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TURBULENT INTERMITTENCY MEASUREMENT ON AN AXIAL COMPRESSOR BLADE

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ABSTRACT

The Turbulent Energy Recognition Algorithm (TERA) is compared with a detector function based on $(\partial u'/\partial t)_{rms}$ for the measurement of turbulent intermittency in transitional boundary layers on an axial compressor stator blade. The layers observed are intermittently separating and subject to periodic disturbances from the wakes of upstream rotor blades. Turbulent spots develop from wave packets modulated by the free-stream periodicity. The TERA method is generally superior to $(\partial u'/\partial t)_{rms}$ as a turbulence detector under these conditions.

INTRODUCTION

The importance of laminar-turbulent transition phenomena in relation to the performance of gas turbine engine components has been discussed in the recent reviews of Mayle (1991) and Walker (1992). Despite significant progress in the understanding of these phenomena, the application of modern computational fluid dynamics techniques for the design of axial turbomachine blades is still greatly limited by deficiencies in current transition models.

The studies of Narasimha (1985), Gostelow and Walker (1990) and Mayle (1991) clearly indicate the importance of turbulent spot theory and the accurate measurement of intermittency as regards the identification of transition phenomena and the improvement of transitional flow modelling. Whilst the literature contains many reports of intermittency measurements these are very largely confined to experiments in zero pressure gradient or accelerating flow. Arnal et al. (1979) and Gostelow and Walker (1990) are among the few workers to report observations in decelerating flow. They report greater difficulty in identifying turbulent spots under these conditions due to the more evolutionary nature of the transition process.

Measurements under the conditions of strong flow deceleration and significant free-stream disturbance levels typical of axial turbomachine blades are quite rare. The present paper describes transitional flow observations on the blading of a research compressor fairly representative of practical turbomachines. The TERA method developed by Falco and Gendrich (1990) for the identifying coherent structures in fully developed turbulent flow is applied (with suitable modification) to determine turbulent intermittency. The results obtained are compared with those of a conventional turbulence detector based on $(\partial u'/\partial t)_{rms}$.

EXPERIMENTAL DETAIL

Measurements were obtained in a single-stage axial-flow compressor comprising inlet guide vane, rotor and stator rows which has been described in detail by Oliver (1961). The blades are of British C4 section on circular arc camber lines, with a chord of 76mm and an aspect ratio of 3.0.

A DISA 55P05 hot wire probe operated by a DISA 55M10 CTA unit was used to survey the midspan boundary layer on a stator blade at 60% chord on the suction surface. The sensor was aligned parallel to the surface and the position zero in the normal (y) direction was read to 5μm, but the likely y-position accuracy was around 0.05mm due to uncertainty about the sensor location on the probe tip. The anemometer output was sampled at 100kHz and filtered at 50kHz before digitisation. Velocity values were evaluated digitally for each sample point from the full dimensionless heat transfer relation for the probe.

Boundary layers at five different stages of transition were observed at this fixed position by varying the compressor flow coefficient (ϕ) so as to alter blade incidence (i) and move the transition region relative to the probe. The compressor speed was continuously controlled to operate at a constant reference Reynolds number (based on rotor chord and mean peripheral speed) of 90,000. The stator chord Reynolds number varied between 70,000 and 90,000 depending on flow coefficient. The rotor speed was typically 385 rpm, giving a rotor blade wake-passing frequency of around 240Hz.

The 5 test cases corresponded to early, mid and late transition (Cases 1,2,3), incipient transition or possibly subtransition (Case 4), and a highly disturbed unstable laminar layer (Case 5). Values of leading parameters for these cases are given in Table I, which lists local freestream velocity at standard atmospheric conditions (U_{std}), freestream disturbance level $(u'_{rms}/U)_\infty$, boundary layer thickness ($\delta_{0.99U}$), momentum thickness (θ), momentum thickness Reynolds number (Re_θ), displacement/momentum thickness shape factor (H), and skin friction coefficient ($C_f = 2\{u_\tau/U\}^2$).

