13th Australasian Fluid Mechanics Conference
Monash University, Melbourne, Australia
13-18 December 1998

COMPARISONS BETWEEN TRIGGERED TURBULENT SPOTS AND WAKE-INDUCED TURBULENT PATCHES ON COMPRESSOR BLADING

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ABSTRACT

Comparisons are made between triggered turbulent spots on a flat plate and wake-induced turbulent patches on compressor stator blading. Interesting similarities are observed and it is concluded that experiments on turbulent spots are directly applicable to the complex flows on compressor blading.

NOMENCLATURE

E	hot film anemometer output voltage
E_0	anemometer output voltage at zero flow
T	rotor blade passing period
U	free-stream velocity
s	surface distance from leading edge
s*	normalised surface distance, s/s_{max}
t	time
t*	normalised time, t/T
u	local velocity
x	streamwise distance
γ	turbulent intermittency
κ	probability of relaxing non-turbulent flow
τ	quasi shear stress, $((E^2-E_0^2)/E_0^2)^3$

INTRODUCTION

The importance of periodic laminar-turbulent transition in flows over turbine blades has been appreciated for many years. The related problem of unsteady transition on axial compressor blades had received comparatively little attention until work at General Electric and the University of Tasmania showed significant unsteady wake-induced transition effects on compressor blades (Halstead et al., 1995, Solomon and Walker, 1995(a)). Many turbomachinery designers and researchers had previously ignored transition phenomena or treated them as essentially two-dimensional time-independent events. A more accurate modelling for most operating conditions would treat the flow over blade surfaces as both unsteady and transitional.

Typical suction surface flow behaviour observed in the General Electric compressor work is depicted in the s~t diagram of Figure 1. Strips of transitional and turbulent flow on the suction surface of a stator blade are periodically induced by the passage of disturbances from upstream rotor blade wakes. Behind each wake-induced strip is an extensive 'calmed' region of non-turbulent fluid in which the wall shear stress is relaxing from the high turbulent value towards a lower laminar value. Gostelow et al. (1997) showed that the velocity profile in this calmed region is more stable than a steady laminar boundary layer in the same local pressure gradient; the amplitude of Tollmien-Schlichting (T-S) instabilities is therefore reduced and the progression to harmonic breakdown and turbulence in this region by natural transition or other modes is consequently delayed. The calmed region flow is also more resistant to separation, and this may have beneficial consequences for stall margin. Between the wake-induced strips (which behave similarly to the isolated turbulent spots of flat plate experiments) are a laminar region, a calmed region, and a secondary transition region with ensuing turbulent region where breakdown occurs via other modes. The turbulent patches from the two transition processes eventually coalesce to form the blade's turbulent boundary layer.

In this paper hot wire traces from wind tunnel testing on a flat plate under an adverse pressure gradient are compared with hot film traces from a compressor stator. In the former case triggered wave packets and turbulent spots are investigated and in the latter case wake-induced turbulent patches.

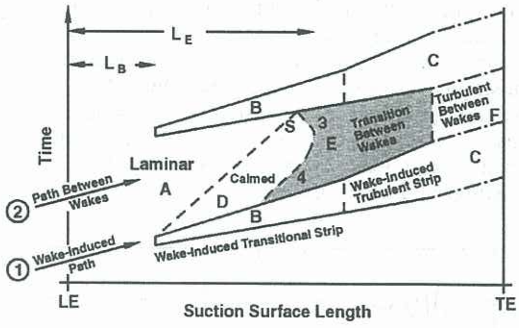

Figure 1 : Unsteady boundary layer development on an axial compressor blade (Halstead et al., 1995).

MEASUREMENTS ON A FLAT PLATE

x~t diagrams obtained from wind tunnel measurements closely resemble s*~t* diagrams from compressor blades. In particular the spot leading and trailing edge celerities are similar as is the behaviour of the calmed region. Both diagrams also provide information on the 'natural' state to which the boundary layer would revert, given sufficient time. Much fundamental work has been performed on triggered spots and the behaviour of the spots is close enough to the events on the compressor blade to provide a good model.

