

Unsteady Flow and Transition Phenomena in an Axial Flow Compressor

by

A. D. Henderson, B.E. (Hons)

School of Engineering

Submitted in fulfilment of the requirements
for the degree of
Doctor of Philosophy

University of Tasmania

November 2006

Declaration of Originality

This thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duly acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis, nor does the thesis contain any material that infringes copyright.

Statement of Authority of Access

This thesis is not to be made available for loan or copying for two years following the date this statement was signed. Following that time the thesis may be made available for loan and limited copying in accordance with the *Copyright Act 1968*.

Alan D. Henderson

Abstract

The unsteady mid-span aerodynamics of an outlet stator row in a 1.5-stage low-speed axial compressor is investigated experimentally and numerically. Two stator blade rows with characteristically different blade profiles are studied: one of standard British C4 section and a controlled diffusion (CD) blade with a circular arc leading edge profile.

A turbulence grid placed at compressor inlet is used to generate turbulence characteristics similar to those occurring in an embedded stage in a multi-stage axial compressor. The stator inlet flow is studied using hot-wire anemometry and compared with previous measurements made in the natural low inlet turbulence configuration of the research compressor. Increased turbulence level enhances the dispersion of inlet guide vane (IGV) wakes. This modifies the interaction between IGV and rotor blade wakes, leading to a more circumferentially uniform flow field at entry to the stator with significantly lower periodic unsteadiness.

Laminar-turbulent transition on a C4 stator blade is studied using an array of surface-mounted hot-film sensors. Comparisons with measurements made at low inlet turbulence show that the increased inlet turbulence level reduces the extent of periodic transitional flow on the stator blade surface. The blade element behaviour flow behaviour at high inlet turbulence closely resembles the low inlet turbulence case with the stator immersed in IGV wake turbulence.

The circular arc leading edge profile of the CD stator produces rapid acceleration and deceleration at the stator leading edge. The influence of this velocity spike on the stator boundary layer development and transitional flow behaviour is studied using an array of surface mounted hot-film sensors. A region of favourable pressure gradient on the suction surface following the leading edge spike has a stabilising effect on the boundary layer, with a large region of flow in a laminar or transitional state. Turbulent spots and instability phenomena in this region are examined for convection speed,

growth rate and evidence of relaminarisation. In contrast, the flow on the pressure surface becomes turbulent near the leading edge. The study shows that compressor blade leading edge profiles have a major influence on boundary layer development over the whole surface.

The effect of upstream rotor wake passing on the stability of stator blade boundary layers is examined. The unsteady quasi-three dimensional flow solver, UNSFLO, is used to interpret surface hot-film data and unsteady laminar flow behaviour at the leading edge of both C4 and CD stators. Rotor wake chopping is found to stabilise the pressure surface boundary layer and destabilise the suction surface boundary layer. Examination of hot-film data points to the leading edge as the principal receptivity site for transitional flow phenomena occurring on the suction surface of both the C4 and CD blading.

Acknowledgements

I would like to thank my colleagues, friends and family for their support throughout my PhD candidature. In particular, I would like to acknowledge help from a number of people.

The project would not have been possible without the encouragement and financial support from the project sponsor, Rolls-Royce Plc. The helpful advice and comments of Jeremy Hughes, Mike Howard and John Coupland were very much appreciated.

The staff at the School of Engineering Workshop assisted in preparing the research compressor and instrumentation for experimental measurements. Peter Seward patiently spent many weeks meticulously instrumenting compressor blades. Glen Mayhew persevered in isolating electrical noise from the research compressor. John McCulloch assisted in setting up and maintaining the data acquisition systems. Ray LeFevre and Nathan Smith provided assistance on numerous occasions.

Many thoughtful discussions with other colleges at the School including Jane Sargison and Michael Kirkpatrick were very much appreciated.

Much gratitude is extended to my supervisor, Greg Walker who has given me helpful advice throughout the project. His thoughtfulness and understanding have been nothing short of inspirational. I could not have wished for a better supervisor.

