 156
Figure 4.30 – Comparison of drag coefficient for full-span and half-span NACA 0021 airfoils, *Re* = 120,000. 156
Figure 4.31 - Comparison of lift coefficient for full-span and half-span NACA 65-021 airfoils, *Re* = 120,000. 158
Figure 4.32 - Comparison of drag coefficient for full-span and half-span NACA 65-021 airfoils, *Re* = 120,000. 158

Figure 4.33 - Tubercle amplitude variation and lift performance for full-span and half-span NACA 0021 models, Re = 120,000. 159

Figure 4.34 - Tubercle amplitude variation and drag performance for full-span and half-span NACA 0021 models, Re = 120,000. 159

Figure 4.35 - Tubercle amplitude variation and lift performance for full-span and half-span NACA 65-021 models, Re = 120,000. 160

Figure 4.36 - Tubercle amplitude variation and drag performance for full-span and half-span NACA 65-021 models, Re = 120,000. 160

Figure 4.37 – Further reduction in tubercle amplitude and the effects on lift coefficient for NACA 0021 models, Re = 120,000. 160

Figure 4.38 – Further reduction in tubercle amplitude and the effects on drag coefficient for NACA 0021 models, Re = 120,000. 160

Figure 4.39 – Tubercle wavelength variation and lift performance for full-span and half-span NACA 0021 models, Re = 120,000. 161

Figure 4.40 – Tubercle wavelength variation and drag performance for full-span and half-span NACA 0021 models, Re = 120,000 161

Figure 4.41 – Wavy airfoils and lift performance for full-span and half-span models, Re = 120,000. 162

Figure 4.42 - Wavy airfoils and drag performance for full-span and half-span models, Re = 120,000. 162

Figure 4.43 - Influence of wall proximity on three-dimensional effects affecting the lift force for unmodified NACA 0021 airfoil, ... 163

Figure 4.44 - Influence of wall proximity on three-dimensional effects affecting the drag force for unmodified NACA 0021 airfoil, ... 163

Figure 4.45 - Influence of wall proximity on three-dimensional effects affecting the lift force for $A2\lambda7.5$ tubercle configuration, Re = 120,000. 164

Figure 4.46 - Influence of wall proximity on three-dimensional effects affecting the drag force for $A2\lambda7.5$ tubercle configuration, ... 164

Figure 4.47 - Influence of wall proximity on three-dimensional effects affecting the lift force for $\theta4\lambda15$ wavy configuration, ... 164

Figure 4.48 - Influence of wall proximity on three-dimensional effects affecting the drag force for $\theta4\lambda15$ wavy configuration, ... 164

Figure 4.49 – Lift coefficient uncertainty analysis for NACA 0021 full-span models, Re = 120,000.. 165

Figure 4.50 – Drag coefficient uncertainty analysis for NACA 0021 full-span models, Re = 120,000. 165

Figure 4.51 – Relative pre-stall contribution of uncertainties in lift coefficient for NACA 0021 airfoils, Re = 120,000. 167

Figure 4.52 – Relative post-stall contribution of uncertainties in lift coefficient for NACA 0021 airfoils, Re = 120,000. 167

Figure 4.53 – Relative pre-stall contribution of uncertainties in drag coefficient for NACA 0021 airfoils, Re = 120,000. 167

Figure 4.54 – Relative post-stall contribution of uncertainties in drag coefficient for NACA 0021 airfoils, Re = 120,000. 167

Figure 4.55 - Relative pre-stall contribution of uncertainties in lift coefficient for NACA 65-021 airfoils, Re = 120,000. 168

Figure 4.56 - Relative pre-stall contribution of uncertainties in drag coefficient for NACA 65-021 airfoils, Re = 120,000. 168

Figure 4.57 - Relative pre-stall contribution of uncertainties in lift coefficient for NACA 65-021 airfoils, Re = 120,000. 169