For triggered spots under a zero pressure gradient the trailing edge of the turbulent region of the spot propagates with a higher celerity than the T-S waves. A conventional explanation of the calmed region was that the region was inaccessible to the T-S waves. For adverse pressure gradients, however, Gostelow et al. (1996) showed that it is the T-S waves which have the higher celerity and that explanation is not applicable.

Figure 2 presents representative single raw traces of velocity ratio u/U from hot wire data, for three streamwise locations on a flat plate at 50mm intervals, taken at a height of 0.3mm (in a boundary layer 4.5mm thick). In trace (a) a quiescent laminar layer hosts a conventional triggered wave packet. In this adverse pressure gradient the wave packet is strongly amplified. At the second station, (b), the natural boundary layer develops strong T-S periodicity. Again the amplification due to the adverse pressure gradient results in relatively pure periodic behaviour of high amplitude. The wave packet, meanwhile, becomes further amplified and develops harmonic content. As demonstrated by Gostelow and Hong (1995) this harmonic behaviour is confined to the wall region. By the third station, (c), the natural boundary layer becomes further amplified and develops similar harmonic content. Here the triggered wave packet develops further harmonics which, by wavelet analysis, were shown to extend to at least 1kHz; it can reasonably be described as a turbulent spot.

The spot is followed by a substantial calmed region which exercises two principal effects:

(i) It acts to reduce the amplitude of fluctuations in the natural boundary layer. In this case the fluctuations in the calmed region have only about one half of the amplitude of the natural boundary layer.

(ii) Perhaps as a result of this amplitude reduction the development of harmonics in the calmed region is also suppressed. The aptly-named calmed region has the effect of delaying the breakdown to turbulence. It plays the important stabilizing role of reducing oscillation amplitudes and delaying harmonic development. The results also demonstrate that the transition processes undergone by the natural boundary layer replicate those of the triggered spot. This is strong evidence that the triggered spot constitutes a valid model for the development of transition in a boundary layer.

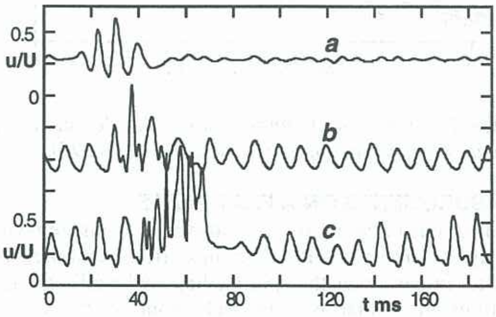

Figure 2 : Hot wire traces from three successive locations for a triggered turbulent spot on a flat plate.

MEASUREMENTS ON A COMPRESSOR STATOR

Transitional events are shown in film gauge data for wakes passing over stator blades of the University of Tasmania research compressor. Removal of one wake (i.e. one rotor blade) showed that the calmed region no longer was able to hold off transition. Plotted are quasi shear stress fluctuations (greyscale) and relaxation parameter (contours). The shading changes from white to black as intermittency changes from zero (laminar) to unity (turbulent). The relaxation parameter κ is defined as the probability that, following a reversion from turbulent to laminar flow, the wall shear stress remains relaxing (identified as $d\tau_s/dt<0$); it provides a useful means of quantifying the extent of the calmed region and a new perspective on the wake-induced transition process.

Figure 3 gives the measured intermittency variation from hot film observations over the stator suction surface at 1° incidence as observed by Solomon (1996). The Reynolds number is 117,000 based on stator inlet velocity and chord. The effects of the impingement of wakes from upstream rotor blades and the subsequent interaction with the developing boundary layer on the stator are shown in the s*~t* diagram.