In the early stages of the project, Frank Sainsbury and Jason Roberts encouraged me to learn and use Unix and Linux operating systems and document preparation in L^AT_EX. These tools made many aspects of my project and preparation of this manuscript much easier than would have otherwise been.

I would like to thank Ruth and James for their continuous love and support. Ruth has been very patient and understanding of the long hours devoted to this thesis. Such kindness I will never forget.

Finally, I would like to thank my parents and other family members for their unending love and support.

Alan D. Henderson

Contents

Abstract	iii
Acknowledgements	v
List of Figures	xi
List of Tables	xx
Nomenclature	xxii
1 Introduction	1
2 Literature Review	6
2.1 Introduction	6
2.2 The Modes of Transition	7
2.2.1 Natural Transition	7
2.2.2 Bypass Transition	9
2.2.3 Separated Flow Transition	10
2.2.4 Relaminarisation	12
2.3 Predicting the Onset of Transition	14
2.4 Linear Stability Theory	16
2.5 Turbulent Spot Theory	20
2.6 Transitional Flow in Turbomachinery	23
2.6.1 Periodic Unsteady Transition	24
2.6.2 Wake Jet Effect	26
2.6.3 Separation Bubbles	27
2.7 Conclusions	29

3	Experimental Facilities	30
3.1	Background	30
3.2	Research Compressor Description	32
3.3	Compressor Detail	34
3.3.1	C4 Compressor Blading	35
3.3.2	CD Stator Blade Row	36
3.4	Instrumentation	40
3.4.1	Pressure Measurement	40
3.4.2	Relative Humidity Probe	40
3.4.3	Thermometer	40
3.4.4	Multimeter	41
3.4.5	Constant Temperature Anemometers	41
3.4.6	Hot-Wire Probes	41
3.4.7	High-Speed Data Acquisition	43
3.4.8	Three-Hole Probe	44
3.5	Research Compressor Control	47
3.5.1	Speed Control	47
3.5.2	Flow Coefficient	48
3.6	Turbulence Generating Grid	49
4	Experimental Approach	50
4.1	Introduction	50
4.2	Inlet Turbulence Level	52
4.3	Blade Row Clocking	53
4.4	Compressor Loading	54
4.5	Reynolds Number	55
4.6	Total Pressure and Flow Angle	57
4.7	Blade Surface Pressure Measurements	60
4.8	Stator Inlet Reynolds Number	61
4.9	Presentation of Hot-Wire Measurements	61
4.10	Presentation of Hot-Film Measurements	63
4.11	Blade Surface Particle Trajectories	65
5	Stator Inlet Flow	66
5.1	Introduction	66

5.2	Experimental Technique	68
5.3	Unsteady Flow Field	70
5.3.1	Turbulence Grid–IGV Blade Row Clocking Effects	75
5.3.2	Ensemble Averaged Velocity-Time Traces	75
5.4	Integral Length Scale	78
5.5	Conclusions	80
6	C4 Stator Observations	81
6.1	Introduction	81
6.2	Range of Investigation	83
6.3	Time-Mean Stator Inlet Flow	85
6.4	Surface Velocity Distributions	85
6.5	Hot-Film Surveys	87
6.5.1	Hot-Film Sensor Array	87
6.5.2	Measurement Technique	88
6.5.3	Surface Intermittency Distributions	89
6.6	Conclusions	98
7	CD Stator Observations	99
7.1	Introduction	99
7.2	Circular Arc Leading Edge Profiles	100
7.3	Preliminary Study of the CD Stator	104
7.3.1	Modelling Approach	105
7.3.2	Predicted Surface Pressure Distributions	105
7.4	Range of Experimental Investigation	109
7.5	Surface Pressure Distribution	111
7.5.1	Introduction	111
7.5.2	Instrumentation	111
7.5.3	Experimental Method	112
7.5.4	Surface Velocity Predictions	113
7.5.5	Surface Velocity Distributions	114
7.6	Hot-Film Surveys	118
7.6.1	Hot-Film Sensor Array	119
7.6.2	Measurement Technique	120
7.6.3	Surface Intermittency Distributions	121

