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Turbulent-Nonturbulent Interface Detection methods in Transitional flows

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Abstract

The separation of unsteadiness (or intermittency) and turbulence is the key to improving understanding of the statistical behavior of the transitional boundary layer flow. In this study an attempt is made to review the different methods used for the detection of turbulent and non-turbulent interface in transitional flows. In this regard, methods for generating the intermittency function, conditional averaging and sampling are discussed. The salient features of each technique is also explained.

Introduction

A distinct boundary between turbulent and non-turbulent regions in a fluid of otherwise constant properties is found in many laboratory and engineering turbulent flows including jets, mixing layers, boundary layers, and wakes. Generally, the flow has mean shear in at least one direction within the turbulent zone, but the non-turbulent zones have no shear (adjacent laminar shear is a different case, e.g. transition in a boundary layer). As expressed by Bisset et al. (1999), there may be purely passive differences between the turbulent and non-turbulent zones, e.g. small variations in temperature or scalar concentration, for which turbulent mixing is an important issue.

The boundary has several major characteristics of interest for the present study. Firstly, the boundary advances into the non-turbulent fluid, or in other words, nonturbulent fluid is entrained. Secondly, the change in turbulence properties across the boundary is remarkably abrupt; strong turbulent motions come close to the nonturbulent fluid, promoting entrainment. Thirdly, the boundary is irregular with a continually changing convoluted shape, which produces statistical intermittency. Its shape is contorted at all scales of the turbulent motion.

When a velocity probe is placed at the edge of a turbulent flow, its output tends to switch back and forth abruptly between a fully turbulent signal and one that is essentially non-turbulent. As discussed by Corrsin & Kistler (1955), this observation was first understood in terms of a sharp convoluted boundary by Corrsin (1943), and Townsend (1948, 1949) made the first measurements of intermittency factor (the proportion of time for which the velocity signal is turbulent).

The intermittent region is perhaps the last stage in the transition to turbulence of a laminar boundary layer. An intensive review of this intermittency was published by Narasimha (1985). In this region, turbulent spots form and grow as they travel downstream. The time trace from a measurement made at a single spatial point inside this region cycles intermittently between laminar and turbulent states depending on whether the point is inside a turbulent region or turbulent spot. Many other flows also exhibit intermittency; one example is the intermittency of the fine-scale regions in turbulent flows. Methods of computing this fine-scale intermittency have been compared by Sreenivasan (1985). The edge of a turbulent boundary layer in a laminar freestream also exhibits intermittency (Corrsin and Kistler 1955, Kovasznay et al., 1970). However, transitional intermittency is the topic of this report.

The intermittency of a laminar-turbulent transition is defined to be the fraction of time in which the flow is turbulent at a fixed point. Unfortunately, this intermittency is not a well-defined function, since it depends on the method used to distinguish the turbulent state. Various methods of distinguishing turbulence are reviewed by Narasimha (1985), who describes two general classes of methods. In the first class, which is the most commonly used, the measured signal (usually from a hot film or hot wire) is processed to form a discriminant signal sensitive to the presence of turbulence. Some form of differentiation is commonly used, due to the presence of high frequencies in the turbulence. This discriminant signal is then smoothed to remove drop-outs due to large fluctuations in the turbulence. The smoothed discriminant is then subjected to a threshold that is set so that the resulting intermittency is subjectively consistent with a visual examination of the original signal. The first class of methods is described in some detail by Hedley and Keffer (1974), who conclude that, 'It is clear that the underlying decisions behind any rationale or algorithm for deciding on turbulence will remain open and that many options are possible'. Some workers have attempted to remove the subjectivity of the threshold by selecting it using a plot of intermittency versus threshold. These workers select the threshold using a point of maximum curvature in this plot (Hedley and Keffer 1974), or using the intersection of two straight lines that can at least sometimes be fitted to the curve (Kuan and Wang 1990). However, these methods for removing the subjectivity involved in the threshold selection cannot always be applied, since the intermittency-versus-threshold plot does not always have the desired shape (see Hedley and Keffer, 1974).

A second class of turbulence-distinguishing methods uses the probability density of the amplitude of a signal. This method is useful when the conditional mean for the laminar portion of the signal is substantially different from the conditional mean for the turbulent portion. A method of this type was used by Hansen and Hoyt (1984) and is advocated by Narasimha (1985). In Hansen and Hoyt's method, the probability density function (PDF) is computed for uncalibrated signals from a flushmounted hot-film sensor. These signals are proportional to the shear stress at the wall. Hansen and Hoyt found a valley in the PDF's between a large peak at the laminar shear and another peak reflecting the turbulent shear. This is to be expected, since the shear in a laminar boundary layer is generally much smaller than that in a turbulent boundary layer. Hansen and Hoyt chose their threshold in this valley, apparently at the minimum, and set the intermittency equal to the fraction of the PDF above this threshold. The fraction of time that the shear is larger than the threshold then represents the proportion of time the shear is 'turbulent', and thus the intermittency. Although this method is easy to apply when such a minimum is clearly apparent, it remains subjective when no clear minimum appears, at low intermittency. Furthermore, the method does not allow for precise reproducible comparisons between results obtained by workers in different facilities, since no measurements of the calibrated wall-shear PDF's were presented. As pointed out by Narasimha (1985), this use of the wall-shear time traces (as opposed to velocity time-traces) may be best for computing transitional intermittency. This is because the wall-shear traces should be free of contamination from the edge intermittency associated with the interface between the sometimes turbulent boundary-layer fluid and the non-turbulent outer-flow fluid.