Figure 4.58 - Relative pre-stall contribution of uncertainties in lift coefficient for NACA 65-021 airfoils, Re = 120,000. 169

Figure 5.1 – Sketch of laminar separation bubble (Horton, 1968). 174

Figure 5.2 – Normalised pressure distribution plots for NACA 0021 unmodified airfoil, where “top” refers to suction surface and “bottom” refers to pressure surface, Re = 120,000. Separation bubble locations found from XFOIL skin friction data are indicated. 176

Figure 5.3 – Friction coefficient against chordwise position for NACA 0021 at low angles of attack (suction surface), ... 177

Figure 5.4 - Friction coefficient against chordwise position for NACA 0021 at high angles of attack (suction surface), ... 177

Figure 5.5 – Explanation for increase in lift curve slope beyond theoretical maximum. 179

Figure 5.6 – Comparison between trapezoidal integration method and XFOIL for lift calculation, Re = 120,000. 181

Figure 5.7 - Trapezoidal integration method for lift calculation using pressure distribution data, *Re* = 120,000. 181
Figure 5.8 – Normalised pressure contours for suction surface of NACA 0021, ... 183
Figure 5.9 – Normalised pressure contours for pressure surface of NACA 0021, ... 183
Figure 5.10 – Normalised pressure distribution plots for NACA 65-021 unmodified airfoil where “top” refers to suction surface and “bottom” refers to pressure surface, *Re* =120,000. Separation bubble locations found from XFOIL skin friction data are indicated. 185
Figure 5.11 – Friction coefficient against chordwise position for NACA 65-021 at low angles of attack (suction surface), ... 186
Figure 5.12 - Friction coefficient against chordwise position for NACA 65-021 at high angles of attack (suction surface), ... 186
Figure 5.13 – Friction coefficient against chordwise position for NACA 65-021 at low angles of attack (pressure surface), ... 186
Figure 5.14 - Friction coefficient against chordwise position for NACA 65-021 at high angles of attack (pressure surface), ... 186
Figure 5.15 – Pressure distribution and boundary layer characteristics for NACA 65-021 airfoil at α = 2° (dashed lines indicate the inviscid solution), *Re* = 120,000 189
Figure 5.16 - Pressure distribution and boundary layer characteristics for NACA 0021 airfoil at α = 2° (dashed lines indicate the inviscid solution), *Re* = 120,000. 189
Figure 5.17 –Lift coefficient against angle of attack for different measurement methods (NACA 65-021), *Re* = 120,000. 191
Figure 5.18 – Normalised pressure contours for suction surface of NACA 65-021, ... 191
Figure 5.19 – Normalised pressure contours for pressure surface of NACA 65-021, ... 191
Figure 5.20 – Normalised pressure distribution plots for airfoil with $A8\lambda30$ tubercle configuration, where symbols are chosen as follows: “•” pressure surface “○” suction surface, ... 194
Figure 5.21 – Lift coefficient for $A8\lambda30$ evaluated from pressure distribution at “peak”, “mid” and “trough” tubercle positions compared to force results, *Re* = 120,000. 196
Figure 5.22 - Normalised pressure contours for suction surface of airfoil with $A8\lambda30$ tubercle configuration, *Re* = 120,000. 197
Figure 5.23 - Normalised pressure contours for pressure surface of airfoil with $A8\lambda30$ tubercle configuration, *Re* = 120,000. 197
Figure 5.24 – Pressure coefficient uncertainty analysis for NACA 0021 at α = 6°, ... 199
Figure 5.25 - Pressure coefficient uncertainty analysis for NACA 0021 at α = 20°, ... 199
Figure 5.26 – Relative uncertainties pre-stall for pressure tappings located on airfoil suction surface (NACA 0021), α = 6°, *Re* = 120,000. 200
Figure 5.27 - Relative uncertainties post-stall for pressure tappings located on airfoil suction surface (NACA 0021), α = 20°, ... 200
Figure 5.28 – Pressure coefficient uncertainty analysis for NACA 65-021 at α = 8°, ... 201
Figure 5.29 – Pressure coefficient uncertainty analysis for NACA 65-021 at α = 20°, ... 201
Figure 5.30 – Relative uncertainties pre-stall for pressure tappings located on suction surface of airfoil (NACA 65-021), ... 201
Figure 5.31 – Relative uncertainties post-stall for pressure tappings located on suction surface of airfoil (NACA 65-021), ... 201
Figure 5.32 – Pressure coefficient uncertainty analysis for $A8\lambda30$ tubercle configuration at α = 5°, 202
Figure 5.33 – Pressure coefficient uncertainty analysis for $A8\lambda30$ tubercle configuration at α = 20°, ... 202
Figure 5.34 – Relative uncertainties pre-stall for tapping located at x/c = 0.1 on suction surface of airfoil, α = 5°, *Re* = 120,000. 203
Figure 5.35 – Relative uncertainties pre-stall for tapping located at x/c = 0.1 on suction surface of airfoil, α = 20°, *Re* = 120,000. 203
Figure 6.1 - Hydrogen bubble visualisation at *Re* = 4370, α = 10°, $A8\lambda30$ configuration (a) angled top view showing stream-wise vortices, (b) side view in plane of trough (c) side view in plane of peak and (d) top view depicting regions of acceleration. Dashed lines show the outline of the leading edge, flow is from left to right. 209
Figure 6.2 - Hydrogen bubble visualization of the NACA 0021, angled top view: (a) unmodified airfoil, (b) $A4\lambda15$ (c) $A4\lambda30$ (d) $A4\lambda60$ and (e) $A8\lambda30$ (*Re* = 5250, α = 10°), flow is from left to right. 210
Figure 6.3 – An example of instantaneous vorticity contours for the 0.4*c* plane at α = 5°, where time spacing beween images is 0.1s, *Re* = 2230 211