TABLE I - TEST PARAMETERS

Case	1	2	3	4	5
i (°)	-3.1	-2.0	2.3	-4.5	-6.3
U_{std} (ms^{-1})	20.3	19.8	17.6	20.8	21.4
$(u_{rms}/U)_\infty$	0.029	0.033	0.050	0.034	0.026
δ (mm)	1.44	1.44	2.80	1.15	1.11
θ (mm)	0.157	0.167	0.287	0.136	0.137
Re_θ	186	197	339	160	161
$H = \delta^*/\theta$	3.77	3.37	2.17	3.92	3.70
C_f*10^3	0.39	0.70	1.73	0.42	0.59

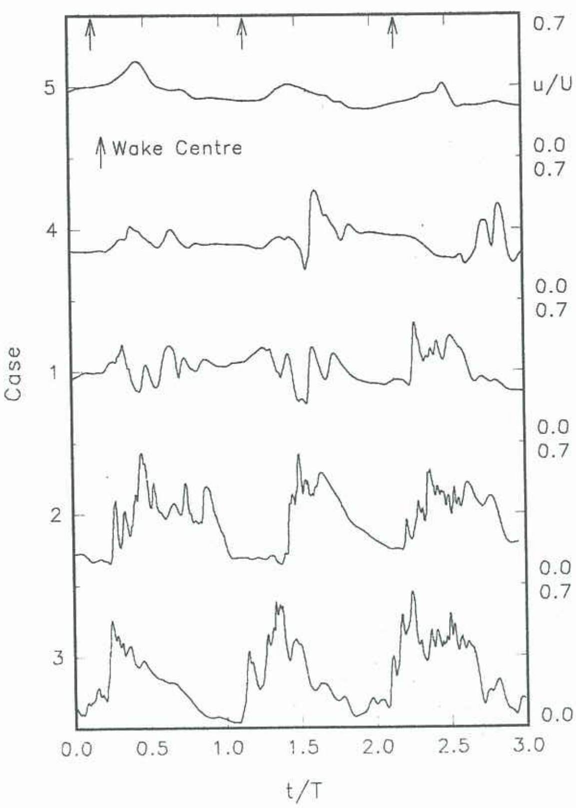

Fig. 1 Typical records of velocity fluctuations observed near the critical layer ($u/U \approx 0.3$) for boundary layers at various stages of transition - Cases 1-5

The stator suction surface flow was decelerating for about 40% chord prior to the measuring station. The values of H indicate that the laminar layers for Cases 4,5 are on the point of separation. Cases 1,2,3 correspond to reattaching transitional flow.

Fig. 1 shows typical records of boundary layer velocity fluctuations near the critical layer plotted against dimensionless time relative to the rotor wake passing period (t/T), starting from a common phase reference. The perturbations produced by the passing wakes induce the regular formation of instability wave packets which significantly lag the wake passage. The record sequence for Cases 5,4,1 clearly indicates the initiation of turbulent spots occurring from the growth and breakdown of these wave packets. The Case 2,3 records illustrate developing turbulent spots interspersed with calmed regions in which the velocity recovers towards the laminar state, For Case 3, the velocity in the laminar region approaches zero, and intermittent flow reversal probably occurs nearer the wall.

INTERMITTENCY MEASUREMENTS

The small scale of the compressor blade boundary layers makes it essential to use detectors based on the u-signal only for determining intermittency. Walker and Wu (1991) examined several such schemes and calibrated them against turbulent boundary layer edge intermittency measurements. The most promising candidate, based on a window-average $(\partial u'/\partial t)_{rms}$ detector, was applied by Solomon (1991) to intermittency measurements in transitional flow on compressor blades, but the threshold settings deduced from fully turbulent flow observations were found inappropriate.

The present program was aimed at examining this threshold problem in more detail, and comparing the $(\partial u'/\partial t)_{rms}$ detector with the TERA method of Falco and Gendrich (1990), identified by Krogstad and Kaspersen (1992) as the most promising u-level method for identifying coherent structures in turbulent flow. The TERA method uses $(u'\partial u'/\partial t)_{rms}$ over a predefined window as the detector (where u' is instantaneous fluctuation from the long-term average velocity); i.e. the rate of change of u-component energy, which closely follows changes in the turbulent shear stress. (TERA also bears some similarity to a combined $\partial u/\partial t$, $\partial^2u/\partial t^2$ detector in that the maxima of u' and $\partial u'/\partial t$ will often be out of phase.)

