OBSERVATIONS OF WAKE-INDUCED TRANSITION ON AN AXIAL COMPRESSOR BLADE

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ABSTRACT
A closely-spaced array of hot-film gages fully covering both suction and pressure surfaces on the outlet stator of a 1.5-stage axial compressor was used to obtain dynamic measurements of wall shear stress. Observations were made over a range of Reynolds numbers at an incidence close to the design value. Various methods of presenting the data, including time-space contour plots of ensemble-average intermittency from the film gages are analyzed; related problems of interpretation are discussed. Extensive regions of laminar flow were identified on the suction surface; at the highest Reynolds number, small laminar patches were still evident at 85% chord and transitional flow covered up to 70% of suction surface length. The influence of passing rotor wakes on transition varied markedly with Reynolds number. The behavior of wake-induced transitional strips on the suction and pressure surfaces of the compressor blade differed significantly; their propagation characteristics also varied in some respects from those observed on turbine airfoils.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>c</td>
<td>blade chord</td>
</tr>
<tr>
<td>i</td>
<td>blade incidence</td>
</tr>
<tr>
<td>k</td>
<td>film calibration constant (Eqn. (1))</td>
</tr>
<tr>
<td>s</td>
<td>surface distance</td>
</tr>
<tr>
<td>s'</td>
<td>non-dimensional surface distance from leading edge, s/S</td>
</tr>
<tr>
<td>t</td>
<td>time</td>
</tr>
<tr>
<td>t*</td>
<td>non-dimensional time, t/T</td>
</tr>
<tr>
<td>E</td>
<td>hot-film anemometer output voltage</td>
</tr>
<tr>
<td>E0</td>
<td>anemometer voltage at zero flow</td>
</tr>
<tr>
<td>N</td>
<td>rotor speed (rpm)</td>
</tr>
<tr>
<td>Q</td>
<td>total heat transfer from film gage</td>
</tr>
<tr>
<td>Qo</td>
<td>heat transfer from film gage at zero flow</td>
</tr>
<tr>
<td>Qs</td>
<td>heat transfer from film gage to the substrate</td>
</tr>
<tr>
<td>Re</td>
<td>rotor and stator average Reynolds number</td>
</tr>
<tr>
<td>Re1</td>
<td>stator blade inlet Reynolds number, U1/c/ν</td>
</tr>
<tr>
<td>S</td>
<td>maximum surface distance</td>
</tr>
<tr>
<td>T</td>
<td>rotor blade passing period</td>
</tr>
<tr>
<td>U</td>
<td>local freestream velocity</td>
</tr>
<tr>
<td>U1</td>
<td>blade row inlet relative velocity</td>
</tr>
<tr>
<td>Umb</td>
<td>rotor blade velocity, at mid blade height</td>
</tr>
<tr>
<td>Va</td>
<td>inlet axial velocity</td>
</tr>
<tr>
<td>γ</td>
<td>turbulent intermittency</td>
</tr>
<tr>
<td>ν</td>
<td>kinematic viscosity</td>
</tr>
<tr>
<td>τ</td>
<td>quasi-wall shear stress (Eqn. (2))</td>
</tr>
<tr>
<td>r</td>
<td>long term mean quasi shear stress</td>
</tr>
<tr>
<td>rτw</td>
<td>wall shear stress</td>
</tr>
<tr>
<td>(r(i)&gt;</td>
<td>ensemble average r at time t = to + iΔt</td>
</tr>
<tr>
<td>(r(i)&gt;RMS</td>
<td>ensemble random unsteadiness of r</td>
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<tr>
<td>(r(i)&gt;Skew</td>
<td>ensemble skew of r</td>
</tr>
<tr>
<td>(r(i)&gt;Kurt</td>
<td>ensemble kurtosis of r</td>
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<tr>
<td>Δt</td>
<td>data acquisition sampling period</td>
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INTRODUCTION
The study of wake-induced transition and the influence of free-stream turbulence on the flow around turbine blades has received a great deal of attention due to the importance of transitional flow and heat transfer in the turbine environment. Early investigators such as Turner (1971) used time-mean measurements of surface heat transfer distributions to examine the influence of free-stream disturbances on the boundary layer behavior. Later workers (Sharma et al., 1982; Doorly and Oldfield, 1985; Hodson, 1985; LaGraff et al., 1990; Addison and Hodson, 1990a, 1990b; Halstead et al., 1990; Hodson et al., 1994; Schulte and Hodson, 1994) used time-resolved measurements from small surface film gages to monitor individual turbulent breakdown events and track the development of wake-induced transition on turbine airfoils. The review by Mayle (1991)
contains a comprehensive bibliography of this research. Recent progress in the modeling of unsteady multi-mode transition processes on gas turbine airfoils has been described by Mayle (1992).

In marked contrast with the turbine situation, the problem of unsteady transition in axial compressors has received comparatively scant attention. This may have been partly due to a general belief that the boundary layer on a compressor blade would be predominantly turbulent. However, the study of Walker (1968) clearly established the existence of extensive laminar flow regions on the stator of a single-stage compressor. Subsequent hot wire observations by Walker (1974) provided the first evidence of unsteady transition phenomena on axial compressor blades in response to passing rotor wakes. Further discussion of this work and more recent hot wire measurements of wake-induced turbulent spots on an axial compressor blade have been given by Walker (1993) and Walker et al. (1993). Detailed hot wire studies of transitional flow phenomena in a compressor cascade both with and without incident wakes have been reported by Dong and Cumpsty (1989a, 1989b).