Thus, existing methods of determining intermittency use a subjective threshold of some kind to distinguish the turbulent state. Although some attempts have been made to set this threshold in an objective and reproducible way, these objective methods only work for particular distributions of intermittency-versus-threshold, and these particular distributions are not always observed. Furthermore, existing methods set the subjective threshold in terms of an uncalibrated electronic signal, so that the particular threshold setting cannot be reproduced by another investigator. Since reasonable variations in the threshold cause small but nontrivial variations in the resultant intermittency, particularly for small intermittencies, this lack of an objective and reproducible method for determining intermittency hinders progress towards a quantitative understanding of the intermittent region of laminar-turbulent transition (Schneider, 1995).

This report is making an investigation on different methods of turbulence detection so far used.

An Assessment of Different Methods:

A conditional sampling technique was applied in a study of the boundary layer undergoing transition from laminar to turbulent flow (Kuan and Wang, 1990). The criterion function, d^2u/dt^2, and a dual-slope method was introduced to find the threshold value. A graphical method for determining the threshold value is shown in Figure 1. By specifying a threshold value, a value of the intermittency factor was determined by use of a computer program that used d^2u/dt^2 as the criterion function and three sampling time intervals as the holding time. Figure 1 shows the cumulative distribution of intermittency factor as a function of the threshold value. Most of the time, the curve of this cumulative intermittency distribution function, P(τ), consisted of two straight lines of different slopes when plotted on semi-log graph paper; the threshold level was then taken to be the value at the intersection of the straight lines. We call this method the "dual-slope method." The corresponding intermittency factor found from this threshold value was then checked with the eyeball method, which applied direct reading of the signal traces of the criterion function.

The threshold value thus determined was then used to separate the signal into turbulent and nonturbulent parts. If a value of $d^2u(t)/dt^2$ was larger than the assigned threshold value, then that value was grouped into the turbulent part until three consecutive values were all smaller than the assigned threshold value; the data were than grouped into the nonturbulent part.

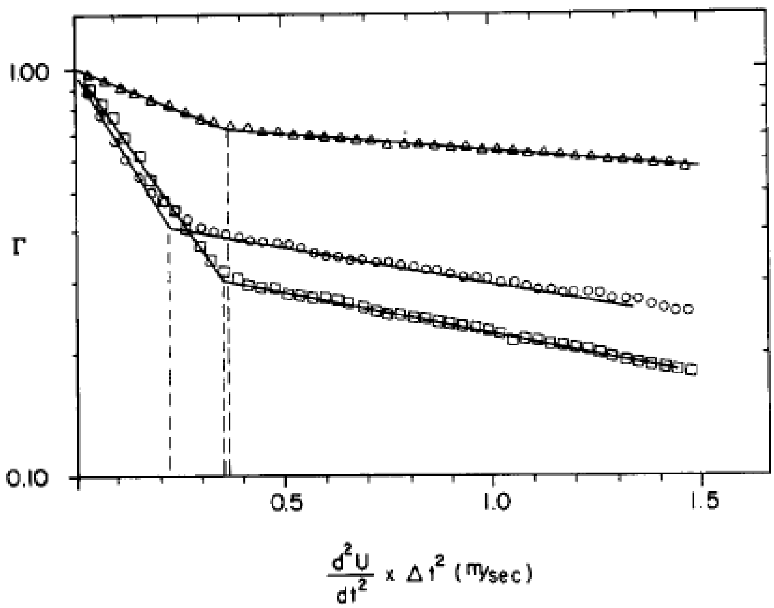


Figure 1: Dual-slope method for determining threshold values. Cumulative intermittency distribution curves are shown for three arbitrary cases.

After the points in the turbulent part were counted, the final intermittency is calculated and the mean velocity and the RMS-u' values of each group were conditionally determined.

Schneider (1995) used a modification to the PDF (probability density function) technique for computing laminar-turbulent intermittency in boundary layers. PDF's plotted in terms of calibrated wall shear showed a remarkable consistency. The turbulent portion of these PDF's correlate well with the amplitude and location of the peak, as long as the data are substantially intermittent. The consistency of these PDF's allows the determination of a turbulent/non turbulent threshold in an objective and reproducible way. Intermittency measurements based on this threshold in the wall-shear can be reproduced by other workers in other facilities with differing equipment.

Later, Zhang et al., (1996) investigated three turbulent intermittency methods, namely the ū, TERA (turbulent energy recognition algorithm), and M-TERA (modified turbulent energy recognition algorithm) methods, for identifying the intermittent flow characteristics associated with boundary layer transition from laminar to turbulent and compared the results.

Comparisons show that the ū and TERA methods are more sensitive to the choice of threshold constants than the M-TERA method. In terms of the intermittency distribution across the boundary layer (Figure 2), the values obtained by the ū and TERA methods are unrealistically high in the near-wall region, while those obtained by the M-TERA method are more realistic. In the outer boundary layer region and outside the boundary layer, the ū and M-TERA methods give reasonable intermittency values, whereas the TERA method produces unrealistically high values in the region outside the boundary layer. In addition, the M-TERA method provides a sharper definition of the end of transition.
Another method that has been adopted for direct identification of turbulent and nonturbulent zones in a transitional flow from velocity fluctuation data is by Jahanmiri et al. (1991, 1997). The output file includes all the data required for finding the turbulent spot shape and further analysis of turbulent signal namely conditional averaging of collected data. This technique which is developed for generating intermittency function, sensitizes the signal by squaring its double derivative as shown in Figure 3, with a variable threshold depending on the noise in the laminar region of the hot-wire signal, and a variable hold time proportional to the Kolmogorov time scale. The falling edge of the pulse driving the loud speaker generally provides an origin for the phase time with respect to which the phases of the leading and trailing edges of the spot and the intermittency function I(t) are generated.