The dark wedges commencing around 30% chord at intervals of t*=1 correspond to transitional and turbulent flow wedges (or strips) induced by passing free stream disturbances from the wakes of upstream rotor blades. These are interspersed with laminar or transitional flow regions extending back to around 90% chord. The turbulent strip which should have been initiated around t*=2 is missing because the corresponding rotor blade was deliberately removed to investigate the influence of changing wake frequency on the unsteady flow behaviour.

The contours at the rear of relaxing flow zones which follow wake-induced transitional/turbulent strips are nearly parallel, with a slope corresponding to a velocity of 0.2U. Initially the extent of the relaxing flow region grows almost linearly with s*, as it did in measurements on a triggered spot. The increase in maximum κ with s* parallels the increase of maximum γ within the wake-induced strip for 0.3 <s*< 0.5.

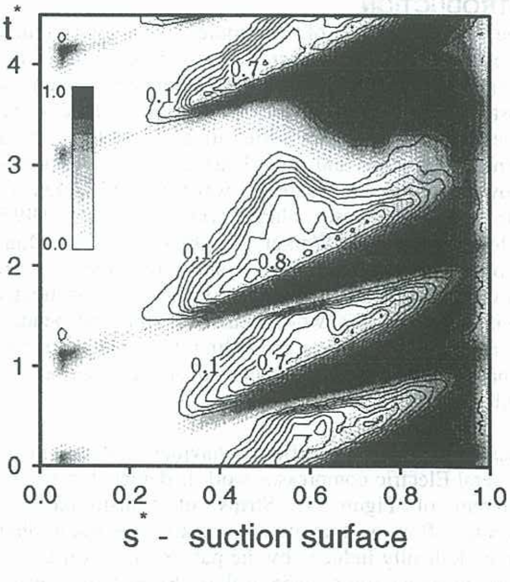

Figure 3: Space-time diagram of periodic transition behaviour caused by rotor wakes passing over compressor stator. One rotor blade deliberately removed to show the effect of the calmed region. Ensemble average intermittency (shading) and relaxation parameter (contours) are plotted.

This provides strong confirmation for the initially transitional nature of these wake-induced strips, which are a collection of isolated and merging spots as described by Halstead et al. (1995).

The Tasmanian compressor work has corroborated the extensive program at General Electric. Solomon and Walker (1995(b)) have particularly emphasised the importance of the calmed region behind each well-developed transitional strip. This has the important effect of greatly extending the length of transitional flow by delaying transition from other modes. It delays the onset of laminar separation because of the periodic energising of wall-layer fluid by the wake-induced turbulent spots.