Surface film gages have been very little used for observing unsteady transition behavior in compressors. Hansen and Okiishi (1989) reported studies of wake-induced transition on an axial compressor stator using surface hot film gages mounted at intervals of 25% chord. The present investigation uses a closely packed array of hot film gages at intervals of about 3% chord over the whole surface of a 1.5-stage axial compressor stator. To the authors’ knowledge, only the parallel study by Halstead et al. (1995) of wake-induced transition in a multi-stage compressor is capable of offering such detailed resolution.

The boundary layers on compressor blades are subjected to relatively extensive regions of positive pressure gradient because the bulk flow is generally decelerating. Turbine blades, on the other hand, normally exhibit quite extensive regions of accelerating flow. Recent research by Walker and Gostelow (1990), Gostelow et al. (1994) and Solomon et al. (1995) has emphasized the fundamental influence of pressure gradient on transition for boundary layers subjected only to random free-stream disturbances. The transition process in a positive pressure gradient occurs much more rapidly and differs significantly in physical character from that in constant pressure or accelerating flows.

It is therefore timely to take the next step and examine unsteady transition phenomena in adverse pressure gradients. The present investigation undertakes this task with particular reference to the problem of wake-induced transition on an axial compressor blade. The practical application of this work is not concerned with heat transfer as in the turbine situation. The ultimate aim is to identify the basic flow physics and examine the ways in which unsteady transition phenomena influence the evolution of losses and alter the ability of compressor blade boundary layers to withstand separation.

**EQUIPMENT AND TEST CASES**

**Research Compressor**

The research compressor is a 1.5-stage axial flow machine with a 37 blade rotor, a 38 blade inlet guide vane (IGV) row and a 38 blade stator row. The blades have a nominal chord of 76.2 mm and are machined to a C4 profile on a circular arc camber line. The hub diameter is 686 mm, the tip diameter 1143 mm, and the blade aspect ratio is 3.0. At mid-blade height the space/chord ratio is 1.02 for the rotor and 0.99 for the stationary rows. The IGV has an inlet blade angle of 0.0° (from axial) and an outlet blade angle of 27.8° at mid-blade height. The corresponding blade angles for the rotor and stator rows are 45.0° at inlet and 14.0° at outlet. The axial clearances for these tests were 1.17c between the IGV trailing edge and the rotor leading edge and 1.05c between the rotor and stator. Fig. 1 shows a cross section of the compressor blading. A full description of this machine may be found in Oliver (1961).

Previous measurements indicate that the long term average total disturbance level in the stator blade passage around mid-chord was about 3%.

A cylindrical sliding throttle at the outlet of an annular diffuser downstream of the compressor is used to adjust the throughput. The compressor is driven by a variable speed DC drive; an optical shaft encoder generating 6000 pulses/rev is used to obtain rotor speed and a zero-marker signal for synchronized sampling.

The inlet axial velocity is found using a pitot-static probe mounted upstream of the IGV row. Inlet temperature is measured using a platinum resistance thermometer. Capacitive transducers are used to measure ambient pressure and inlet dynamic pressure. All low-speed data acquisition and control of the compressor speed and throttle position is performed by IBM-compatible PC. The control program sets the throttle position to obtain the required flow coefficient before a test, and adjusts speed continuously to maintain constant Reynolds number as atmospheric conditions vary.

**Test cases**

The three test cases presented here examine the influence of Reynolds number on transition behavior for a machine flow coefficient \(\left(\frac{V_a}{U_{mb}}\right)\) of 0.675. This is close to the design incidence of the machine and gives a nearly constant incidence angle over the Reynolds number range. A summary of the test conditions is given in Table 1. The values of \(U_{mb}\) and rotational speed \(N\) quoted are for standard atmospheric conditions. The actual speed changed through the tests according to ambient temperature and pressure.

**Surface velocity distributions**

Two adjacent stator blades are fitted with pressure tappings opening into the same flow passage. All tappings were plumbed through a Scanivalve to a capacitative pressure transducing system and signal conditioner. The PC system was used to set operating points...
and read the output from the pressure transducer system. Total pressure was obtained using a Kiel probe inserted 0.5c upstream of the stator leading edge so that the surface velocities could be determined. The overall uncertainty of the time-averaged pressure signals is estimated at 0.15%.

The surface velocity distributions for the three test cases, all close to zero incidence, are shown in Fig. 2. They are generally slightly convex on the suction surface and slightly concave on the pressure surface. There is little difference between the distributions at inlet Reynolds numbers of Re1 = 160000 and 112000. For the lowest Reynolds number of Re1 = 55400 the distribution shows the influence of slightly lower incidence near the leading edge; a slight perturbation between 60% and 70% chord indicates the development of a mid-chord laminar separation bubble on the suction surface. In retrospect, it would have been preferable to vary the operating flow coefficient with Reynolds number to eliminate this slight incidence variation.