7.6.4	General Observations	126
7.6.5	Incidence Effects	136
7.6.6	Reynolds Number Effects	137
7.7	Stator Wake Surveys	138
7.7.1	Experimental Method	138
7.7.2	Stator Outlet Flow Field	139
7.7.3	Time-Mean Stator Pressure Loss	142
7.8	Conclusions	146
8	Unsteady Transition Phenomena at the Leading Edge of Compressor	
	Blades	148
8.1	Scope of Experimental Investigation	150
8.2	Unsteady Flow Simulation	152
8.2.1	The UNSFLO Solver	152
8.2.2	Model Description	153
8.2.3	Model Results	154
8.2.4	Predicted Leading Edge Boundary Layer Behaviour	159
8.2.5	Effect of Varying Rotor–Stator Axial Spacing	167
8.3	Transitional Flow Observations	173
8.3.1	C4 Stator	173
8.3.2	CD Stator	175
8.4	Discussion	178
8.5	Conclusions	180
9	Conclusions and Recommendations for Future Research	182
A	Stator Blade Instrumentation	187
A.1	C4 Stator Blade Instrumentation	187
A.2	CD Stator Blade Instrumentation	191
B	Design of the Turbulence Grid	195
B.1	Turbulence Intensity	196
B.2	Integral Length Scale	196
B.3	Pressure Loss	196

C Compressor Reference Pressure	198
C.1 Model of Research Compressor Inlet Contraction	198
C.2 Calibration of Inlet Contraction	202
Bibliography	203

List of Figures

2.1	Smoke visualisation of vortex trusses (from Knapp and Roache [96]) .	8
2.2	Schematic diagram of the natural transition process (from White [188])	8
2.3	Visualisation of DNS solution showing streaks proceeding turbulent breakdown (from Jacobs and Durbin [90])	10
2.4	Schematic diagram of separated flow transition (from Mayle [111]) . .	11
2.5	Disturbance amplification curves for the boundary layer on a flat plate at zero incidence. δ_1 denotes boundary layer displacement thickness (from Schlichting [147]).	18
2.6	Comparison of critical Re_θ for turbulent breakdown for both the e^n and Abu Ghannam and Shaw [1] methods (from Drela [35]). Critical amplification ratio, turbulence intensity, and momentum thickness Reynolds number are indicated by N_{crit} , t and $Rtheta$, respectively.	19
2.7	Schematic diagram of turbulent spot development (from Paxson and Mayle [129])	20
2.8	The domain of dependence for a turbulent spot (from Mayle [111]) . .	21
2.9	Schematic showing the morphology of periodic unsteady transition on a compressor suction surface (from Halstead et al. [61])	24
2.10	Interaction between a convecting wake and flat plate (adapted from Hodson [73] after Meyer [115])	26
2.11	Vectors and streamlines showing the interaction between a negative jet and a suction side boundary layer on a LP turbine blade (from Hodson and Howell [75])	26
2.12	Schematic showing leading edge separation bubble (from Tain and Cumpsty [167])	28

3.1	UTAS research compressor with the compressor section open showing the rotor and stator blade rows	31
3.2	Schematic diagram of the research compressor (adapted from Oliver [122])	33
3.3	The research compressor showing original C4 rotor and stator blade rows (left) and the CD stator blade row with rotor disk removed (right)	35
3.4	Radial view of C4 and CD stator blades showing hub, mid-span and tip sections.	37
3.5	United Sensor CA120 three-hole probe	44
3.6	United Sensor CA120 three-hole probe calibration	46
3.7	Photograph of the research compressor inlet section showing the turbulence grid	49
4.1	Cross-section of the research compressor showing mid-span blade row configuration and typical instantaneous wake dispersion pattern (C4 stator)	54
4.2	Reynolds number variation in the PW2037 high bypass ratio turbofan at altitude cruise (from Hourmouziadis [79])	56
4.3	Pitchwise variation of total pressure coefficient in the rotor–stator axial gap at mid-span. Three-hole probe measurements 20.7% <i>c</i> axially upstream from the stator leading edge (from Hughes [83], $Re_c = 120000$)	58
4.4	Pitchwise variation of total pressure coefficient with grid–IGV alignment in the rotor–stator axial gap at mid-span height. Total pressure tube measurements at 18.7% <i>c</i> axially upstream from the CD stator leading edge (based on C4 chord length, $Re_c = 120000$, $\phi = 0.675$) . .	59
5.1	View looking upstream showing the path of the probe relative to the IGV blade row	70
5.2	Unsteady flow field in the rotor–stator axial space at low compressor load ($\phi = 0.840$, and $Re_c = 120000$). Top: low turbulence case without grid. Bottom: high turbulence case with grid (grid wakes in IGV passage $g/S = 0.5$). Filled contours show ensemble-averaged velocity $\langle u \rangle / \bar{u}_s$. Line contours show ensemble-averaged turbulence level $\langle Tu \rangle$ in 1% intervals.	72