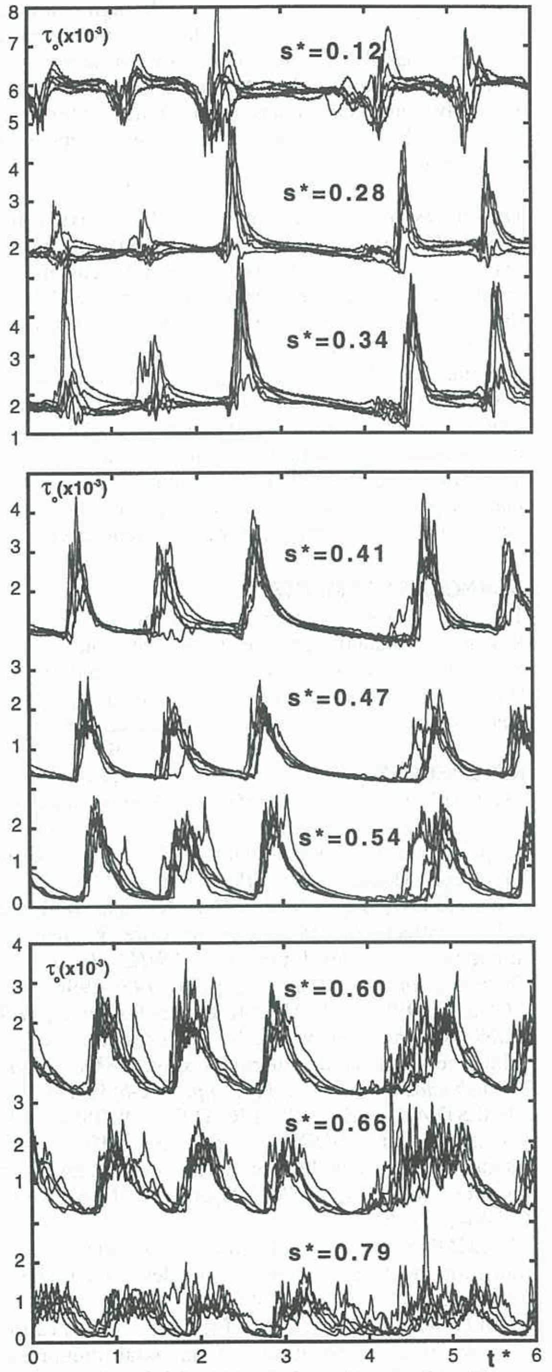

Figure 4 : Film gauge traces from stator blade suction surface. Six traces are given for each of nine streamwise locations on the blade.

Figure 3 demonstrates the engineering significance of relaxation (or calming) effects on the blades of axial turbomachines. Provided the wake passing frequency is sufficiently high the altered boundary layer velocity profile behind the wake-induced transitional strip maintains laminar flow over the majority of the blade chord whilst preventing intermittent laminar separation. Optimisation of blade design requires a detailed understanding of these phenomena and an ability to incorporate them into design calculations.

Figure 4 gives six synchronised traces, (corresponding to passages of the same regions of the blades on different revolutions) at each of nine streamwise locations. In the leading edge region the boundary layer is attached and τ_o is relatively high. Further downstream τ_o drops; for locations beyond s*=0.4 τ_o fluctuates between maximum values around 0.002 and zero. The fluctuations are clearly associated with rotor wake passage events and the resultant turbulent burst activity on the blade surface. This burst activity is seen to be not a result of direct wake interaction but rather of the response of the blade boundary layer to the incident wake. Whether the response is to the relatively high turbulence in the wake, or to its other influences such as local pressure gradients, is beyond the scope of this paper. The effects of the wake will be shown to cause calmed regions which suppress laminar separation before finally breaking down with the global appearance of turbulent spot-like activity.

Typical individual film gauge records are extracted and shown in Figure 5. They provide evidence of T-S wave activity and wave packet development near the end of the calmed region. The measured frequency of these oscillations is consistent with predicted T-S frequencies under these conditions as shown in Figure 6.

Frequency domain analysis of these traces, using a Morlet 5.5 wavelet, was undertaken to elucidate the

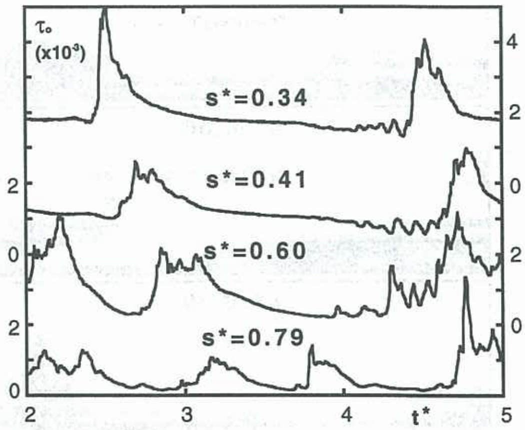

Figure 5 : Typical individual records from film gauges at four locations on the compressor stator, showing effects of removing a rotor blade.

variation of harmonic content through the region of interest; the modulus results are given in Figure 6. These confirm that the wake-induced patch has frequency content at around the T-S harmonic. The undisturbed boundary layer begins to oscillate at T-S frequency and then itself develops harmonic content.