**Surface film gages and high speed data acquisition**

One of the pressure-tapped stator blades was replaced by a hot-film instrumented blade. The root of this blade was machined at the University of Tasmania to accept the sensor wires from the films. The sensor array itself was manufactured and bonded to the surface of the prepared blade by Analytical Services and Materials, Inc. The sensor array consists of 61 metal sensors plated onto a kapton sheet at 2.54 mm intervals. The sheet was wrapped around the blade from the trailing edge on the suction surface to the trailing edge on the pressure surface, with the sensors in-line at mid-blade height. This resulted in a smooth blade surface except near the root where the lead wires were connected to the sensor sheet. The latter region was immersed in the annulus wall boundary layer.

Up to five TSI IFA-100 constant temperature anemometer bridges and signal conditioners were available for most of the testing. Simultaneous operation of sensors was only implemented with every second gage to minimize any inter-gage interference. Each sensor was operated at an overheat ratio of 1.5.

A second IBM-compatible PC fitted with a 1 MHz analog/digital card was used to obtain high speed data from the film gages. The best frequency response observed for the films (using the square wave test of Freymuth and Fingerson (1977)) was around 30kHz. The relative power spectral density of a typical trace was below -80dB at frequencies above 10kHz except for a spike of noise from the anemometer at 14kHz. Voltage data from the signal conditioner was sampled at 50kHz per channel. AC coupled. The high pass filter was set at 0.1 Hz, with the low pass (anti-aliasing) filter at 20 kHz. An amplifier gain of either 50 or 100 was used to give a good signal to noise ratio without saturating the input to the data acquisition system. Long term average bridge voltage at the operating point and at zero flow was taken directly from the IFA-100 anemometer digital panel meter.

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**TABLE 1: Test conditions**

<table>
<thead>
<tr>
<th>(Re)</th>
<th>(Re_1)</th>
<th>(U_{mb}(\text{ms}^{-1}))</th>
<th>(N) (rpm)</th>
<th>(\theta)</th>
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<tr>
<td>171000</td>
<td>160000</td>
<td>32.6</td>
<td>680.0</td>
<td>-0.1</td>
</tr>
<tr>
<td>120000</td>
<td>112000</td>
<td>23.0</td>
<td>480.6</td>
<td>-0.3</td>
</tr>
<tr>
<td>59400</td>
<td>55400</td>
<td>11.0</td>
<td>240.3</td>
<td>-1.0</td>
</tr>
</tbody>
</table>

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**PROCESSING OF THE HOT-FILM DATA**

Direct calibration of the gages was not attempted because of the inherent difficulty of such a procedure. Instead a semi-quantitative method developed by Hodson (1985) has been used to process the hot-film data. Bellhouse and Schultz (1966) show that if the thermal boundary layer thickness is small compared with the velocity boundary layer thickness, and if the pressure gradient is small enough for the thermal boundary layer profile to be linear, then

\[
(Q - Q_s) = k \tau_w^{1/3}
\]

where \(Q\) is the total instantaneous power dissipated by the film and \(Q_s\) is the power loss to the substrate. For hot-films, \(Q_s\) can be of the same order as \(Q\) and must be accurately measured. Hodson (1985) overcame this difficulty by assuming that \(Q_s\) is approximately equal to the heat transfer under zero flow conditions, \(Q_0\). The relationship between wall shear stress and anemometer bridge voltage then becomes

\[
\tau_w \propto \left( \frac{E^2 - E_0^2}{E_0^2} \right)^3 = r
\]

The normalization by \(E_0^2\) in this equation will remove the effects of differences in the sizes and resistances of individual sensors from the results, provided that the rate of heat transfer to the air and substrate have similar dependencies on these variables.

Results of this investigation are presented in a non-dimensional form as "quasi shear stress" \(\tau\). Other workers (Aedison and Hodson, 1990a; Halsead et al., 1990) have presented hot film results in the form \((E - E_0)/E_0\), but more recent work seems to have settled on the current method (Hodson et al., 1994; Halsead et al., 1995).

Fig. 3 (a) shows some typical raw voltage traces from the sensor at \(\theta = 0.60\). Fig. 3 (b) shows the same signals re-processed to give quasi shear stress. The effect of the processing is to strongly enhance the peaks of the signal. \(\tau\) gives a much better indication of the approach of the boundary layer to separation than the raw voltage \(E\). The fluctuating arrival time of individual wake events for separate traces should be noted in passing. This oscillation produces a high random unsteadiness of the sensor signals at phases corresponding to the leading edge of these events.

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**FIGURE 2:** Stator blade surface velocity distributions
Time-distance diagrams can be resolved and ensemble statistics calculated. Quasi shear stress data samples at times of interest is given by the square root of the variance of \( \tau \), so that

\[
\text{Ensemble mean of quasi shear stress} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\tau(i) - \bar{\tau})^2}
\]

where \( \bar{\tau} \) is the ensemble mean of \( \tau \), and \( \text{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\tau(i) - \bar{\tau})^2} \)

The standard deviation or ensemble averaged random unsteadiness is given by the square root of the variance of \( \tau \), so that

\[
\text{Ensemble standard deviation} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\tau(i) - \bar{\tau})^2}
\]

The ensemble skew is found from

\[
\text{Ensemble skew} = \frac{1}{n} \sum_{k=1}^{n} (\tau(i, k) - \tau(i)) -\bar{\tau(i)}\text{RMS}
\]

Ensemble kurtosis was calculated as

\[
\text{Ensemble kurtosis} = \frac{1}{n} \sum_{k=1}^{n} (\tau(i, k) - \tau(i)) -\bar{\tau(i)}\text{RMS}
\]

The current method uses a detector function of the form \( \partial \tau / \partial t \) where \( \partial \tau / \partial t \) is found by central differencing. All intermittency calculation has been done by digital post-processing of the gage records.

