Unsteady Flow and Transition Phenomena in an Axial Flow Compressor

by

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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.

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Alan D. Henderson

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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 $= \delta^*/\theta$
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	periperal 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 $= \mu/\rho$
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
$\overline{\varpi}$	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