

## INTERMITTENCY DETECTION FROM SURFACE FILM ARRAYS ON AEROFOILS IN UNSTEADY FLOW

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### ABSTRACT

A method of turbulent intermittency detection which makes use of the probability density function of output from hot film gauges has been successfully applied to turbomachine blade boundary layer data. The threshold is automatically determined by the method and user intervention is minimised.

### INTRODUCTION

Multi-element surface hot film gauge arrays have been widely used to investigate boundary layer transition phenomena in turbomachinery (Hodson, 1985; Halstead et al., 1995; Solomon and Walker, 1995). This class of instrument is particularly useful for identifying the onset and extent of the transition region. Techniques for interpreting the results from these sensors have varied from visual inspection of the voltage traces (Hodson, 1985) to elaborate intermittency detection algorithms such as the present method.

Accurate quantitative descriptions of transition require the determination of turbulent intermittency from the gauge output. Some workers (Engber and Fottner, 1995) have simply assumed a point transition identified by the peak of the RMS of the gauge output; transition length is ignored with this method. Another simple model proposed by Halstead et al. (1995) suggests that the location corresponding to  $\gamma = 0.5$  will be characterised by a peak in the RMS level (due to maximum switching between laminar and turbulent levels) and a corresponding zero in the skew of the signal. For this argument to hold exactly the laminar and turbulent parts of the signal would need to have zero (or compensating) skews and the same standard deviation. These conditions cannot generally be guaranteed and this approach seems less successful at low Reynolds numbers. Boundary layer separation can also give misleading results due to rectification of the unsteady surface film signal.

Intermittency detection algorithms of the type commonly applied to the output of hot wire anemometers have been used with multi-element hot films on swept wings by Agarwal et al. (1991) and on turbomachine blades by Solomon

and Walker (1995). Intermittency detection is a relatively simple process in zero pressure gradient or accelerating flows, where the breakdown of laminar flow is catastrophic and the turbulent and non-turbulent flow regions are markedly different in character. The discrimination between these regions becomes much more difficult in decelerating flow, where the transition process is evolutionary in character and accompanied by strong instability wave activity. The situation is further complicated where transition occurs on the surface of an aerofoil and spatial wall shear stress variations imposed by changing pressure gradients are superimposed on those arising from the laminar-turbulent transition.

A review of intermittency detection schemes is given in Hedley and Keffer (1974). Most schemes convert the output from the flow sensors to a detector function which is chosen to enhance the discrimination between turbulent and non-turbulent features. The detector function is then smoothed and compared to some chosen threshold level. Areas where the threshold level is exceeded by the smoothed detector function are identified as turbulence. The turbulent intermittency is found by measuring the fraction of time the flow is identified as turbulent.

The present study is concerned with the determination of intermittency from an array of film gauges on the surface of an axial compressor stator blade subjected to regular disturbances from the passing wakes of upstream rotor blades. Ensemble averaged intermittency (phase-locked with rotor position) is of particular interest. The flow (Fig. 1) is characterised by the appearance of regular patches of turbulence followed by non-turbulent regions where the shear stress relaxes back to the undisturbed laminar level and instability waves are absent. A suitable detection scheme must differentiate between relaxing flow and true turbulence.

Existing methods of data processing such as that used in Walker and Solomon (1992) proved quite inadequate for analysing these records. A hybrid method of turbulence identification, based on the probability density function (PDF) of the detector function and peak-valley counting of the gauge output signal was subsequently developed



to overcome the problems experienced. This new technique gives credible values for intermittency over the majority of the blade surface, with the thresholds for turbulence detection being determined automatically.

#### DATA ACQUISITION AND PROCESSING

Hot film gauges with a streamwise spacing of around 3% chord were operated in groups of five using normal hot wire anemometer bridges. The bridge voltage was filtered at 20kHz and sampled at 50kHz to minimise aliasing. The frequency response of these gauges was around 30kHz. A more complete description of the experimental arrangement may be found in Solomon and Walker (1995). All the results here are for the  $Re_1 = 112000$ ,  $i = -0.3^\circ$  case.

The film gauge output was processed by the method of Hodson et al. (1994) to produce a dimensionless quantity

$$\tau = \left( \frac{E^2 - E_0^2}{E_0^2} \right)^3 \quad (1)$$

where  $E$  is the anemometer bridge voltage and  $E_0$  is its value at zero flow. Quasi shear stress,  $\tau$ , is the local wall shear stress normalised by some (unknown) film calibration coefficient. Direct calibration of these gauges was not performed. Normalisation by  $E_0^2$  reduces effects of variations in sensor size and resistance, which is particularly important where the results from a number of different gauges are to be compared.