Often the detector function is passed through a smoothing function to yield a criterion function. Turbulent regions are then identified as regions where the value of the criterion function exceeds some threshold (Hedley and Keffler, 1974). For this work a slightly different approach based on the Turbulent Energy Recognition Algorithm, TERA, developed by Falco and Gendrich (1990) and modified by Walker and Solomon (1992) for obtaining intermittency from hot wire measurements in compressor blade boundary layers, has been used. Instead of smoothing the detector function, this

The values of 0.88U and 0.5U correspond to typical leading and trailing edge velocities of a turbulent spot in zero pressure gradient, as described by Schubauer and Klebanoff (1955); 0.7U is an approximate mean velocity of propagation for such a spot and for wake-induced turbulent strips (Mayle, 1992). The speed of 0.35U is a typical convection velocity for Tollmien-Schlichting waves; it also corresponds approximately to the trailing edge velocity of the calming region following a turbulent spot (Mayle, 1992).

The data plotted on the t-s diagrams were aligned so that \( t^* = 0 \) coincided with the appearance of the wake center at the film closest to the leading edge. The wake center was identified as the peak of the \( \text{RMS} \) plot for this gage and could be determined to a precision of 0.02 in \( t^* \).

**INTERMITTENCY**

**Flatness method**

Early investigators of isotropic turbulence theory proposed that the intermittency of transitional flow could be inferred from the flatness or kurtosis of the velocity signal (Townsend, 1948). In the current work this method has been applied to infer intermittency from the ensemble kurtosis of quasi shear stress data. The method assumes that the turbulent regions are locally isotropic. Ensemble average intermittency is then found as

\[
\langle \gamma(i) \rangle_{\text{KURT}} = 3.0 / \langle \tau(i) \rangle_{\text{KURT}}
\]

The constant 3.0 in this expression arises from the kurtosis value obtained from a Gaussian distribution. As noted by Corrsin and Kistler (1955), this method is not expected to give accurate results at low values of intermittency.
The threshold level for this work was individually set for each sensor in each flow. Instantaneous quasi shear stress traces were displayed with laminar and turbulent portions of contrasting colors. (Line thickness has been used in Figs. 4 (a) (b) and (c) to convey the same information.) Thresholds were then adjusted until the identification of turbulent-flow regions appeared reasonable. Since this process is time consuming and somewhat arbitrary, substantial effort has been spent looking for suitable non-dimensionalizing parameters which might lead to a universal value of dimensionless threshold level. At this point in time however, no automatic method has yielded results in acceptable agreement with manual identification at all points on the blade surface.

OBSERVATIONS AND DISCUSSION

Individual gage records

Figs. 4 (a) to (c) show sets of typical records from individual gages over the whole blade surface for the three flow cases investigated. The results are presented in the form of quasi shear stress and plotted against dimensionless time in the form of rotor blade passing periods. Quasi shear stress values have been normalized by the local value of long term mean quasi shear stress.

The composite pictures combine subsets of simultaneous samples from either 3 or 5 neighboring gages, as indicated by bracketing in the sidebars. Samples are shown for every second gage only. Thickening of the line style is used to mark sections of each record identified as turbulent; a detailed discussion of this aspect was covered later under intermittency.

Results for the highest Reynolds number case of Re₁ = 160000 are shown in Fig. 4 (a). The upper part of this figure shows strong evidence of wake-induced transition on the suction surface (s* > 0). The appearance of wake-induced turbulent spots can be noted from the records at 0.21s* and 0.28s*. Comparing the behavior within and between these two records (which have been obtained from different subsets) indicates some variability in the position at which these spots appear for successive rotor wake passages and for passage of wakes from the same rotor blade on different revolutions of the machine. This variability must be associated with unsteadiness in the free-stream, or within the wakes themselves. By 0.34s*, however, the appearance of the wake-induced spots is surprisingly regular. The leading edges of these spots are very sharply defined.

The wake-induced turbulent spots grow steadily with distance downstream, and exhibit the classic calming period with exponential recovery in velocity towards the undisturbed state within the laminar region immediately following each spot. There is little evidence of any Tollmien-Schlichting wave activity here. Around 0.95s* additional disturbances start to appear in the remaining laminar regions. Some occasional laminar patches can still be seen at 0.86s*, but by 0.92s* the flow between the wake-induced spots has become completely turbulent. Some unsteadiness at the rotor blade passing frequency is still apparent for the gage closest to the trailing edge.

The flow behavior on the pressure surface at Re₁ = 160000 (lower half of Fig. 4 (a), s* < 0) is quite different. Wake-induced turbulent spots are again present, but they are much weaker and more irregular in their appearance. The associated calming and relaxation effects are similarly weak; there is now frequent evidence of higher frequency disturbances characteristic of Tollmien-Schlichting waves and examples of breakdown occurring from packets of such waves. Transition proceeds more rapidly on the pressure surface and is essentially complete by -0.71s*.