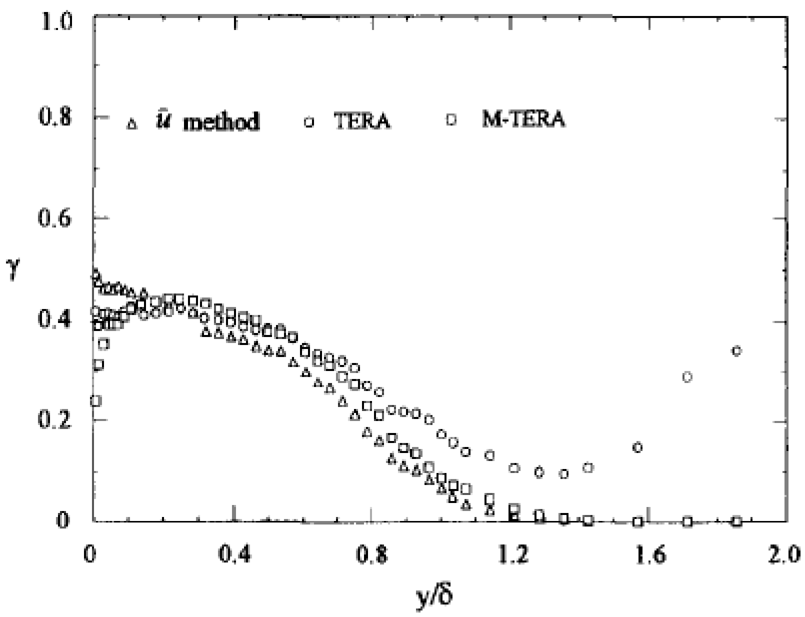


Figure 2: Variations of turbulent intermittency factor γ across the flat-plate boundary layer (at x=1350 mm), obtained by the ū method, TERA method and M-TERA method for free-stream velocity U_0 = 6 m/s.

Three different averaging procedures have been adopted in this work: (i) averaging over the turbulent or non-turbulent region based on the discrimination procedure described above, leading to 'zonal' averages (e.g. mean velocity during the passage of the spot); (ii) averaging with respect to constant phase from the falling edge of the pulse driving the loudspeaker (e.g. average time of arrival of the leading edge of a spot at a given point); (iii) averaging with respect to constant phase from the leading edge of the spot (e.g. the average velocity distribution inside a spot). The size of the ensemble for phase averaging was chosen as 100 spots; beyond 50 the phase averages do not show any appreciable changes (see also Jahanmiri et al., 1995 & 1996).

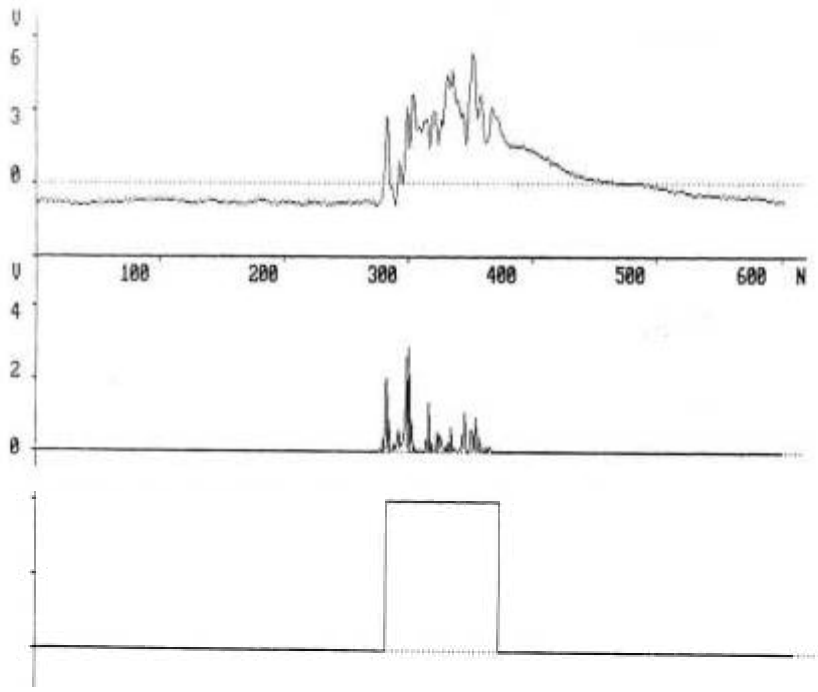


Figure 3: A time trace of turbulent signal in the spot (above), the square of double differentiation of turbulent signal (middle), and corresponding generated intermittency function (below).

Following the detection method developed by Jahanmiri et al. (1991), Ramesh et al. (1996) used a similar method for investigation on transitional intermittency distribution in a three dimensional constant pressure diverging flow. The hotwire anemometer output (e') is sensitized in order to enhance the contrast between turbulent and non-turbulent parts by double differentiating with respect to time, t, to obtain (d^2e'/dt^2), using a second-order central difference scheme. Since differentiation enhances the high frequency components which are indicative of the "burstiness" due to the small-scale intermittency of the turbulence (Rao et al. 1971), the resulting sensitized signal is an effective discriminator between turbulent and non-turbulent fluctuations. The double differentiated signal is then squared ($D = (d^2e'/dt^2)^2$) in order to make it positive valued for comparison with a threshold (Jahanmiri et al. 1991; Hazarika and Hirsch, 1993).
Since the turbulent and non-turbulent parts have variances differing by orders of magnitude, the probability distribution function (PDF) of D would exhibit a change in slope. Such a location where there is a change of slope is taken to be the threshold, Th, for discriminating the turbulent and non-turbulent parts of the signal (Jahanmiri et al. 1991; Hazarika and Hirsch, 1993).
The intermittency function defined as:

$$I(t)=\begin{cases}0 & D(t)\leqslant Th\\ 1 & D(t)>Th\end{cases}$$

is constructed. The intermittency, defined as the fraction of time the flow is turbulent, is then obtained by integrating over a sufficiently long interval T,

$$\gamma=\frac{1}{T}\int_0^T I(t)\,\mathrm{d}t$$

A typical intermittent signal along with the corresponding time series of D, I(t) and PDF are shown in Figure 4. It can be seen in Fig. 4d that the change in slope in the PDF occurs around $0.01 \le D \le 0.03$ within which the threshold lies.
For very low and very high intermittencies, the threshold requires little tuning for the estimated γ to be consistent with the visual observation of the intermittent signals. This difficulty (Narasimha 1985) stems from the fact that at very high and very low values of intermittencies (i.e., $\gamma\simeq1$ and $\gamma\simeq0$, respectively), the demarcation between the turbulent and non-turbulent

portions is not so distinct. This is so because only one of the two disjoint curves (laminar or turbulent) would be dominantly present at these intermittencies thereby obfuscating the clear choice of threshold. Unlike at the intermediate values of intermittency, at these extreme values some tuning is therefore required. It follows from the above discussion that any threshold-based detection scheme would not be able to exactly estimate, for instance, the intermittency of a fully turbulent signal as unity; even Th=0 will not yield γ=1 in view of the first condition in equation for I(t) mentioned above.

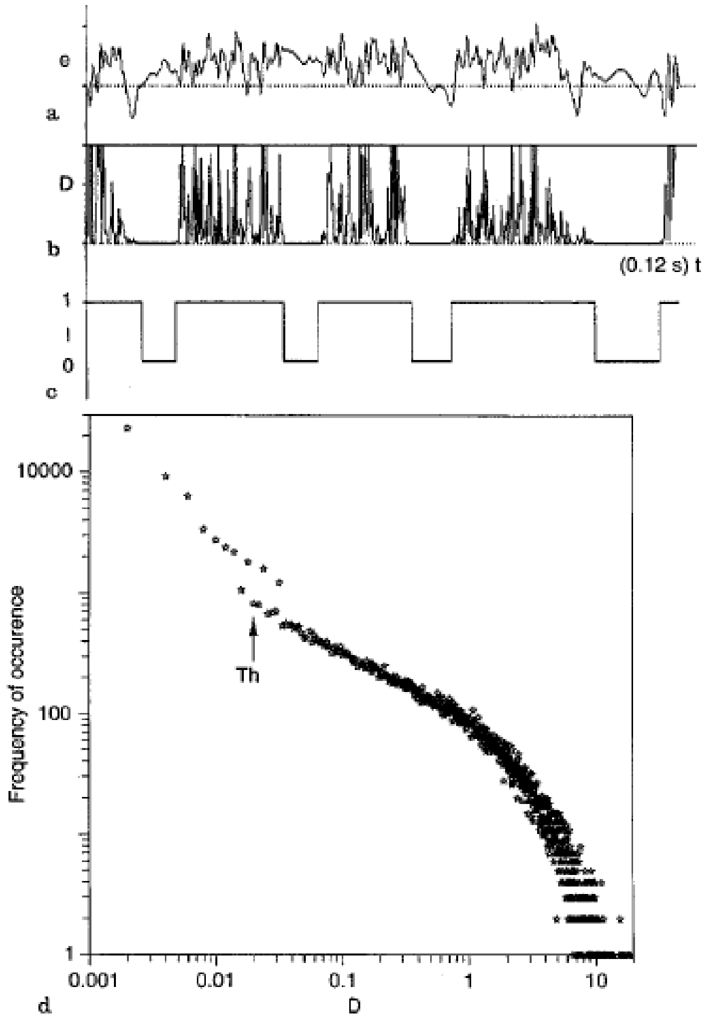
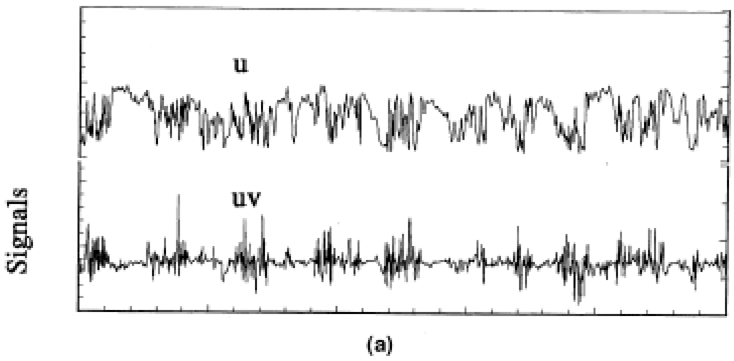


Figure 4: a) Typical raw signal; b) its double-differentiated and squared value; c) corresponding intermittency; d) probability distribution function of the intermittent signal (in Fig. 4b); (signal here is for 30 s while in Figs. 4a-c it is of 0.12 s duration; γ=40%).