A typical set of records from surface film gauges at various fractional positions  $s^*$  along the blade suction surface is shown in Fig. 1. Time  $t^*$  is non-dimensionalised by the rotor blade passing period and sampling of all gauges is synchronised with a zero marker on the rotor shaft. Regular turbulent events induced by the passing rotor wake disturbances are clearly evident. These are followed by classical "calming periods" at points on the blade rear of  $s^* = 0.34$ .

#### INTERMITTENCY DETECTION SCHEMES

##### Turbulent Energy Recognition Algorithm

As a first attempt at turbulence detection from the surface film gauge signals an existing scheme developed for use with hot wire anemometer sensors was adapted. The Turbulent Energy Recognition Algorithm (TERA) of Falco and Gendrich (1990) as modified by Walker and Solomon (1992) had shown promise for use in compressor blade boundary layers. For use with the film gauges this method was further modified to use the time derivative of quasi shear stress as the detector function, rather than the time derivative of turbulent energy used with the hot wire output.

The TERA method reacts immediately to peaks in the instantaneous level of the detector function and then classifies the event as turbulence only if the detector function or its running average subsequently exceed the specified threshold for a given window time. This approach was favoured over other possible smoothing schemes because it resolved the start of turbulent patches accurately in time.

As in the hot wire investigations of Walker and Solomon (1992) the intermittency results were found rather insensitive to window time. The window should be as short as possible to maximise the resolution of transition behavior in the unsteady flow associated with the rotor blade passing; but it should not be so short that spurious dropouts in turbulent zones, or turbulent spikes in laminar zones, occur. With TERA a window period of 120  $\mu s$  (or 6

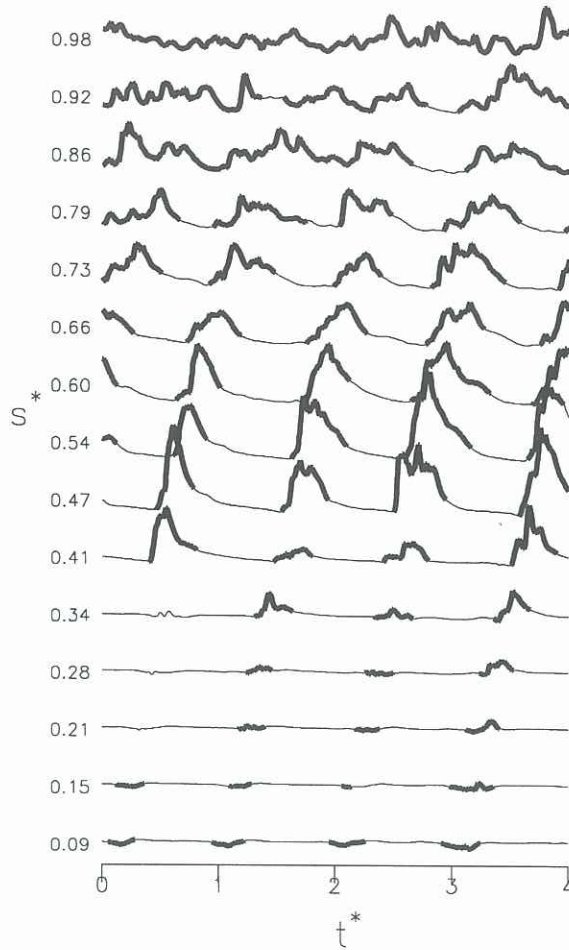


FIGURE 1: Typical individual quasi shear stress records at fractional positions  $s^*$  over the blade suction surface plotted against dimensionless time  $t^*$ . Thick line-style indicates areas identified as turbulent.

samples at 50 kHz) was used. This corresponds to 4% of the rotor blade passing period at  $Re_1 = 112000$ .

The major difficulty in intermittency measurement arises in the choice of a suitable threshold value for turbulence detection. The intermittency values vary continuously with threshold and there is no clear indication of the appropriate level from a plot of intermittency against threshold from the above method. The problem is exacerbated by the extremely large variations in time-mean wall shear stress which occur over the blade surface in response to the boundary layer growth, the laminar-turbulent transition and the changing pressure gradient. Attempts to overcome the effects of these variations by using thresholds normalised with respect to local variables were tried without any marked success.

The initial solution to this problem was to manually adjust the threshold values for individual gauges so that the turbulence identifications from individual film records appeared reasonable. Fig. 2 shows a contour plot of ensemble average intermittency over the blade surface obtained with the manual thresholding procedure. The results are fairly credible, but the contours are still rather ragged and the necessity of using such a subjective procedure is both time-consuming and unsatisfying.