Records for the intermediate Reynolds number case of Re₁ = 112000 are shown in Fig. 4 (b). The reduction in Reynolds number has significantly stabilized the flow, and the transition region has moved rearwards by about 0.1s* on both surfaces compared to the corresponding locations at Re₁ = 160000. The wake-induced turbulent spots on the suction surface are more irregular in appearance, and there is a little more unsteadiness in the laminar regions between them. Apart from this, the records are generally similar in character to those at the higher Reynolds number.

The flow behavior changes much more dramatically as Re₁ is reduced to its lowest value of 55400, as shown in Fig. 4 (c). The transition regions on both surfaces move even further rearward, and intermittent laminar separation is probably occurring in the regions between the wake-induced turbulent spots on the suction surface around s* = 0.5. The appearance of these spots is now strongly irregular, and some examples of instability wave activity can be seen between them. Large spikes typical of turbulent breakdown events are occasionally evident from the last gage on the suction surface at 0.98s*. The large magnitude of these spikes could be an artefact of the low values of long term mean quasi shear stress used to normalize the records at this position (see Fig. 5 (c)).

Gage temporal means and envelope curves

Fig. 5 shows the variation along the blade surface of various temporal mean values of gage output, together with the envelopes of instantaneous maximum and minimum values. The results are plotted as quasi shear stress, r. A logarithmic scale is used to accommodate the wide range of values of this variable. The central solid curve represents the long term time-mean value for each gage; this gives some indications of the general boundary layer development and the onset of transition and separation. The immediately adjacent long dash curves represent the maximum and minimum ensemble average values over the whole sampling period; their displacement gives an indication of the magnitude of periodic unsteadiness in the flow. The outer short dash curves correspond to the instantaneous maxima and minima of gage readings over the whole sampling period; their displacement is due to a combination of periodic and random unsteadiness, but principally reflects the...
FIGURE 4: Typical individual quasi shear stress records over the whole blade surface. Thicker linestyle indicates regions identified as turbulent. Bracketing indicates groups of sensors sampled simultaneously. $s^* = 0$ at stator leading edge; $s^* < 0$ corresponds to pressure surface.

The displacement between the ensemble average envelope curves gives a useful indication of the degree of periodic unsteadiness and the progress of wake-induced transition. On the suction surface, there is a significant reduction in periodic unsteadiness at the lowest Reynolds number; at the two higher Reynolds numbers the periodicity is similar in magnitude. There is a consistent trend for the onset of noticeable periodicity to move rearward as Reynolds number is reduced: divergence of the ensemble average envelope curves becomes noticeable around $s^* = 0.1$, $0.2$ and $0.3$ for $Re_1 = 160000$, $112000$ and $55400$ respectively. The ensemble average envelope curves converge again around $s^* = 0.9$, which places a downstream limit on the extent of wake-influenced transition: it should be noted that periodic unsteadiness may persist for some distance into the fully turbulent flow region. A similar behavior is observed on the pressure surface, but the periodicity there is relatively much smaller in magnitude. These results provide useful confirmation of the inferences drawn from the individual gage records above.

The divergence of the envelope curves for instantaneous values of $\tau$ is largely dependent on random shear stress fluctuations. This divergence commences quite close to the leading edge, where it probably reflects potential flow interactions associated with freestream turbulence. It subsequently increases to reach a maximum around the center of the transition zone, and decreases to a lower value thereafter. As Reynolds number is reduced, the ratio of divergence in the instantaneous $\tau$ envelopes to that of the ensemble random component of gage fluctuations.

Figs. 5 (a) - (c) present results for the three different cases studied. All show a maximum value of $\bar{\tau}$ in the stagnation region at the leading edge. The values of $\bar{\tau}$ fall rapidly in the adjacent regions of strong acceleration up to about $s^* = 0.05$ on both suction and pressure surfaces. The separation of envelopes for ensemble mean and instantaneous values is masked in this region by the steep gradient of the curves. On the suction surface ($s^* > 0$) there is a general tendency for $\bar{\tau}$ to fall as the pressure gradient becomes increasingly adverse towards the trailing edge. This is resisted by the progress of wake-induced transition around mid-chord, but even the resulting turbulent layer is unable to withstand the strong gradients for $s^* > 0.9$, where $\bar{\tau}$ falls rapidly and turbulent separation is approached. With reducing Reynolds number the rearward movement of the transition zone allows the gradual development of laminar separation on the suction surface; this is particularly evident from Fig. 5 (c) at $Re_1 = 55400$ where local minima appear in all curves around $s^* = 0.5$.

On the pressure surface, the values of $\bar{\tau}$ generally fall until $s^* = -0.4$, where the progress of transition causes $\bar{\tau}$ to rise. The shear stress remains fairly stable after $s^* = -0.6$, apart from a rise associated with the flow acceleration between $s^* = -0.8$ and $-0.9$ and a subsequent decrease which suggests some diffusion close to the trailing edge. There is little evidence of laminar separation on the pressure surface.
average envelopes steadily increases. This reflects the weakening of periodic wake-induced transition phenomena which was noted from the individual gage records.