5.3	Unsteady flow field in the rotor–stator axial space at medium compressor load ($\phi = 0.675$, and $Re_c = 120000$). Top: low turbulence case without grid. Bottom: high turbulence case with grid (grid wakes in IGV passage $g/S = 0.5$). Filled contours show ensemble-averaged velocity $\langle u \rangle / \bar{u}_s$. Line contours show ensemble-averaged turbulence level $\langle Tu \rangle >$ in 1% intervals.	73
5.4	Unsteady flow field in the rotor–stator axial space at high compressor load ($\phi = 0.600$ and $Re_c = 120000$). Top: low turbulence case without grid. Bottom: high turbulence case with grid (grid wakes in IGV passage $g/S = 0.5$). Filled contours show ensemble-averaged velocity $\langle u \rangle / \bar{u}_s$. Line contours show ensemble-averaged turbulence level $\langle Tu \rangle >$ in 1% intervals.	74
5.5	Unsteady flow field in the rotor–stator axial space at medium compressor load with the turbulence grid ($\phi = 0.675$ and $Re_c = 120000$). Top: grid wakes incident on IGV blade row ($g/S = 0.0$). Bottom: grid wakes in IGV passage ($g/S = 0.5$). Filled contours show ensemble-averaged velocity $\langle u \rangle / \bar{u}_s$. Line contours show ensemble-averaged turbulence level $\langle Tu \rangle >$ in 1% intervals.	76
5.6	Temporal variation in velocity at several circumferential positions for medium load ($\phi = 0.675$ and $Re_c = 120000$). Common time origin $t^* = 0.5$ at centre of rotor wake disturbance.	77
6.1	C4 stator surface velocity distribution at mid-span ($Re_c = 120000$) for LAG configuration. Experimental data from Solomon [154]	84
6.2	C4 stator suction surface velocity distributions at mid-span ($Re_c = 120000$). Measurements without grid from Hughes [83].	86
6.3	The C4 stator instrumented with an array of surface hot-film sensors .	88
6.4	C4 stator surface intermittency distribution at high loading ($\phi = 0.600$, $Re_c = 120000$). Colour filled contours show ensemble average intermittency ($\langle \gamma \rangle$), line contours show probability of relaxing flow in 1% intervals, and particle trajectories at 1.0U, 0.88U, 0.7U and 0.5U . . .	90