A modified conditional sampling technique was applied to separate the turbulent and non-turbulent parts of the transitional boundary layers subjected to elevated free-stream turbulence intensity (FSTI) from 3.8% to 6.4% (Wang and Zhou, 1998). This modified method applied one slope on the accumulative probability diagram to determine threshold values. It was convenient to apply and was also theoretically verified. The results showed that using the Reynolds stress signal (uv) instead of u' signal can enhance the certainty for demarcation of the turbulent and non-turbulent signals. This implies that using turbulence transport behavior was superior to using the turbulence energy for separating the turbulent and nonturbulent signals.
The conditionally sampled results showed that the non-turbulent part was highly disturbed at elevated FSTI cases, as could be seen from the large values of u', t' and, $\overline{ut}$ which were comparable to the magnitude of the turbulent part. This was contrary to the low FSTI cases. Similar to the low FSTI cases, the major turbulence transport of momentum and heat, i.e., $\overline{uv}$

and $\overline{vt}$, were insignificant in the non-turbulent part. This implies that although the velocity trace of the non-turbulent part was hardly distinguishable from the turbulent part in the elevated FSTI conditions, the flow and thermal transport mechanisms of the non-turbulent part were distinctively different from the turbulent part.
As can be seen in Figure 5, the Reynolds shear stress $\overline{uv}$, which indicates the turbulent transport, is much better than u, which is related to the turbulence energy, in demarcating the difference between turbulent and non-turbulent parts of the flow.



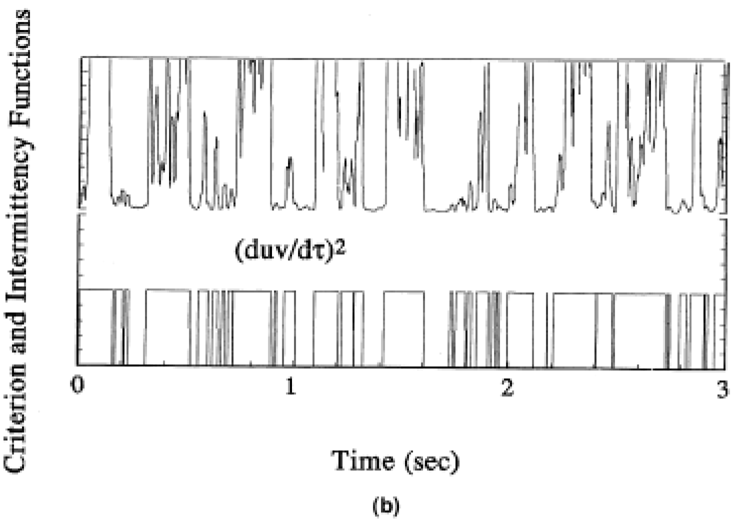


Figure 5: (a) Representative instantaneous signals of streamwise velocity fluctuations and Reynolds shear stress in a transitional boundary layer with FSTI�6.4%. (b) An example of the criterion function $(d\overline{uv}=d\tau)^2$ and intermittency functions.

A neural network has been used to predict the flow intermittency from velocity signals in the transition zone in a boundary layer by Chattopadhyay et al. (1999) . Unlike many of the available intermittency detection methods requiring a proper threshold choice in order to distinguish between the turbulent and non-turbulent parts of a signal, a trained neural network does not involve any threshold decision. The intermittency prediction based on the neural network has been found to be very satisfactory.
A neural network is useful to develop a correlation between inputs and outputs of a system within the range of the training data set without any prior knowledge of the system. As the objective here is to develop a intermittency prediction scheme, which is free from the subjective threshold problem, mentioned earlier, it is planned to design the network with the following two signal based inputs. A short description of the technique is as follows.
The digitized velocity signal is differentiated (D=de'/dt) using a central difference scheme. The total number of digitized points of the signal acquired, is denoted by N. From the time series of D, the number of zero crossings of the differentiated signal are counted; this is denoted by M_z;

the subscript z denotes the zero crossing condition. The first input to the network is $N^{-1}M_z$. The values of $|D^2|_z$ at the corresponding zero crossing points are then obtained. The second input is:

$$N^{-1}\left(\sum_{M_z}|D^2|_z\right)$$

where Σ denotes the sum of all $|D^2|_z$ values for the entire stretch of the signal.
A typical intermittent velocity signal, and the corresponding time series of D and $|D^2|_z$ are shown in Figure 6. The time series of D shows that the number of zero crossings corresponding to the high frequency part of the velocity signal is very high compared to the low frequency part of the signal. Similarly, $|D^2|_z$ corresponding to the high frequency part is also very distinct. If the neural network is to be trained with M_z and $|D^2|_z$ corresponding to the high frequency part alone, then one requires a threshold to distinguish between the low and high frequency fluctuations. In order to avoid this threshold problem, the network is trained with the two inputs mentioned above.

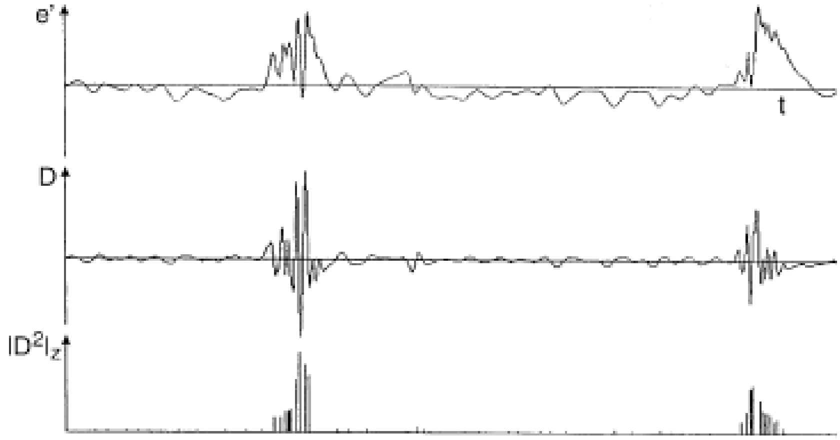


Figure 6: Time series of raw signal, D and $|D^2|_z$.

The Neural Network used is a Back Propagation Feed Forward type with two hidden layers having four nodes in the first layer and three nodes in the second layer, as shown in Figure 7. There are two input nodes in the input layer, and one output node in the output layer.