**Time-distance contour plots - intermediate Reynolds number case**

The analysis of surface film data from time-distance contour plots of ensemble-average quantities will now be examined with particular reference to the results for the \( Re_1 = 112000 \) case. Various functions of the hot-film signals will be investigated and problems of interpreting the flow behavior from the resulting plots will be discussed. The most useful of these functions will be used to examine the variation in flow behavior with Reynolds number.

**(a) Ensemble-average quasi shear stress.** Fig. 6 shows a time-distance contour plot of ensemble average quasi shear stress, \( \langle \tau(i) \rangle \). Values are plotted on a log scale as in Fig. 5, and the data for \(-0.1 < s^* < 0.1\) is omitted to reduce the range of values covered.

**FIGURE 5:** Variation of long term mean (solid line), maximum and minimum ensemble means (long dash) and maximum and minimum instantaneous values (short dash) of quasi shear stress, \( \tau \).

The general variation of \( \tau \) (corresponding to an average along \( s^* = \) constant) with \( s^* \) is as described by Fig. 5 (b). However, more detailed information about periodic phenomena is now available from this figure.

The suction surface plot shows a marked periodicity developing around \( s^* = 0.3 \). Further downstream, there are regular avenues of higher \( \langle \tau(i) \rangle \) which indicate the presence of wake-induced transitional strips. Their formation clearly lags the wake path in the free-stream (1.0U trajectory). Within these avenues, \( \langle \tau(i) \rangle \) increases to reach a maximum at about \( s^* = 0.6 \) as transition develops; it subsequently falls again in response to the increasing pressure gradient. The contour gradients in the vertical direction (\( s^* = \) constant) clearly show a sharp rise as a wake-induced strip arrives, and a slower fall in the relaxing laminar flow region following its passage. This relaxation region expands with distance downstream, and covers the whole region between successive wakes by \( s^* = 0.6 \). The degree of periodicity decays for \( s^* > 0.6 \), but there is still some noticeable unsteadiness at the gage closest to the trailing edge.

The periodic unsteadiness is much smaller in magnitude on the pressure surface. There is again evidence of wake-induced transition with the origin of increased shear lagging the wake. However, the resulting avenues of increased \( \langle \tau(i) \rangle \) are less distinct and the passing wakes seem to play more of a modulating role. The periodicity decays rapidly downstream of \( s^* = -0.8 \) and has effectively disappeared by \( s^* = -0.9 \).

**(b) Ensemble average RMS quasi shear stress.** A number of workers such as Addison and Hodson (1990a) and Halstead et al. (1990) have used plots of RMS output from surface film gages to follow the progress of laminar-turbulent transition. The long term average RMS value typically rises from a low background level at transition onset to a maximum around the center of the transition.
The application of this technique to flow on an airfoil surface is complicated by the significant changes in wall shear stress which occur in response to varying pressure gradients. Some form of normalization to reduce these effects is obviously desirable, but this must be done with care as the following examples will show. We now examine three alternative forms of plotting the RMS data to illustrate their features and associated problems of interpretation.

The first (and simplest) form uses the un-normalized \( \langle r(i) \rangle_{\text{RMS}} \). A time-distance contour plot of this quantity is shown in Fig. 7. It has been necessary to omit data for \(-0.1 < s < 0.1\) because of the large range of values involved. This plot exhibits the broad features of the wake-induced transition which were evident from the plot of \( \langle r(1) \rangle \) in Fig. 6, and the positions of these features in the two plots correspond quite closely. However, the use of un-normalized values gives undue prominence to disturbances associated with the wake passage near the leading edge \((-0.2 < s < 0.2)\); there is a danger of interpreting these as the start of wake-induced transition, whereas inspection of individual gage records in Fig. 4 (b) shows this is not the case. Other problems with un-normalized plots are:

(i) a loss of detail towards the trailing edge on the suction surface as both \( \langle r(i) \rangle \) and \( \langle r(i) \rangle_{\text{RMS}} \) fall to low levels in the increasing pressure gradient; and

(ii) a peak of \( \langle r(i) \rangle \) extending over a broad range of \( s \) on the suction surface which does not clearly indicate the center of the transition zone.

Normalization of \( \langle r(i) \rangle_{\text{RMS}} \) by the local value \( \langle r(i) \rangle \) is superficially attractive as a possible solution to these problems. The method is successful in removing the spurious clutter near the leading edge, and in maintaining relatively higher values toward the trailing edge. However, it completely alters the shape and location of the highlighted features. The location of peak normalized RMS occurs around the leading edge of the wake-induced transitional strip due to the low values of the normalizing factor \( \langle r(i) \rangle \) immediately prior to the strip arriving: it is at this location that the greatest relaxation in wall shear has occurred following the passage of the preceding wake-induced strip.

These problems are largely overcome by changing to the local long term mean value of \( r \) as the normalizing parameter, as shown in Fig. 8. The regions of high \( \langle r(i) \rangle_{\text{RMS}} \) agree much more closely with the regions of high \( \langle r(i) \rangle \), whilst the improvements in behavior near the leading and trailing edges are preserved. There is still a tendency for the high normalized RMS strip to precede the high shear strip, which is also evident in the un-normalized RMS plot; this is thought to reflect unsteadiness in the arrival times of the rotor wakes and their associated transitional strips. (As seen from Fig. 3, this results in very large velocity fluctuations as the flow switches between laminar and turbulent in different realizations.) Another advantage of this method is that the peak normalized RMS location is now more tightly defined (compared to Fig. 7) and corresponds quite closely to the estimated center of the transition zone.