6.5	C4 stator surface intermittency distribution at medium loading ($\phi = 0.675$, $Re_c = 120000$). Colour filled contours show ensemble average intermittency ($\langle\gamma\rangle$), line contours show probability of relaxing flow in 1% intervals, and particle trajectories at 1.0U, 0.88U, 0.7U and 0.5U .	91
6.6	C4 stator surface intermittency distribution at low loading ($\phi = 0.840$, $Re_c = 120000$). Colour filled contours show ensemble average intermittency ($\langle\gamma\rangle$), line contours show probability of relaxing flow in 1% intervals, and particle trajectories at 1.0U, 0.88U, 0.7U and 0.5U . . .	92
6.7	C4 stator surface intermittency distribution at medium loading with IGV wakes in stator blade row passage ($a/S = 0.5$, $\phi = 0.675$ and $Re_c = 120000$). Colour filled contours show ensemble average intermittency ($\langle\gamma\rangle$), line contours show probability of relaxing flow in 1% intervals, particle trajectories at 1.0U, 0.88U, 0.7U and 0.5U	96
6.8	Time-mean ensemble averaged intermittency distribution for the C4 stator ($\overline{\gamma}$)	97
7.1	Predicted CD stator surface pressure distributions at various incidences (MISES, $Tu=4\%$, $Re_1=230000$)	106
7.2	Predicted exit angle (top), pressure loss coefficient (centre), and dimensionless surface length to transition onset on the suction surface (bottom) from the MISES flow solver ($Tu=4.0\%$ and $Re_1=230000$) . .	108
7.3	CADKEY model of the CD stator blade with mounting boss showing milling paths for pressure tube tracks (suction surface view)	112
7.4	CD stator surface velocity distributions. Experimental results and MISES predictions for incidence Cases A and B	115
7.5	CD stator surface velocity distributions. Experimental results and MISES predictions for incidence Cases C and D.	116
7.6	CD stator surface velocity distributions around leading edge. Experimental results and MISES predictions for Cases A–D	117
7.7	CD stator blade with array of surface mounted hot-film sensors installed in the UTAS research compressor	119

7.8	CD stator surface intermittency distributions for incidence Case A. Colour contours show ensemble average intermittency ($\langle\gamma\rangle$); line contours show probability of calmed flow in intervals of 0.1; white lines show particle trajectories at 1.0U, 0.88U, 0.7U and 0.5U	122
7.9	CD stator surface intermittency distributions for incidence Case B. Colour contours show ensemble average intermittency ($\langle\gamma\rangle$); line contours show probability of calmed flow in intervals of 0.1; white lines show particle trajectories at 1.0U, 0.88U, 0.7U and 0.5U	123
7.10	CD stator surface intermittency distributions for incidence Case C. Colour contours show ensemble average intermittency ($\langle\gamma\rangle$); line contours show probability of calmed flow in intervals of 0.1; white lines show particle trajectories at 1.0U, 0.88U, 0.7U and 0.5U	124
7.11	CD stator surface intermittency distributions for incidence Case D. Colour contours show ensemble average intermittency ($\langle\gamma\rangle$); line contours show probability of calmed flow in intervals of 0.1; white lines show particle trajectories at 1.0U, 0.88U, 0.7U and 0.5U	125
7.12	Temporal variation of ensemble average turbulent intermittency ($\langle\gamma\rangle$) (colour contours) around the CD stator leading edge ($Re_c = 120000$) .	126
7.13	Hot-film measurements near the CD stator trailing edge (Case D, $Re_c = 120000$). Top: colour contours of ensemble average intermittency ($\langle\gamma\rangle$) with line contours of probability of calmed flow in intervals of 0.1. Bottom: typical set of simultaneously acquired quasi wall shear stress measurements. Sensor locations are indicated by ∇ . Lines show particle trajectories at speeds of 1.0U, 0.88, 0.7U and 0.5U	129
7.14	CD stator hot-film traces at $Re_c = 95000$	130
7.15	CD stator hot-film traces at $Re_c = 120000$	131
7.16	CD stator hot-film traces at $Re_c = 160000$	132
7.17	Predicted acceleration parameter and momentum thickness Reynolds number for the CD stator (MISES, Cases A and B)	134
7.18	Predicted acceleration parameter and momentum thickness Reynolds number for the CD stator (MISES, Cases C and D)	135