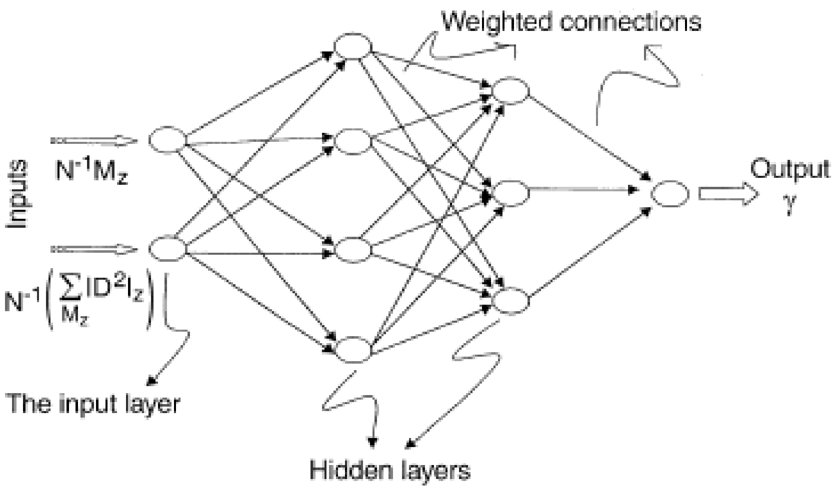


Figure 7: Neural network setup.

Following Zhang et al., (1996) who investigated three turbulent intermittency methods including M-TERA (Modified Turbulent Energy Recognition Algorithm), An envelope method for detection of turbulence intermittency in a transitional boundary layer developed by Chew and co-workers (1999). The main aim of the this work was to develop a convenient and objective method which can be applied to streamwise velocity fluctuations to obtain distributions of the turbulence intermittency factor across the boundary layer in the transition region. For this purpose, based on the M-TERA method, an envelope method, called EM-TERA, employing two detection criteria for detection of turbulence intermittency, is proposed. The results indicate that this method can detect the turbulence intermittency conveniently and reliably with its two respective threshold coefficients kept constant (C_1=0.5 and C_2=0.1) in the entire transitional region of a boundary layer, except for the very near-wall region. The main advantage of the EM-TERA method is that the threshold coefficients do not need to be adjusted at different y positions and at different streamwise locations. It can also be satisfactorily used for the detection of turbulence intermittency in the fully turbulent boundary flow. Compared with the other methods, it appears to be more convenient, objective and reliable for an overall detection of turbulence intermittency in the whole transition region.
To avoid the subjectivity associated with the selection of a hold time in the M-TERA method, the envelope of rectified $u(\partial u/\partial t)$ was employed instead of a hold time. EM-TERA method is thus proposed as follows. Firstly, a 50Hz high-pass digital filter was applied to the streamwise velocity fluctuation. Then $u(\partial u/\partial t)$ of the filtered streamwise velocity fluctuation was calculated and rectified. An envelope (represented as "f") was then constructed. Finally, the following two conditions were applied to the envelope f for a detection of turbulence burst:

$$\left|\frac{\mathrm{d}f}{\mathrm{d}t}\right| > C_1\left(\frac{\mathrm{d}f}{\mathrm{d}t}\right)_{\mathrm{rms}},$$

$$f > C_2\left(\frac{\overline{U}}{U_{\mathrm{e}}}\right)^2\left[\overline{U}\left(\frac{\partial u}{\partial t}\right)_{\mathrm{rms}}\Big/\left(u\frac{\partial u}{\partial t}\right)_{\mathrm{rms}}\right],$$

where C_1 and C_2 are dimensionless and dimensional coefficients respectively. The above first equation is introduced because it is found that usually a turbulent burst is accompanied by a rapid increase in the amplitude of the envelope, whereas the change from turbulent to non-turbulent flow is accompanied by a rapid decrease of the amplitude of the envelope (as shown in Figure 8a and 8b). The slope of the envelope is a sensitive indication of the change of the amplitude of the envelope, and should therefore capture the interface between the turbulent-nonturbulent part. However, inside a turbulent burst, the slope is not necessarily large especially near a peak of the envelope, which is indeed a part of turbulent burst because of the large amplitude of the envelope. So, a second condition in the form of above second equation is used when the first condition is not met, to represent the fact that a large amplitude indeed indicates turbulent state.
After the two coefficients C_1 and C_2 were determined, detection of turbulence bursts was carried out across the boundary layer at various streamwise locations using the EM-TERA method. Figure 8c shows the streamwise velocity fluctuation at one position and the corresponding indicator function obtained by the EM-TERA method. The corresponding indicator function reflects the turbulent burst correctly.