Figure 6.4 – Average velocity contours compared with velocity fluctuation contours, 0.4*c* plane at . 212
Figure 6.5 - Comparison between (a) velocity vector field and (b) vorticity contour plot at α = 15°, x/c = 0.4, Re = 2230. 213
Figure 6.6 - Vorticity contours (1/s) for sequential chordwise planes at α = 5°, x/c = 0.4, ... 214
Figure 6.7 - Vorticity contours for x/c = 0.2 at α = 10°. 216
Figure 6.8 - Vorticity contours for sequential chordwise planes at α = 10°, (a) x/c = 0.4, (b) x/c = 0.6, (c) x/c = 0.8, (d) x/c = 1, Re = 2230. Asterisks mark secondary vortex structures. Note that a different vorticity scale is shown for the x/c = 1 plane. 216
Figure 6.9 - Vorticity contours for sequential chordwise planes at α = 15°, (a) x/c = 0.4, (b) x/c = 0.6, (c) x/c = 0.8, Re = 2230. 217
Figure 6.10 - Path of integration and enclosed region for α = 5°, where: (a) x/c = 0.4, (b) x/c = 0.6, (c) x/c = 0.8, (d) x/c = 1, Re = 2230. Red - positive vortex core, blue - negative vortex core. 219
Figure 6.11 - Path of integration and enclosed region for α = 10°, x/c = 0.2 plane. Red - positive vortex core, blue - negative vortex core. 220
Figure 6.12 - Path of integration and enclosed region for α = 10°, where: (a) x/c = 0.4, (b) x/c = 0.6, (c) x/c = 0.8, (d) x/c = 1, Re = 2230. Red - positive vortex core, blue - negative vortex core. The yellow arrow indicates a possible pathway of vorticity entrainment. 221
Figure 6.13 - Path of integration and enclosed region for α = 10°, where: (a) x/c = 0.4, (b) x/c = 0.6, (c) x/c = 0.8, (d) x/c = 1, Re = 2230. Red - positive vortex core, blue - negative vortex core. Yellow arrows indicate possible pathways of vorticity entrainment. 222
Figure 6.14 – Circulation variation with angle of attack and chordwise position 223
Figure 6.15 – Schematic showing wall vorticity close to the surface being entrained by the primary vortices at adjacent locations. Dashed arrows indicate transport of vorticity to adjacent troughs between tubercles 224
Figure 6.16 – Vector plot of velocity vectors for $0.4\bar{c}$, α = 5° case, where the dashed red lines cross at the point of maximum positive vorticity, Re = 2230. 228
Figure 6.17 – Particle displacement in z with respect to y location, where dashed red line shows the associated maximum gradient, Re = 2230. 228
Figure 6.18 – Particle displacement in y with respect to z location, where dashed red line shows the associated maximum gradient, Re = 2230. 228
Figure 7.1 – Measured signal after calibration using 94dB calibrator. 234
Figure 7.2 – Measured signal after calibration using 114dB calibrator. 234
Figure 7.3 – Sound pressure level (SPL) against frequency, f, for NACA 0021 at angle of attack, α = 1-8° (microphone at window), Re = 120,000 236
Figure 7.4 - Sound pressure level (SPL) against frequency, f, for NACA 0021 at angle of attack, α = 1-8° (microphone at exit), Re = 120,000. 236
Figure 7.5 - SPL against frequency for unmodified NACA 0021 at α = 5°for three separate runs (microphone at window), Re = 120,000 237
Figure 7.6 - SPL against frequency for variation tubercle of amplitude (small A) for 237
Figure 7.7 - SPL against frequency for variation of tubercle amplitude (large A) for NACA 0021 at α = 5° (microphone at window), Re = 120,000. 237
Figure 7.8 - SPL against frequency for variation of tubercle wavelength (small λ) for NACA 0021 at α = 5° (microphone at window), Re = 120,000. 237
Figure 7.9 - SPL against frequency for wavy NACA 0021 variations at α = 5° (microphone at window), Re = 120,000. 237
Figure 7.10 - Strouhal no. against angle of attack for NACA 0021 tubercle configurations with tonal noise 239
Figure 7.11 - Strouhal no. against angle of attack for NACA 0021 tubercle configurations with tonal noise 239
Figure 7.12 - SPL against angle of attack for tubercle configurations with tonal noise (microphone at window), Re = 120,000. 239
Figure 7.13 - SPL against angle of attack for tubercle configurations with tonal noise (microphone at exit), Re = 120,000. 239
Figure 7.14 - SPL against frequency for NACA 65-021 at angle of attack, α = 7-10° (microphone at window), Re = 120,000. 240
Figure 7.15 - SPL against frequency for NACA 65-021 at angle of attack, α = 7-10° (microphone at exit), Re = 120,000. 240
Figure 7.16 - SPL against frequency for NACA 65-021 at α = 8° for variation tubercle amplitude (microphone at window), Re = 120,000. 240