(c) Ensemble average skew of quasi shear stress. Techniques for using the ensemble average skew of surface film gages to monitor the progress of transition have been described in detail by Halstead et al. (1995). They found the skew to be extremely useful for analyzing attached high Reynolds number flows on multistage compressor and turbine blading; however, it was of no value at all for low Reynolds number flows involving laminar separation. Hodson et al. (1994) had earlier applied this parameter with some success to tracing the progress of transition on the suction surface of an LP turbine blade.
Corrsin and Kistler (1955). Rearward of over the leading edge of the blade and the initial part of the transition completely confusing and gives no useful information whatsoever circumstances.

The intermittency routine basically identifies as turbulent any region in which high frequency shear stress fluctuations occur. This provides a more regular and coherent picture of the progress of transition which is much less affected by the effects of unsteadiness in the wake arrival time or changes in $\tau$ along the surface. The development of regular wake-induced transitional strips on both surfaces is now clearly apparent. The contour plot shading changes from black to white as the flow changes from laminar to turbulent, corresponding to $\gamma$ increasing from 0 to 1.

The origin of the wake-induced strips agrees with the appearance of turbulent spikes in the individual gage records (see Fig. 4 (b)) as expected from the manual threshold setting procedure. A particularly interesting feature of the wake-induced strip on the suction surface is that the flow at the center of the strip does not become fully turbulent until around $s^* = 0.5$; this indicates that the strip is initially transitional for about half its total length. Similar conclusions are drawn by Halstead et al. (1995) on the basis of $<r(i)>_{RMS}$ and $<r(i)>_{SKew}$ observations on both compressor and turbine blades.

The leading edges of the transitional strips on the suction surface are quite sharply defined and rather insensitive to the threshold settings chosen. Unsteadiness in the strip location associated with fluctuations in wake strength or arrival time simply produces a shading at the strip leading edge. It does not produce the large peaks observed in $<r(i)>_{RMS}$ and $<r(i)>_{SKew}$ plots which are associated with laminar-turbulent profile switching effects. The trailing edges of the transitional/turbulent strips exhibit a much lower gradient of intermittency with time, and their limits are accordingly much more sensitive to the choice of threshold for turbulence identification.
The wake-induced strips on the suction surface appear to spread with a leading edge celerity of about 0.7U and a trailing edge celerity of about 0.5U. This suggests a mean velocity of around 0.6U, which is rather lower than that suggested by other workers from studies of constant pressure or turbine airfoil flows (Mayle, 1992). Transition is completed around $s^* = 0.8$ not by merging of the adjacent wake-induced strips but rather from the appearance of other transition modes in the remaining laminar regions between them. This corresponds to a situation of multi-mode transition as described by Mayle (1992).

The transition behavior on the pressure surface differs significantly. Wake-induced transitional strips are still evident, but they are much less prominent. The spreading rate of these strips appears much larger, with the leading edge propagating even faster than the local free-stream velocity $U$ and the trailing edge propagating at around 0.4U. This suggests a combined rather than multimode process, where the mode of turbulent breakdown at a particular location in the $r^* = s^*$ plane may alternate with time. It is also reminiscent of the "creative" mode of transition described in the oscillating flow transition experiments of Obremski and Fejer (1967).

It should be borne in mind when analyzing data from surface gages that the intermittency values obtained will be somewhat lower than the peak values within the boundary layer. As shown by the hot wire observations of Walker et al. (1993) the variation of intermittency through layers subject to positive pressure gradient may become quite large. Where laminar separation occurs, there may be a significant lag between the initiation of turbulent breakdown within the layer and the subsequent appearance of turbulent signals from surface gages. This may cause some displacement in the apparent location of the transition zone in both time and space.

Reynolds number effects

The preceding discussion has indicated that $<r(t)>_R M S / U$ and $<r(t)>$ are the most useful quantities for monitoring the progress of transition. Composite contour plots of these variables for all three test cases have been provided in Fig. 11 to illustrate the influence of Reynolds number on the compressor blade transition phenomena. The extents of the transition zones are summarized in Table 2.

In keeping with the individual gage records of Fig. 4, the random disturbance level and intermittency plots both indicate a clear trend for the influence of wake-induced transition to increase with Reynolds number. As $Re_t$ increases, the transition onset moves steadily forward. The wake-induced transitional strips become more sharply defined and their rate of expansion slows, thus increasing the extent of the transition region. This reflects a stronger calming effect due to the greater regularity in appearance of these strips.

The change in behavior as $Re_t$ is reduced from 112000 to 55400 is quite marked. The calming effect becomes relatively weak and the passing rotor wakes now tend to modulate the streamwise transition onset rather than producing distinct transitional strips which spread in the classical convective manner of turbulent spots. Conventional wake-induced transition or multi-mode transition models would certainly be inappropriate here. The $Re_t = 55400$ case closely corresponds to that in the early study of unsteady transition in this compressor reported by Walker (1974).