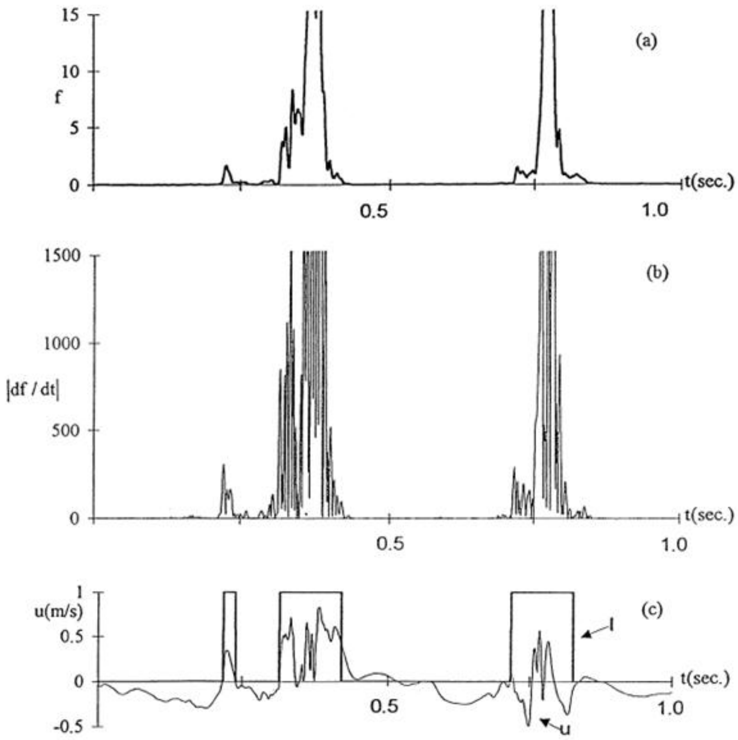


Figure 8: (a) Envelope of rectified ($u\partial u/\partial t$) at x=1.75 m, y=1.8 mm; (b) slope of the envelope; (c) typical streamwise velocity fluctuation at x=1.75 m, y=1.8 mm, and indicator function I obtained using the EM-TERA method.

Canepa et al. (2002) made a review on the application of the intermittency detection techniques to hot-film signals in transitional boundary layers. This work started because of the need to select an intermittency detection method to be employed for the analysis of hot-film data in transitional boundary layers on turbine blade profiles. Several intermittency evaluation methods have been considered and analyzed and finally the following conclusions were made.

1) The simple PDF (probability density function) method based on the direct statistical analysis of the $q\tau_w$ signal was found to be suitable for separating turbulent and non-turbulent events for the relevant experiments. However, this result cannot be generalized since pdf distributions of $q\tau_w$ at low Reynolds numbers may present less accentuate difference between turbulent and nonturbulent parts.

2) All the detector functions examined show suitable discriminatory capability (see Figure 9). The function $q\tau_w\partial(q\tau_w)/\partial(t)$ proposed in the this work gives a higher S_t/S_{nt} ratio (ratio between turbulent and non-turbulent time averages) with respect to the other functions. The detection of the leading edge of turbulent spots and the recognition of laminar spikes are more precise.

3) All the examined turbulent event detector algorithms show acceptable results. Peak-Valley Counting (PVC) algorithm proposed by Solomon (1996) presents the best capability in discriminating the relaxing portions of signal at the trailing edge of turbulent spots.

4) Among the threshold level evaluation techniques, the pdf based selection procedure is the less subjective and more physically based, but requires an initial evaluation of the threshold. This analysis suggests that a suitable choice of the initial value can be done on the basis of the non-conditional pdf.

5) Window time depends strongly on the time-varying structure of the turbulent flow which varies significantly with the Reynolds number of the experiment. Indications from literature give rise to a large range of values. A non-subjective measure of the mean time of the largest turbulent eddies is the integral time scale of the turbulent portion of the flow. The estimation of this time scale based on the pds of the $q\tau_w$ signal after the transition completion fits well with

the turbulent event detection procedure for the Reynolds numbers considered in the investigation.

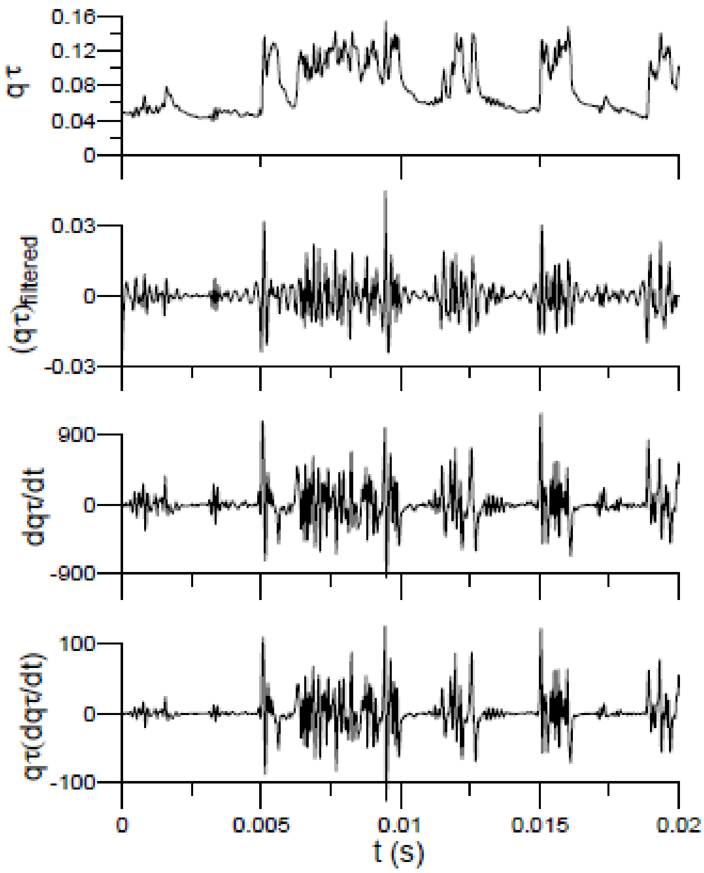


Figure 9: Comparison of different detector functions.

Sometimes later, conditional sampling has been performed on data from a transitional boundary layer subject to high (initially 9%) freestream turbulence and strong acceleration (Volino et al., 2003). Methods for separating the turbulent and nonturbulent zone data based on the instantaneous streamwise velocity and the turbulent shear stress were tested and found to agree and produced essentially equal conditional sampling results.

To emphasize, the intermittency function (Γ) indicates whether the boundary layer is instantaneously turbulent or nonturbulent at a measurement location. It is assigned a value of zero for nonturbulent flow and one for turbulent flow. The time average of Γ is the intermittency, γ.