7.19	Unsteady flow field 19.7% axial downstream from CD stator trailing edge. Top: Case A ($\phi = 0.750$). Bottom: Case B ($\phi = 0.710$). Left: time-mean ensemble averaged velocity. Centre: time-mean random, periodic and total disturbance level. Right: colour contours of ensemble averaged velocity; line contours of ensemble average turbulence Tu with 1% interval spacing ($Re_c = 120000$)	140
7.20	Unsteady flow field 19.7% axial downstream from CD stator trailing edge. Top: Case C ($\phi = 0.675$). Bottom: Case D ($\phi = 0.600$). Left: time-mean ensemble averaged velocity. Centre: time-mean random, periodic and total disturbance level. Right: colour contours of ensemble averaged velocity; line contours of ensemble average turbulence Tu with 1% interval spacing ($Re_c = 120000$)	141
7.21	Time-mean wake velocity profile of a CD stator blade showing estimated linear inviscid velocity distribution (Case A, $\phi = 0.750$, $Re_c = 120000$)	143
7.22	Variation of pitchwise average stator exit flow angle (α_2) with incidence (top); variation of total pressure loss coefficient ($\bar{\omega}$) with incidence (centre); and variation in predicted suction surface transition onset location (MISES) and extent of suction surface transitional flow ($0.2 < \bar{\gamma} < 0.8$) with incidence (bottom). All measurements made at $Re_c = 120000$. . .	145
8.1	Unsteady flow field around C4 stator leading edge (UNSFLO) for LAG configuration (Case A, $\phi = 0.675$, $Re_c = 120000$). Vectors indicate perturbation from local time-mean velocity. Colour shading indicates fluid entropy relative to the maximum level at the wake centre	156
8.2	Unsteady flow field around C4 stator leading edge (UNSFLO) for SAG configuration (Case C, $\phi = 0.675$, $Re_c = 120000$). Vectors indicate perturbation from local time-mean velocity. Colour shading indicates fluid entropy relative to the maximum level at the wake centre	157
8.3	Unsteady flow field around CD stator leading edge (UNSFLO) for SAG configuration (Case E, $\phi = 0.675$, $Re_c = 120000$). Vectors indicate perturbation from local time-mean velocity. Colour shading indicates fluid entropy relative to the maximum level at the wake centre	158

8.4	Comparison of dimensionless ensemble-averaged quasi wall shear stress $\langle \tau_q \rangle / \overline{\tau_q}$ from hot-film sensors (left) and dimensionless skin friction factor $c_f / \overline{c_f}$ from UNSFLO (right). C4 stator, LAG configuration, Case A, $\phi = 0.675$, $Re_c = 120000$	160
8.5	Comparison of dimensionless ensemble-averaged quasi wall shear stress $\langle \tau_q \rangle / \overline{\tau_q}$ from hot-film sensors (left) and dimensionless skin friction factor $c_f / \overline{c_f}$ from UNSFLO (right). C4 stator, SAG configuration, Case C, $\phi = 0.675$, $Re_c = 120000$	161
8.6	Comparison of dimensionless ensemble-averaged quasi wall shear stress $\langle \tau_q \rangle / \overline{\tau_q}$ from hot-film sensors (left) and dimensionless skin friction factor $c_f / \overline{c_f}$ from UNSFLO (right). CD stator, SAG configuration, Case E, $\phi = 0.675$, $Re_c = 120000$	162
8.7	Temporal variation in momentum thickness Reynolds number and shape factor from UNSFLO computations. C4 stator, LAG configuration (Case A, $\phi = 0.675$, $Re_c = 120000$)	163
8.8	Temporal variation in momentum thickness Reynolds number and shape factor from UNSFLO computations. C4 stator, SAG configuration (Case C, $\phi = 0.675$, $Re_c = 120000$)	164
8.9	Temporal variation in momentum thickness Reynolds number and shape factor from UNSFLO computations. CD stator, SAG configuration (Case E, $\phi = 0.675$, $Re_c = 120000$)	165
8.10	C4 stator surface ensemble-averaged intermittency (colour contours) and probability of instability wave occurrence (line contours) with superimposed particle trajectories at different proportions of local free-stream velocity (adapted from Hughes and Walker [85]) and added neutral stability boundary predicted by the present study (Case A, LAG, $Re_c = 120000$)	168
8.11	C4 stator surface ensemble-averaged intermittency (colour contours) and probability of instability wave occurrence (line contours) with superimposed particle trajectories at different proportions of local free-stream velocity (adapted from Hughes and Walker [85]) and added neutral stability boundary predicted by the present study (Case B, LAG, $Re_c = 120000$)	169