The pressure surface behavior broadly resembles that on the suction surface. However, the wake-induced transitional strips are much less well defined and expand at a much faster rate. Boundary layer calculations indicate that neither laminar separation nor Görtler instability should have been a factor in the pressure surface transition. Concave curvature commences only at $s^* = 0.25$; the Görtler stability criterion is not exceeded until at least $s^* = 0.6$, by which transition time is well advanced. The different behavior here may have been influenced by the opposite sense of the jet-wake effect, which causes fluid discharging from the passing rotor wakes to accumulate on the stator pressure surface.

### Table 2: Extent of transitional regions. $s^* = 0.1 - s^* = 0.9$

<table>
<thead>
<tr>
<th>$Re_t$</th>
<th>Wake induced transitional strips</th>
<th>Transition between wakes</th>
</tr>
</thead>
<tbody>
<tr>
<td>160000</td>
<td>0.14-0.34</td>
<td>0.25-0.56</td>
</tr>
<tr>
<td>112000</td>
<td>0.22-0.52</td>
<td>0.26-0.66</td>
</tr>
<tr>
<td>55400</td>
<td>0.28-0.72</td>
<td>0.44-0.90</td>
</tr>
</tbody>
</table>

1 Most forward locations of the $\gamma = 0.1$ and $\gamma = 0.9$ contours.
2 Most rearward locations of the $\gamma = 0.1$ and $\gamma = 0.9$ contours.
3 Ill-defined.

### CONCLUSIONS

Dynamic measurements of wall shear stress have been obtained from a closely-spaced array of hot film gages on the outlet stator of a 1.5-stage axial compressor. The results obtained provide new information about wake-induced transition under positive pressure gradient conditions. Wake-induced transitional strips were observed to extend for as much as 70% of suction surface length, and regions of laminar flow were still evident at 85% chord for zero blade incidence.

The large variation in mean shear stress along the surface of the compressor airfoil greatly complicated the interpretation of surface film data. Time-distance plots of ensemble average quasi shear stress gave useful indications of the general flow behavior and the development of laminar-turbulent transition. Plots of RMS quasi shear stress were found to be less reliable: the contour plots obtained were very sensitive to the method of normalization applied to reduce the influence of mean shear variation. Even the best of the RMS plots did not indicate the exact locations for wake-induced transitional strips; at worst, these regions were completely misidentified. These problems arose from high values of $<r(t)>_{R M S}$ produced by profile switching at the leading edge of wake-induced strips through fluctuations in their arrival time, or from low values of normalizing factors associated with laminar separation.

Time-distance contour plots of ensemble average intermittency proved the most reliable indicator of transition. The present study is believed to represent the first such presentation of intermittency data for turbomachinery blading. Further work is needed to improve the selection of threshold values for the turbulent flow detection. It must also be borne in mind that the intermittency obtained from surface sensors will underestimate the peak intermittency within the boundary layer under positive pressure gradient conditions.

The nature of unsteady transition phenomena on the compressor blade was found to be strongly dependent on Reynolds number, within the range $160000 > Re_t > 55400$. In the upper half of this range, the wake-induced transitional strips on the suction sur-
face were sharply defined. Their propagation velocity appeared somewhat lower than that observed for spreading of turbulent spots in constant pressure flows. At the higher Reynolds numbers, a multi-mode transition process was clearly observed on the suction surface: turbulent breakdown was first initiated by passing rotor wakes; this produced transitional strips which spread at a constant rate with increasing distance downstream; the completion of transition was associated with other modes of transition occurring between the wake-induced strips. A significant observation was that the wake-induced strips were initially transitional, rather than being completely turbulent as widely assumed in the literature. At the lowest Reynolds number investigated, the wake-induced transition became very weak; here passing wakes produced only slight modulations of the laminar-turbulent transition boundary.

The pressure surface transition behavior differed from that on the suction surface in some important respects. The wake-induced transition was relatively weak and various modes of transition alternated in appearance at the same location in the t-s plane. The spreading of wake induced strips was much more rapid than on the suction surface. The application of conventional wake-induced transition or multi-mode transition models in this situation would be quite inappropriate.

These results generally support the conclusions of a parallel study by Halsead et al. (1995) in multi-stage compressor and turbine facilities. The present investigation is complementary in its application to a 1.5-stage machine, the different form of blade surface pressure distribution involved, the presentation of intermittency data, the lower Reynolds number range, the greater detail of pressure surface phenomena and the identification of significant differences in wake-induced transition behavior on the pressure surface. Comparing the results of these two studies suggests that 1.5-stage axial machines can give a reasonable indication of the flow behavior on blading in multi-stage facilities typical of modern gas turbine engines provided the Reynolds number is sufficiently high. A full upstream stage is necessary to provide the essential features of wake dispersion shown in Fig. 1.

FIGURE 11: Time-distance contour plots: (a,b,c) ensemble average RMS quasi shear stress (normalized by local $f$); (d,e,f) ensemble average intermittency. Particle trajectories for 1.0$U$, 0.88$U$, 0.7$U$, 0.5$U$, 0.35$U$ overlaid. (a,d) $Re_{i} = 160000$, $i = -0.1^\circ$; (b,e) $Re_{i} = 112000$, $i = -0.3^\circ$; (c,f) $Re_{i} = 55400$, $i = -1.0^\circ$.
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REFERENCES