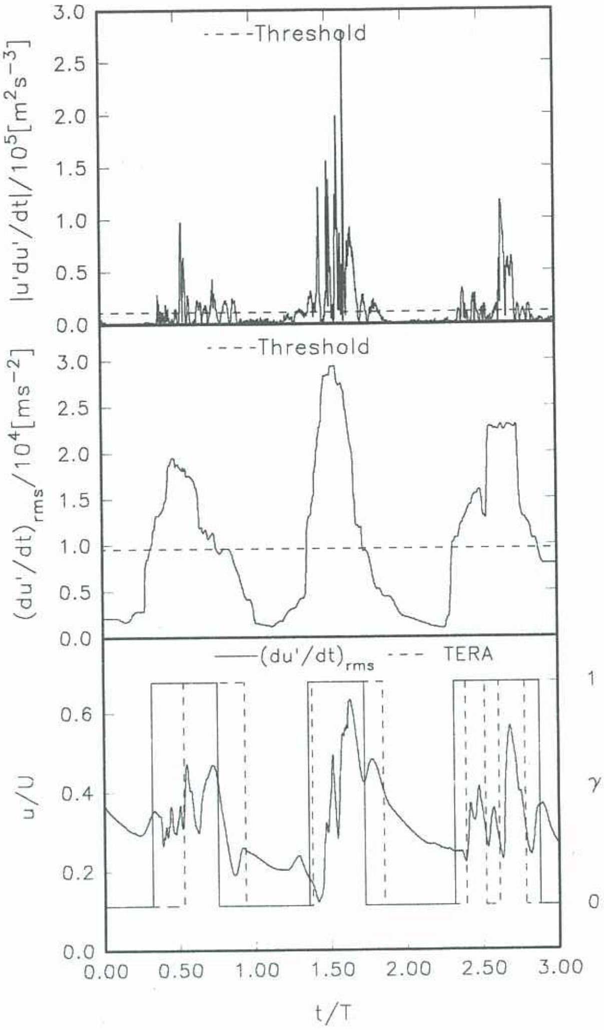

Fig. 2 Typical examples of turbulence detection for a velocity fluctuation record from Case 1 at $y/\delta = 0.29$:
$(\partial u'/\partial t)_{rms}$ Window = 880μs Threshold = $9600 ms^{-2}$
TERA Window = 250μs Threshold = $11200 m^2s^{-3}$

Fig. 2 illustrates the application of these detectors to a typical u-velocity fluctuation record from a compressor blade boundary layer. The TERA method discriminates more clearly between the laminar and turbulent patches, doubtless assisted by the weighting of the large u' values associated with switching between the laminar and turbulent profiles. Note, however, the late detection by TERA of the first turbulent patch when it happens to occur with a u-level comparable to the long-term mean.

Sensitivity to window time is examined in Fig. 3. The TERA method has the very desirable characteristic of negligible sensitivity to window time above about 200μs;

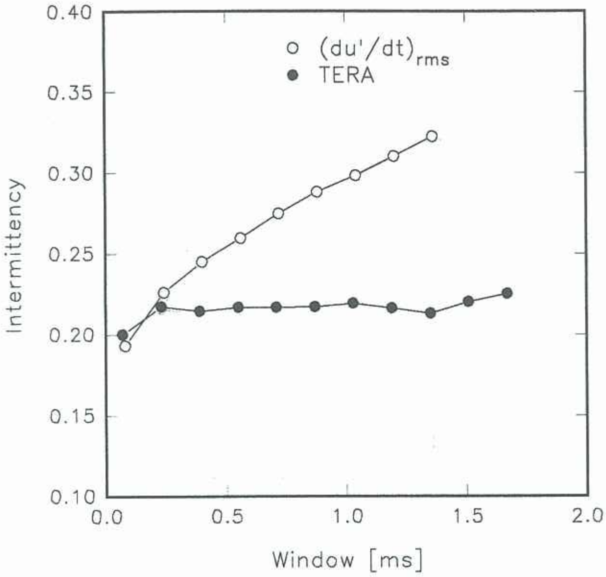

Fig. 3 Variation of intermittency with window time for Case 1 observations at $y/\delta = 0.29$ (fixed threshold) :

$(\partial u'/\partial t)_{rms}$ Threshold = $9600 ms^{-2}$
TERA Threshold = $12800 m^2 s^{-3}$