The traces have features in common with those of Figure 2. T-S activity is endemic but moderated by the calmed region. For conventional blade spacings it is not seen. For wider blade spacings, with an extensive calmed region, T-S activity breaks out at the end of the calmed region. The trace at s*=0.60 has similarities with trace "c" of Figure 2 in that the T-S fluctuations develop harmonic content. This process is retarded in the calmed region. The harmonic structure develops into turbulence which can then be seen to invade the calmed region.

At s* = 0.79 there are incipient turbulent spots more characteristic of bypass transition. These precede the T-S wave packet in the region where the flow is more strongly relaxing. This typifies the multi-mode nature of transition on axial turbomachine blades. The relative frequency of breakdown by different modes is strongly influenced by the local pressure gradient: Solomon and Walker (1995(a)) observed a more frequent occurrence of T-S wave packets on the stator pressure surface, where the wake-induced transitional strips and their associated calming effects were weaker.

The multiple-trace records in Figure 4 indicate the time-average behaviour of turbulent flow development between the wake-induced turbulent strips. The invasion of turbulent spots clearly develops from the rear of the calmed region where the relaxation effects are weakest; by s* = 0.79 with the intermittent proliferation of spots the flow appears to become entirely turbulent. The turbulent spreading process is aided by the weakening of the wall shear relaxation with increasing s* due to thickening of the turbulent boundary layer in the wake-induced turbulent strips. The general similarity between the flow behaviour around isolated turbulent spots in decelerating flow and wake-induced turbulent strips on the compressor blade is striking, considering that the latter are more two-dimensional in nature.

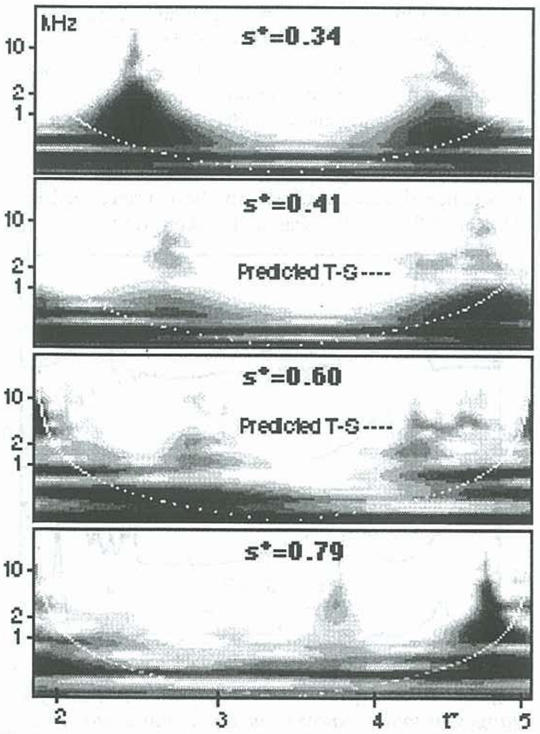

Figure 6: Wavelet modulus for four different stages of turbulent patch development.

CONCLUSIONS

There are strong similarities between the transitional breakdown processes occurring through turbulent spots in a wind tunnel and through the turbulent patches, caused by wake interaction, observed on a compressor stator blade. Although this latter case is not fully understood it has been studied extensively; the available data are a valuable resource for modelling.

Data traces and the associated wavelet analyses have shown that the calmed region, which may be present even behind a wave packet, acts by reducing the amplitude of dangerous instabilities and by delaying the associated harmonic development. The turbulence of the surrounding boundary layer eventually contaminates the calmed region and leads to its destruction although this process may be quite protracted. The calmed region exhibits a significantly more stable velocity profile than the boundary layer. The calmed region behind a turbulent spot or a wake-induced patch is extensive and exhibits a complex interaction with the encroaching turbulent layer.

ACKNOWLEDGEMENTS

This work was supported by grants from the Australian Research Council and Rolls-Royce plc. The experimental work of Bill Solomon and Jeremy Hughes is duly acknowledged. Geoff Spedding of USC kindly consented to the use of his wavelet routine.

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