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UNSTEADY EFFECTS ON SEPARATED FLOW TRANSITION IN AN AXIAL FLOW COMPRESSOR

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ABSTRACT

A surface hot-film array on the outlet stator of a 1.5 stage axial compressor is used to examine the periodic wake-induced transition on both suction and pressure surfaces. For a given surface pressure distribution which is known to give transition through leading edge and mid-chord separation bubbles, the effect of inlet disturbance field and axial row spacing are investigated.

Ensemble average distance~time plots of turbulent intermittency and probability of relaxing non-turbulent flow are presented. These show the periodic transition in separation bubbles to be significantly altered by both blade row spacing and clocking effects.

INTRODUCTION

The embedded blade row in a multistage axial turbomachine is periodically swept by turbulent wakes from upstream blading. The blade boundary layer behaviour under these conditions is dominated by periodic wake-induced transition. Mayle (1991, 1992) notes that transition by other modes is observed in regions between the wake-induced transitional or turbulent strips and refers to this behaviour as "Multi-moded Transition". Mayle's (1991,1992) reviews provide a thorough summary of the relevant literature.

The current practice in designing aeroengines is to use steady flow theory to design compressor and turbine blades. Typical blade elements are subjected to high levels of flow periodicity and freestream turbulence, as well as strong pressure gradients. Under these adverse conditions, transition modeling is not sufficiently well developed that Navier-Stokes type solvers designed for the solution of flows in turbomachinery are particularly accurate.

Prediction of the boundary layer development through transition is necessary for a precise calculation of the heat transfer and blade losses. The aim of the present study is to provide a base for more accurate modelling of the unsteady transition process, and facilitate the development of blade designs which gain maximum benefit from unsteady effects.

EXPERIMENTAL DETAIL

Research Compressor

The compressor is a 1.5-stage axial flow machine with three blade rows: inlet guide vanes (IGV), rotor and stator. Fig. 1 shows a cross-section of the compressor blading at mid-passage. There are 38 blades in each of the stationary rows and 37 blades in the rotor, giving space/chord (S/c) ratios at mid-blade height of 0.99 and 1.02 respectively. The blades all have a constant chord of 76.2 mm and an aspect ratio of 3.0. The blade sections were designed for free vortex flow with 50% reaction at mid-blade height at a flow coefficient (axial velocity/rotor mid-blade speed, $\phi = V_a/U_{mb}$) of 0.76. The design values of inlet and outlet blade angles from axial at mid-blade height are, respectively: IGV 0.0°, 27.8°; rotor and stator 45.0°, 14.0°. Downstream of the compressor there is an annular diffuser, and a cylindrical sliding throttle at the outlet is used to control the through flow.

The IGV and stator rows are each mounted on rotatable supporting rings to permit clocking of one row relative to the other. Further details of the research compressor can be found in Solomon (1996).

Measurement Techniques

The compressor and measurement systems were controlled by two IBM-compatible 486 personal computers. One computer was used to control the compressor and acquire data from slow response instrumentation. The other was used for high speed data acquisition from the hot-film anemometers. Operating speeds were typically 500 rpm, and the compressor speed was continuously adjusted with a speed setting accuracy of ± 0.1 rpm to maintain constant Reynolds number. After initial positioning, the throttle setting was left unchanged during individual flow traverses.

Surface velocity distributions were obtained from static pressure measurements on two adjacent stator blades fitted with pressure tappings opening into the same blade passage. Total pressure values on the stagnation streamline were obtained from a Kiel probe 50%c upstream of the stator leading edge, and verified using a cobra type 3-hole probe. The overall uncertainty of time-mean pressure data was 0.15%.

One stator blade was instrumented with an array of 61 hot-film sensors at mid-blade height. The metal sensors, spaced at 2.54 mm intervals, were plated onto a kapton sheet which was wrapped around the whole blade surface. Data were acquired simultaneously from sets of 5 film gauges using TSI IFA-100 anemometers.

For hot-film observations each anemometer output was AC coupled with a high-pass cut off frequency of 0.1Hz. The signal was then low-pass filtered at 20 kHz before sampling at 50 kHz and data storage. The signal conditioner amplification was set automatically for each spatial measurement point to optimise signal to noise ratio. The frequency response of the hot-film measurements was better than 30 kHz. The rotor blade passing frequency for these tests was 300 Hz.

Ensemble-average values were obtained from 512 records. Sampling was triggered at the same point on each rotor revolution by an optical encoder so that the wakes of the same rotor blades were observed in each record. Each record consisted of 1024 samples typically covering about 6 rotor blade passing periods.