8.12	C4 stator surface ensemble-averaged intermittency (colour contours) and probability of instability wave occurrence (line contours) with superimposed particle trajectories at different proportions of local free-stream velocity and added neutral stability boundary predicted by the present study (Case C, SAG, $Re_c = 120000$)	170
8.13	C4 stator surface ensemble-averaged intermittency (colour contours) and probability of instability wave occurrence (line contours) with superimposed particle trajectories at different proportions of local free-stream velocity and added neutral stability boundary predicted by the present study (Case D, SAG, $Re_c = 120000$)	171
8.14	CD stator surface ensemble-averaged intermittency (colour contours) and probability of instability wave occurrence (line contours) with superimposed particle trajectories at different proportions of local free-stream velocity and neutral stability boundary predicted by the present study (Case E, SAG, $Re_c = 120000$)	172
8.15	Typical raw quasi wall shear stress traces on C4 stator surface (LAG configuration). Top: IGV wakes aligned in stator passage (Case A). Bottom: IGV wakes incident on stator blade row (Case B). LAG, $Re_c = 120000$	176
8.16	Typical raw quasi wall shear stress traces on C4 stator surface (SAG configuration). Top: IGV wakes aligned in stator passage (Case C). Bottom: IGV wakes incident on stator blade row (Case D). SAG, $Re_c = 120000$	177
8.17	Typical raw quasi wall shear stress traces on CD stator surface (Case E, SAG, $Re_c = 120000$)	178
A.1	Mid-span pressure tapping locations of C4 stator blade (top) and mid-span hot-film sensor locations of C4 stator blade (bottom)	188
A.2	Mid-span surface pressure tapping locations of CD stator blade (top) and mid-span hot-film sensor locations of CD stator blade (bottom)	192
C.1	Numerical simulation of research compressor inlet contraction (CFX). Rendered view of intake model (top) with corresponding contours of pressure coefficient on a radial plane and pressure coefficient of intake surfaces with and without loss terms for the grid included (bottom)	201

C.2 Calibration of research compressor contraction pressure coefficient without turbulence grid installed (markers). Lines indicate flow coefficient calculated by the method presented above	203
---	-----

List of Tables

3.1	Compressor blade details for studies of Solomon [154], Hughes [83], and present investigation	37
5.1	Pitchwise averaged integral length scale for low and high turbulence cases (medium loading $\phi = 0.675$)	79
6.1	Circumferentially averaged C4 stator inlet incidence with corresponding stator inlet Reynolds number at low and high inlet turbulence	85
7.1	Matrix of measured operating conditions for the CD stator blade row: pitchwise average incidence (i°) and inlet Reynolds number (Re_1) at entry to the CD stator blade row for various values of flow coefficient (ϕ) and reference Reynolds number (Re_c)	110
8.1	Matrix of test conditions for the study of the flow around the leading edge of the C4 and CD stator blades. All measurements were made at constant reference Reynolds number ($Re_c = 120000$)	151
A.1	Mid-span pressure tapping locations of C4 stator blade suction surface. All coordinates are relative to the geometrical blade leading edge defined as the intersection of the leading edge and camber line ($x = y = x^* = s^* = 0$). $x^* = x/c_x$ is dimensionless axial distance. $c_x = c \cos(\xi)$ is the axial projection of chord length. $s^* = s/s_{max}$ is dimensionless surface length. $c = 76.2$ mm and $s_{max} = 79.23$ mm (adapted from Solomon [154])	189