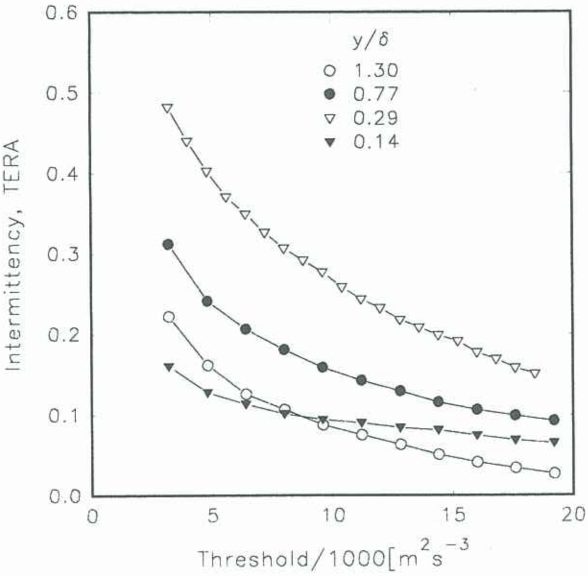

Fig. 4 Variation of intermittency with threshold for Case 1 at various y/δ (fixed window time) :

TERA Window = 500μs

similar results were obtained for other threshold levels. The minimum window time, which corresponds to 20 sample periods, is sufficiently low to give good discrimination of turbulent spot behaviour within the rotor blade passing period (about 4ms in this case). The $(\partial u'/\partial t)_{rms}$ detector, on the other hand, exhibits a continuous change in intermittency value with window time over the whole range of practical interest.

The dimensionless window time $t^+ = tu_\tau^2/\nu$ is clearly irrelevant for measuring intermittency in separating flow. In this case only time scales such as tU/δ can be applied. The minimum acceptable window length of 200μs for the TERA method corresponds to $tU/\delta \approx 3.5$ at incipient transition (Case 4). This agrees reasonably well with $tU/\delta \approx 2.5$ successfully used by Blair (1991) for measurements with a $(\partial u/'\partial t)_{rms}$ detector in an accelerating layer subjected to about 1% freestream turbulence (Condition 1). However, it is much higher than the minimum values of $tU/\delta = 0.4$-0.8 observed by Falco and Gendrich (1990) for identification of bursting in a fully turbulent layer (corresponding to their $t^+ = 5$-10).

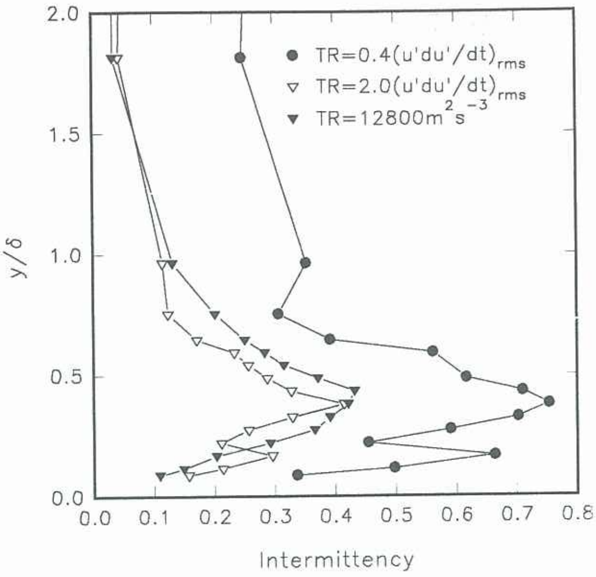

Fig. 5 Boundary layer intermittency distribution by TERA method for Case 2 - comparison of fixed and variable threshold results. Window 250μs.

The behaviour of TERA with regard to threshold level is not quite as favourable. Fig. 4 shows a continuous variation of intermittency with threshold at all levels in the boundary layer for Case 1. The curves have no plateau or break in slope to suggest a particular choice of threshold. However, the sensitivity is low enough around the appropriate threshold range to anticipate intermittency measurements accurate to a few percent for thresholds set by visual inspection. The sensitivity of the $(\partial u'/\partial t)_{rms}$ detector to threshold is around twice that of TERA for this case.

The boundary layer intermittency distributions obtained by using the TERA and $(\partial u'/\partial t)_{rms}$ detectors with fixed window and threshold values in the appropriate range agreed very well in the inner half of the layer ($y/\delta < 0.5$) for Case 2. The $(\partial u'/\partial t)_{rms}$ detector indicated significantly greater intermittency values in the outer part of the layer and the freestream.

The conventional TERA method uses a threshold setting of $C*(u'\partial u'/\partial t)_{rms}$ which is determined from a *long-term* average of the *local* velocity fluctuations and varies throughout the layer. For determining intermittency in a transitional flow, it is rather a *zonal* average of the *local* velocity fluctuations in *laminar flow* patches which is required.A simplified implementation can be achieved by using corresponding values of the detector in the unstable laminar layer *upstream* of the transition region, and the results for Case 2 are illustrated in Fig. 5. Here, the distribution of $(u'\partial u'/\partial t)_{rms}$ with y/δ was assumed to be identical with that of the pre-transitional layer, Case 5. (A similar approach was successfully used by Blair (1991) when implementing a $(\partial u'/\partial t)_{rms}$ detector for intermittency measurement in accelerating flow subjected to high levels of freestream disturbance.)