Range of Investigation

Measurements were conducted at mid-span, where radial flows are small. Data were obtained at a flow coefficient ($\phi = V_a/U_{mb}$) of 0.840. This corresponds to a lightly loaded stator with mid-span incidence of -6.1°. Tests were performed at a constant reference Reynolds number of $Re_{ref} = 120000$, which corresponds to a stator inlet Reynolds number of $Re_1 = 130000$. This value is low compared with typical values of aircraft gas turbine engine operation; however surface hot-film observations reported by Solomon (1996) show essentially similar behaviour to that in the higher Reynolds number multistage compressor experiments of Halstead et al. (1995).

The stator boundary layer transition behaviour was investigated for two IGV clocking and two axial blade row spacing conditions. The two IGV clocking positions, $a/S = 0.00$ and 0.50 (see Fig. 1), correspond approximately to the cases of minimum and maximum rotor wake periodicity experienced by the stator blade element at mid-blade height (see Walker et al., 1997). The large axial separation of the rotor and stator in the first blade row spacing condition, 106% chord, was such that the interactions of the stator with the upstream rotor potential flow field were minimal. The second condition, 41% chord axial spacing, is closer to current industry design practice.

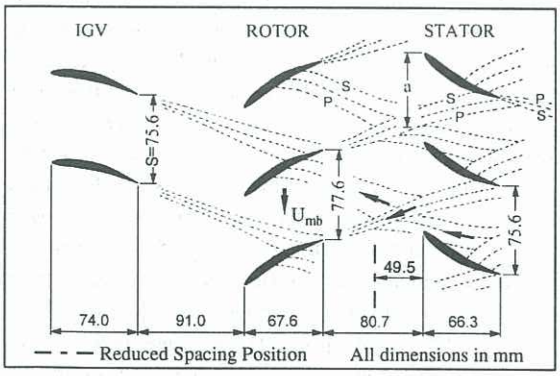

Figure 1: Cross-section of compressor blading at mid-span, showing instantaneous wake dispersion. S = Suction side. P = Pressure side. Arrows indicate relative flow in wakes. a = circumferential offset of stator leading edge from centre of IGV wake street.

OBSERVATIONS AND DISCUSSION

Surface Velocity Distribution

The stator surface velocity distribution obtained from mid-span surface pressure tappings is shown in Fig. 2. The suction surface distribution exhibits a plateau which peaks near 30% chord; a discontinuity in velocity gradient around 70% chord clearly indicates the development of a laminar separation bubble. The pressure surface velocity distribution shows a deceleration over the forward part of the blade, which is severe enough to cause a leading edge laminar separation bubble, followed by an acceleration towards the trailing edge.

Ensemble average intermittency

Ensemble average values of turbulent intermittency $\langle\gamma\rangle$ obtained from the surface hot-film measurements of wall shear stress τ are indicated by shading on distance~time plots in Figs. 3 and 4. The grading is from white for laminar flow ($\langle\gamma\rangle = 0$) to black for fully turbulent flow ($\langle\gamma\rangle = 1$). Values of γ were determined by a hybrid probability distribution function and peak-valley counting method described by Solomon (1996).

Figs. 3 and 4 also show line contours of constant ensemble average relaxing non-turbulent flow probability $\langle\kappa\rangle$. The latter type of flow was identified by $d\tau/dt$ remaining negative immediately following the passage of a turbulent spot. It is characterised by a higher wall shear stress, with a resulting increase in stability and resistance to separation, compared to a steady laminar boundary layer subjected to the same

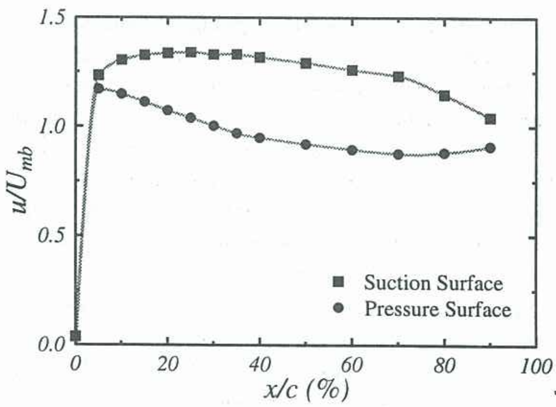

Figure 2: Stator surface velocity distribution at mid blade height. $Re_{ref} = 120000$, $\phi = 0.840$.