A.2	Mid-span hot-film sensor locations of C4 stator blade. All coordinates are relative to the geometrical blade leading edge defined as the intersection of the leading edge and camber line ($x = y = x^* = s^* = 0$). $x^* = x/c_x$ is dimensionless axial distance. $c_x = c \cos(\xi)$ is the axial projection of chord length. $s^* = s/s_{max}$ is dimensionless surface length. $c = 76.2$ mm, $s_{max} = 79.23$ mm on the suction surface and $s_{max} = 76.27$ on the pressure surface (adapted from Solomon [154]) . . .	190
A.3	Mid-span pressure tapping locations of CD stator blade. All coordinates are relative to the geometrical blade leading edge defined as the intersection of the leading edge and camber line ($x = y = x^* = s^* = 0$). $x^* = x/c_x$ is dimensionless axial distance. $c_x = c \cos(\xi)$ is the axial projection of chord length. $s^* = s/s_{max}$ is dimensionless surface length. $c = 152.4$ mm and $s_{max} = 162.1$ mm on the suction surface and $s_{max} = 154.8$ mm on the pressure surface	193
A.4	Mid-span hot-film sensor locations of CD stator blade. All coordinates are relative to the geometrical blade leading edge defined as the intersection of the leading edge and camber line ($x = y = x^* = s^* = 0$). $x^* = x/c_x$ is dimensionless axial distance. $c_x = c \cos(\xi)$ is the axial projection of chord length. $s^* = s/s_{max}$ is dimensionless surface length. $c = 152.4$ mm and $s_{max} = 162.1$ mm on the suction surface and $s_{max} = 154.8$ mm on the pressure surface	194
C.1	Table of CFX model parameters	200

Nomenclature

General Variables

c	blade chord
c_f	skin friction coefficient = $2\tau_w/\rho U^2$
C_p	surface pressure coefficient = $(P_1 - p)/(P_1 - p_1)$
D	diameter
E	anemometer bridge voltage
E_o	anemometer bridge voltage at zero flow = $((E^2 - E_o^2)/E_o^2)^3$
H	boundary layer or wake shape factor = δ^*/θ
i	blade incidence angle = $\alpha - \beta$
K	acceleration parameter = $(\nu/U^2)dU/dx$
L	length
p	static pressure
P	total pressure
R	radius
Re_a	compressor inlet Reynolds number = $V_a.c/\nu$
Re_c	compressor reference Reynolds number = $U_{mb}.c/\nu$
Re_1	stator inlet Reynolds number = $V_1.c/\nu$
s	surface length
s^*	dimensionless surface length = s/s_{max}
s_{max}	surface length from leading to trailing edge
S	blade pitch
S^*	dimensionless pitchwise distance = w/S
t	time
t^*	dimensionless time = t/T
T	rotor passing period
Tu	random disturbance level or ‘turbulence’

$\tilde{T}u$	periodic disturbance level
Tu_D	apparent or ‘total’ disturbance level
U	local free-stream velocity
U_{mb}	mid-blade rotor blade speed
V_a	axial velocity at compressor inlet
w	peripheral distance
x	axial coordinate
α	flow angle relative to axial direction, turbulent spot spreading angle
β	blade angle relative to axial axial direction
γ	turbulent intermittency
λ_θ	pressure gradient parameter = $(\theta^2/\nu)dU/dx$
Λ	integral or ‘macro’ turbulence scale
ρ	air density
ϕ	flow coefficient = V_a/U_{mb}
σ	blade row solidity = c/S
ν	kinematic viscosity = μ/ρ
μ	absolute viscosity
τ_w	wall shear stress
τ_q	quasi wall shear stress
θ	boundary layer momentum thickness, wake momentum thickness, blade camber angle = $\beta_1 - \beta_2$
δ^*	boundary layer displacement thickness, wake displacement thickness
ξ	blade stagger angle
$\bar{\omega}$	total pressure loss coefficient = $(P_1 - P_2)/(P_1 - p_1)$

Subscripts

1	stator blade row inlet
2	stator blade row outlet
cr	critical
in	compressor inlet (upstream from IGV)
le	leading edge
mb	mid-blade
te	trailing edge

Acronyms

AVDR	axial velocity – density ratio
CD	controlled diffusion
CFD	computational fluid dynamics
DNS	direct numerical simulation
HP	high-pressure
LAG	long axial gap
LDA	laser-doppler anemometry
LDV	laser-doppler velocimetry
LES	large eddy simulation
LP	low-pressure
OD	outer diameter
PDF	probability density function
PVC	peak-valley counting
RANS	Reynolds-averaged Navier–Stokes
SAG	short axial gap
UTAS	University of Tasmania

Mathematical Notation

$\overline{(\)}$	time average
$\langle \ \rangle$	phase-lock or ensemble averaging