Figure 7.17 - SPL against frequency for NACA 65-021 at α = 9° for variation tubercle amplitude (microphone at window), *Re* = 120,000. 240
Figure 7.18 - Strouhal no. against angle of attack for NACA 65-021 unmodified airfoil with tonal noise, *Re* = 120,000. 241
Figure 7.19 - SPL against angle of attack for unmodified NACA 65-021 with tonal noise, *Re* = 120,000. 241
Figure 7.20 – SPL for NACA 0021 unmodified airfoil with larger frequency range, $50 \leq f \leq 10{,}000$Hz in AWT, *Re* = 120,000. 242
Figure 7.21 – SPL for *A*4λ7.5 tubercle configuration with larger frequency range, $50 \leq f \leq 10{,}000$Hz, in AWT *Re* = 120,000. 242
Figure 7.22 - SPL against frequency measured in anechoic wind tunnel (AWT) for a) unmodified 0021 b) *A*2λ7.5 c) *A*4λ7.5 d) *A*4λ15 e) *A*4λ30 f) *A*4λ60 g) *A*8λ30 h) θ2λ30 i) θ4λ30 j) θ4λ15, *Re* = 120,000 243
Figure 7.23 – Effect of amplitude-to-wavelength ratio on SPL of tonal noise. 244
Figure 7.24 - Strouhal no. against angle of attack for NACA 0021 airfoils with tonal noise in AWT, *Re* = 120,000. ....Error! Bookmark not defined.
Figure 7.25 - SPL against angle of attack for NACA 0021 airfoils with tonal noise in AWT, *Re* = 120,000. ....Error! Bookmark not defined.
Figure 7.26 - SPL against frequency measured in AWT for a) unmodified 65-021 b) 6 *A*4λ30 c) 6 *A*8λ30, *Re* = 120,000. 245
Figure 7.27 – Schematic of feedback loop (Arbey & Bataille, 1983) 246