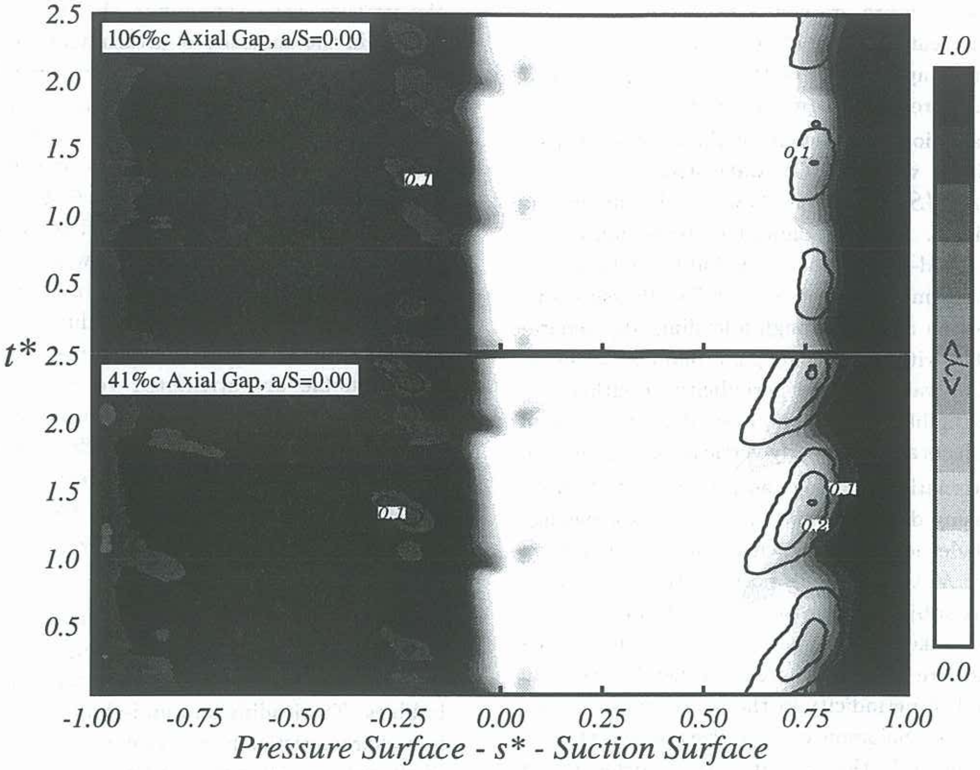

Figure 3: IGV wake street on stator (a/S=0.00). Ensemble average turbulent intermittency $\langle\gamma\rangle$ (shading) and probability of relaxing non-turbulent flow $\langle\kappa\rangle$ (line contours) in stator blade boundary layer. s^* = ratio of local to maximum surface distance from leading edge. t^* = time non-dimensionalised by rotor passing period.