It is now suspected that the problems of threshold setting experienced with TERA were caused by the region of relaxing flow. This region was having undesirable effects on



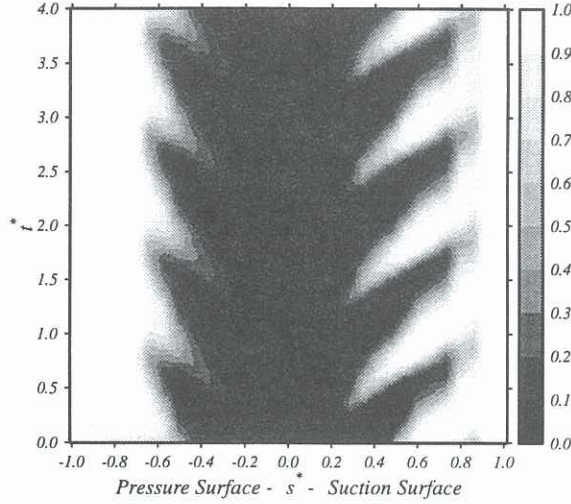


FIGURE 2: Time-distance contour plot: ensemble average intermittency, manual threshold method.

the running average part of the TERA algorithm. A minor improvement was obtained by requiring that only a fraction of the running average be used to hold the turbulence on; but the necessary fraction still varied significantly along the blade and so TERA was finally abandoned.

### The new detection scheme

The problems caused by the calmed region were significantly reduced by introducing a peak-valley identification concept similar to that of Zohar (1990). Fluctuations in the detector function characteristic of fine-scale turbulent mixing are used to identify regions of turbulence. The detector function is still based on  $|d\tau/dt|$  except that the threshold is introduced at this stage to set all parts of the detector function with  $|d\tau/dt|$  values less than the threshold to zero. This is a simple approach for eliminating many of the spurious low level peaks which occur due to digitization and noise.

A simple algorithm now examines the resulting signal and identifies peaks and valleys. The start and end points of regions where the  $|d\tau/dt|$  values were below the threshold were also flagged (which was found to be necessary for good detection). This gave a train of pulses corresponding to peaks, valleys and threshold crossings. Regions where groups of pulses are closer together than one window length are identified as turbulence. A second pass then eliminates any regions of turbulence shorter than one window. Smoothing the pulse train in this manner ensures accurate detection of leading edges of turbulent regions.

The window time used in this procedure was around  $600\mu s$ . This is rather longer than that used in the TERA method and corresponds to around 17% of a blade passing period at  $Re_1 = 112000$ .

### A better threshold finding method

One suggested method of determining a reasonable value of threshold is the so-called dual slope method. Here a plot of intermittency vs threshold level is made such as Fig. 3. Typical results resemble our  $s^* = 0.41$  case where two straight lines could conceivably be fitted and their crossover (at around 0.5) could then be used as the threshold. Clearly this approach is not suitable for some of our other data. Another disadvantage of this method is the requirement to re-

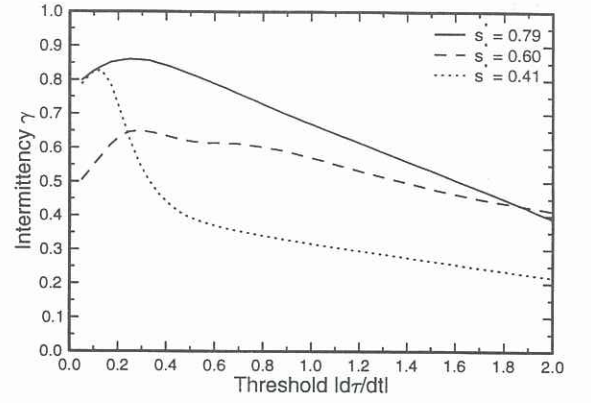


FIGURE 3: Effect of threshold variation on intermittency

peat the data processing with many different threshold values.

Workers who have studied the separating flow about C4 shaped leading edges on flat plates (Hazarika and Hirsch, 1995; Kalfas and Elder, 1995) have used the probability density functions of the conditionally sampled turbulent and non-turbulent components of the detector function to help determine the correct threshold level. This technique is based on the assumption that the signal from the intermittently turbulent flow region will be a combination of two Gaussian functions with significantly different standard deviations. The correct choice of threshold will be given by the intersection point of the two distributions. Useful results are obtained from this assumption even though the distributions may not be truly Gaussian.

An iterative procedure based on this concept has been developed. To start the procedure an initial threshold of 0.7 times the standard deviation of the total detector function is used. The intermittency distribution and conditional statistics are then calculated. The standard deviation of the detector function is obtained over the non-turbulent ( $\sigma_n$ ) and turbulent zones ( $\sigma_t$ ). For the next iteration the threshold  $T$  is determined from the intersection of the PDF's from the turbulent and non-turbulent zones. Assuming both PDF's to be of Gaussian form,  $T$  is obtained from

$$T^2 = \frac{\ln(\sigma_t/\sigma_n)}{0.5(\sigma_n^{-2} - \sigma_t^{-2})} \quad (2)$$

Iteration continues until  $T$  is found to an appropriate accuracy. A degree of under-relaxation was necessary to obtain convergence in some cases.