List of tables

Table 1.1 - Flow control devices and their corresponding effects and benefits. 26

Table 2.1 – Summary of variations in performance for finite span models. 40

Table 3.1 – Considerations affecting chord length selection 67

Table 3.2 - Relative wavelength determined from Fish and Battle (1995) 68

Table 3.3 - Tubercle configurations and adopted terminology. 69

Table 3.4 – Wavy airfoil configurations and adopted terminology. 71

Table 3.5 – Determining degrees of freedom for a given uncertainty approximation. 97

Table 3.6 – Values of relevant parameters for measurement uncertainty analysis 98

Table 3.7 – Pressure tap positions for unmodified airfoil. 102

Table 3.8 – Pressure tap positions for modified airfoil 103

Table 3.9 - Values of relevant parameters for uncertainty analysis. 105

Table 3.10 – Time delay used for particle image velocimetry measurements of freestream velocity. 113

Table 3.11 – Summary of measurement planes and associated time delay, ΔT. 120

Table 3.12 – Summary of PIV recording parameters. 132

Table 3.13 – Measurement parameters for resonance frequency testing (transfer function). 137

Table 3.14 – Summary of position combinations for accelerometer and impact hammer 138

Table 3.15 - Measurement parameters for resonance frequency testing (auto power spectrum). 139

Table 3.16 - Hard-walled wind tunnel (vertical airfoil mount) 139

Table 4.1 – Nomenclature used in figures showing uncertainty in force measurements. 166

Table 5.1 – Chordwise extent of laminar separation bubble determined from the friction coefficient for the suction surface (NACA 0021), *Re* = 120,000. 177

Table 5.2 - Chordwise extent of laminar separation bubble and final separation location determined from friction coefficient for the suction surface (NACA 65-021), *Re* = 120,000. 187

Table 5.3 – Chordwise extent of laminar separation bubble determined from the friction coefficient for the pressure surface (NACA 65-021), *Re* = 120,000. 188

Table 5.4 – Location of separation bubbles for NACA 0021 airfoil with $A8\lambda30$ tubercles at trough cross-section on suction surface. 195

Table 5.5 - Nomenclature used in figures showing uncertainties in force measurements 199

Table 5.6 – Summary of separation characteristics. 205

Table 6.1 – Positive and negative peak vorticity for chordwise measurements planes (α = 5°). 215

Table 6.2 - Positive and negative peak vorticity for chordwise measurements planes (α = 10°). 217

Table 6.3 - Positive and negative peak vorticity for chordwise measurements planes (α = 15°). 218

Table 6.4 - Circulation for chordwise measurements planes (α = 5°). 220

Table 6.5 - Circulation for chordwise measurements planes (α = 10°). 221

Table 6.6 - Circulation for chordwise measurements planes (α = 15°). Circulation values calculated without erroneous region are shown in brackets. 223

Table 7.1 – Summary of tonal noise characteristics at α = 5° for the NACA 65-021 airfoil 246

Table 7.2 – Separation characteristics calculated using XFOIL at α = 5° 248