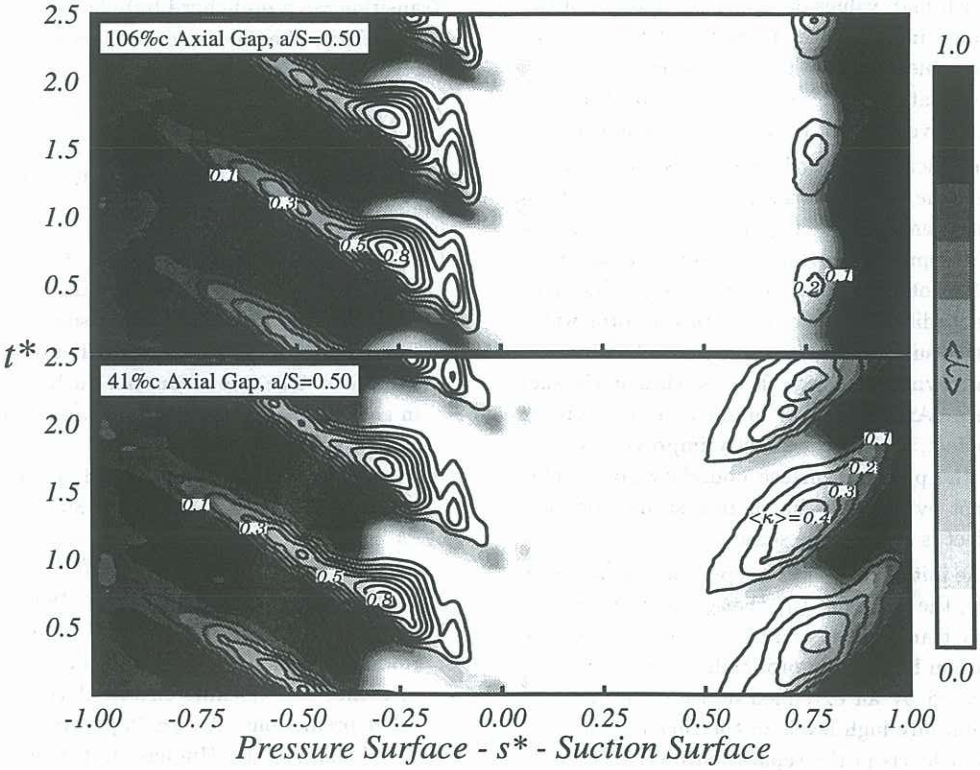

Figure 4: IGV wake street in passage (a/S=0.50). Ensemble average turbulent intermittency $\langle\gamma\rangle$ (shading) and probability of relaxing non-turbulent flow $\langle\kappa\rangle$ (line contours) in stator blade boundary layer.

streamwise pressure gradient. Higher values of $\langle\kappa\rangle$ indicate a greater degree of "calming" effects, and a more regular appearance of the preceding turbulent spots which are a pre-requisite for this type of flow.

The transitional behaviour for the large axial spacing condition, with the IGV wake street incident on the stator (a/S = 0.00), is shown in the upper portion of Fig. 3. The suction surface transition occurs through a mid-chord separation bubble with turbulent re-attachment around s^* = 0.75. Pressure surface transition occurs through a leading edge separation bubble with re-attachment around s^* = -0.10. Evidence of wake induced periodicity on either surface is negligible, and is emphasised by the lack of calming effects and the nearly vertical contours of $\langle\gamma\rangle$.

The alternative clocking case, with the IGV wake street passing down the middle of the stator passage at mid-blade height, is shown in the upper portion of Fig. 4. At this clocking position the stator leading edge is subjected to disturbances from relatively pure rotor wakes. Although the changes on the suction surface are minimal, there is a general increase in the amount of periodicity in the transitional flow for both surfaces. Solomon et al. (1998) show evidence that the change in the pressure surface behaviour is largely due to changes in the inflow random turbulence caused by clocking.

On the pressure surface the wake-induced strips appear as dark tongues followed by regions of strong calming with high values of $\langle\kappa\rangle$. The contours of $\langle\kappa\rangle$ give the best indication of transitional flow periodicity. $\langle\kappa\rangle$ values peak at 0.8, at about s^* = -0.25; this means that a wake induced transitional strip is occurring in over 80% of rotor wake passing events.

The identification of turbulence close to the leading edge on the suction surface may be partly due to genuine incipient turbulent spots which subsequently decay, or to spurious turbulence identification associated with potential flow fluctuations produced as the stator leading edge cuts through the rotor wake. The pressure surface has an associated calmed region which is antisymmetric with these patches on the suction surface. Another factor here could be the rotor wake-jet effect, which will directly impress turbulent fluid into the pressure surface boundary layer. This effect is not evident on the suction surface because the jet effect is of opposite sense.

After the initial decay of the spurious leading edge turbulence, the values of $\langle\gamma\rangle$ then increase monotonically until transition is complete. In the region of the separation bubble the probability of relaxing flow is accentuated by an extended decay of shear stress from the initially high levels in the turbulent spot to the very low levels in the separation bubble.

The effect of reduced axial blade row spacing on unsteady transition behaviour is seen by comparing the top and bottom of Figs. 3 and 4. The effects on the pressure surface are minor, although there is some change in the unsteady re-attachment location of the leading edge bubble in the path between wake induced strips. The effects on the suction surface are more pronounced with the appearance of stronger wake-induced transition strips. These occur at $s^* \simeq 0.60$ and 0.50 for the a/S = 0.00 and 0.50 cases, respectively. The stronger wake-induced strip is accompanied by an increase in relaxing flow probability. This increase in calming lengthens the transitional flow region in the path between wake-induced events.

The unsteady effects on the transition in the mid-chord bubble are attributed to the increased rotor wake turbulence combined with the increase in strength of the rotor wake-jet effect, although the relative magnitude of the two effects is not known. These unsteady changes are to far rearward to be influenced by leading edge interactions.

CONCLUDING REMARKS

The investigation of periodic transition on the outlet stator of a 1.5 stage axial compressor highlights the unsteady effects on transition through separation bubbles. The leading and mid-chord bubbles respond in a characteristically different manner to the effects of altered inlet disturbance field and axial blade row spacing. The effects of blade row clocking or changing the freestream disturbance are most pronounced when transition occurs through a leading edge bubble; there is little change in mid-chord bubble behaviour. Transition via a mid-chord bubble was more sensitive to the effects of axial blade row spacing than to blade row clocking.

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