Case 2 was originally chosen by visual inspection as a layer roughly midway through transition. Fig. 5 indicates that a

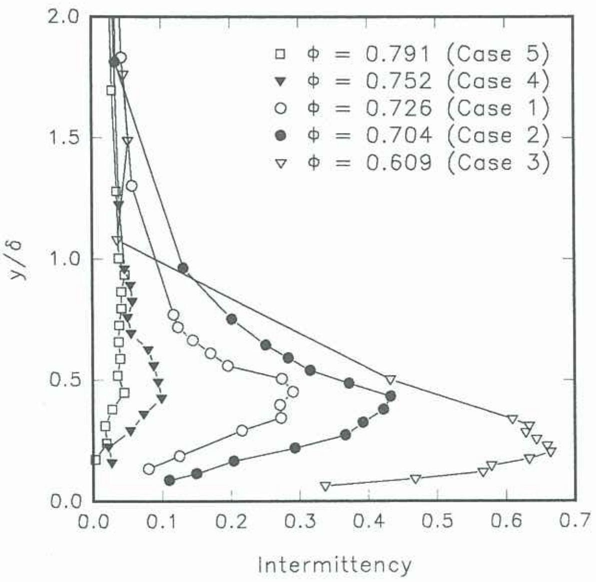

Fig. 6 Intermittency distributions for boundary layers at various stages of transition - Cases 1-5 (fixed window and threshold) :

TERA Window = 250μs Threshold = $12800 m^2 s^{-3}$

value of the TERA threshold constant C = 0.4 (as recommended for identifying coherent structures in turbulent flow) gives values of intermittency which are far too high. Choosing C = 2.0, again consistent with Blair's (1991) recommendations, gives a peak intermittency in the expected range. The irregularity of the intermittency distributions thus obtained reflects similar perturbations in the distribution of $(u'\partial u'/\partial t)_{rms}$ for transitional layers, which exhibit marked local peaks due to switching between laminar and turbulent profiles.

This problem of irregularity could possibly be overcome by suitable smoothing of the threshold distribution through the boundary layer. However, this does not appear necessary as the comparison with the intermittency distribution for a fixed threshold value shown in Fig. 5 indicates that satisfactory results can be obtained by this method.

Finally, the TERA detector is applied to all of the flow cases examined, using suitable fixed values of threshold and window time as determined above. The resulting intermittency distributions are shown in Fig. 6. The peak value of intermittency occurs near y/δ = 0.5 for the incipient or early transition layers (Cases5,4,1), which is consistent with the expected behaviour in a separating flow. In Cases 2,3, where transition is further advanced, the peak intermittency occurs closer to the wall. However,there is still a marked fall in intermittency towards the wall which is confirmed by a visual inspection of individual velocity fluctuation records. This is probably due to lower shear stress and higher viscous damping levels close to the wall, combined with edge intermittency effects in a periodically separated shear layer. Similar effects of smaller magnitude were observed by Gostelow and Walker (1990) in transitional layers subjected to milder deceleration.

The lower near-wall intermittency values have significant implications for interpreting surface film gauge observations.

CONCLUSIONS

The TERA detector of Falco and Gendrich (1990) has been successfully applied to determine turbulent intermittency in transitional flow on an axial compressor blade under conditions of strong deceleration and high freestream disturbance level. Slightly longer window times and significantly higher values of threshold parameter (relative to those used for identifying coherent structures in turbulence) were required in order to obtain realistic values of intermittency.

The TERA method was superior to that of a conventional turbulence detector based on $(\partial u'/\partial t)_{rms}$. It exhibited negligible sensitivity to window time above a certain minimum value, and a rather lower sensitivity to threshold setting.

The transitional boundary layers studied were characterised by the development of turbulent spots from wave packets modulated by periodic disturbances from passing rotor blade wakes. The flow was intermittently separating and a marked reduction in intermittency was observed near the wall.

Further investigations are desirable to investigate the variation of TERA threshold parameter with Reynolds number and the performance of the TERA intermittency detector in very late stages of transition.

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