The ratio  $\sigma_t/\sigma_n$  (Fig. 4) gives an indication of the level of difficulty in discriminating between non-turbulent and turbulent flow. In zero or favourable pressure gradient flows this ratio may be over 10 and the choice of threshold is relatively easy. In adverse pressure gradients (the current situation) values as low as 3 were obtained. The PDF method was, however, still able to select reasonable threshold levels.

Interestingly if this iterative threshold improvement scheme is turned off and a threshold value of  $0.7|d\tau/dt|_{RMS}$  is used, only small changes in long term average intermittency occur (Fig. 5). Evidently much of the improvement in performance obtained with the new method is due to the superior (peak/valley) detection scheme.

A time-space contour plot of ensemble-average intermittency from this hybrid procedure (with PDF threshold re-



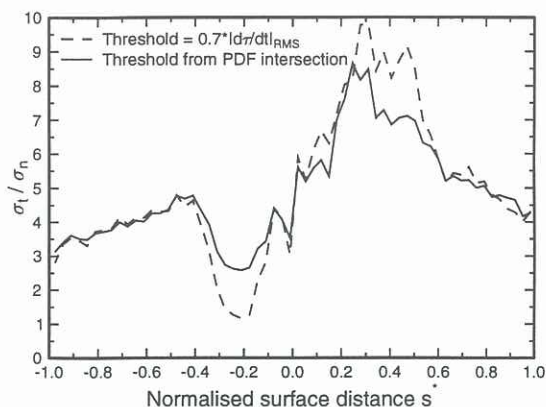


FIGURE 4: Ratio of standard deviations of turbulent and non-turbulent components of the detector function

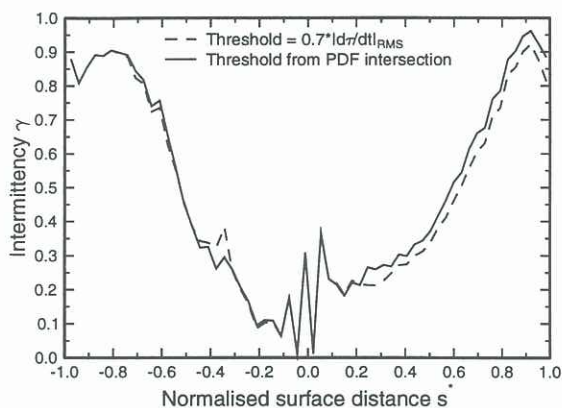


FIGURE 5: Effectiveness of the PDF threshold refinement technique

finement) is presented in Fig. 6. This gives a very credible picture of the wake-induced transition processes over the majority of the blade surface which correlates well with the typical set of individual film traces shown in Fig. 1. The only exception is the region close to the leading edge stagnation point, where the boundary layer is very thin and the large temporal gradients of  $\tau$  accompanying the passage of rotor wakes may cause some of these potential flow interaction effects to be misidentified as turbulence. Here lower limits for the threshold value were imposed.

## CONCLUSIONS

A hybrid method of turbulent flow identification from surface hot film data has been developed, based on a combination of a PDF method of threshold setting and peak-valley counting to identify turbulent flow regions. The new method has been successfully applied to map the variation of turbulent intermittency in periodic unsteady flow over the surface of an axial compressor blade. It requires no user intervention apart from the specification of a window time which is not particularly sensitive above a certain minimum value.

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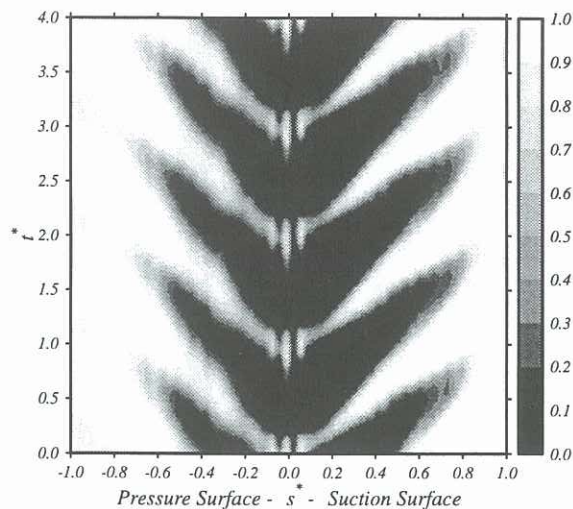


FIGURE 6: Time-distance contour plot: ensemble average intermittency, PDF method.

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