In the study carried out by Volino et al. (2003), two intermittency detection techniques were utilized and compared. The first, as used in Volino and Hultgren (23), is based on the instantaneous streamwise velocity, u. The u signal is first digitally high-pass filtered with a cutoff frequency:

$$f_{HP} = 200 \cdot U_\infty$$

where f_{HP} is in Hz and U_∞ in m/s. The filter eliminates low frequency fluctuations, which are common to both the turbulent and nonturbulent zones. The filtered signal is then used to determine an intermittency function.

A second intermittency function is computed based on the instantaneous turbulent shear stress. Without pre-filtering of the velocity signal, an intermittency function is computed.

The results of intermittency profiles for the ten measurement stations are shown in Figure 10. Agreement between the u and shear stress based γ is good.

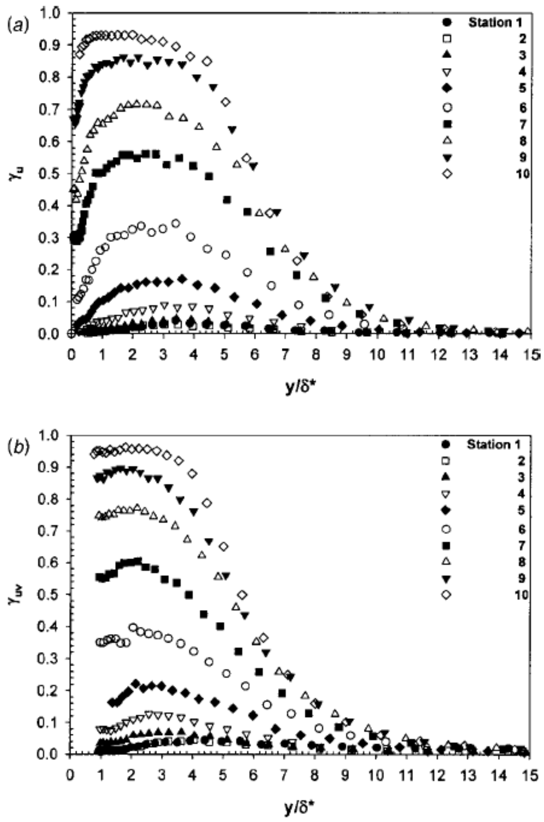


Figure 10: Intermittency profiles based on: (a) u and (b) Reynolds shear stress.

Chokani (2005) applied VITA (variable interval time-averaging) technique for measurements of transition in transitional hypersonic boundary layer flows. The average duration of conditionally sampled events is used to detect the transition region. It is found that the stability Reynolds number at the peak in the average duration of conditionally sampled events correlates well with the stability Reynolds number that is intermediate to the onset of transition and peak heating. This VITA-identified location of transition moves upstream under the effects of both an adverse pressure gradient and wall cooling; this agrees with previous experimental and computational studies. The VITA technique, therefore, offers an alternative method to obtain details of the location of transition in hypersonic stability experiments, in which hot-wire measurements of the transitioning boundary layers are made.

The VITA technique is described in the work of Blackwelder and Kaplan (1976), who used the technique to detect events in the streamwise velocity that are associated with the turbulence production in an incompressible boundary layer. The basic idea in VITA is to compare the variance of a short-period signal, which is extracted from a measured signal, with the variance of a longer period of measurement. If the short time variance, or so-called VITA variance, exceeds a user-defined fraction of the long time variance, an event is said to have occurred (Figure 11) (Bogard and Tiederman 1986). The work performed by Chokani (2005) is the first application that uses VITA to identify a structure in a transitioning compressible boundary layer flow and to relate this identified structure to the onset of transition.

A few pertinent details of VITA technique are presented in the following for the sake of completeness. The short-time-averaged, or VITA, variance of a fluctuating signal, v(t), is defined as:

$$\mathrm{var}_v(t,T) = \frac{1}{T}\int_{t-1/2T}^{t+1/2T} v^2(t')\,\mathrm{d}t' - \left(\frac{1}{T}\int_{t-1/2T}^{t+1/2T} v(t')\,\mathrm{d}t'\right)^2$$

When T, the averaging time, or time scale for the event passage, becomes large, the right-hand side tends to the long-time-averaged, or conventional, variance, v^2_{rms}:

$$v^2_{\mathrm{rms}} = \lim_{T \to \infty} \mathrm{var}_v(t, T)$$

which is commonly referred to as the mean square. In terms of the power spectrum, the VITA technique may be considered as a band-pass filter centered on a frequency of 1/T (Johansson and Alfredsson, 1982). Thus, the VITA variance, $\mathrm{var}_v(t, T)$, which is a time-localized measure of the fluctuating energy, can be represented as an area under a portion of the power spectrum, whereas the long-time-averaged variance is the area under the entire power spectrum.
An event is detected when the VITA variance exceeds the product of a predefined threshold level and the longtime-averaged variance, that is Kv^2_{rms}:

$$D(t) = \begin{cases} 1 & \text{if } \mathrm{var}_v(t, T) \geqslant Kv^2_{\mathrm{rms}} \\ 0 & \text{otherwise} \end{cases}$$

It is evident that the detection of an event depends upon the threshold value, K, and the averaging time, T.
In order to characterize the magnitude of the detected event, it is convenient to define as a characteristic time, the average duration of detection, T_d:

$$T_{\mathrm{d}} = \frac{1}{N_{\mathrm{d}}} \sum_{i=1}^{N} \frac{D_i(t)}{F_{\mathrm{s}}}$$

where N is the total number of data points in the measured signal, N_d is the total number of detections (where D(t) is 0 or 1), and F_s is the sampling frequency.

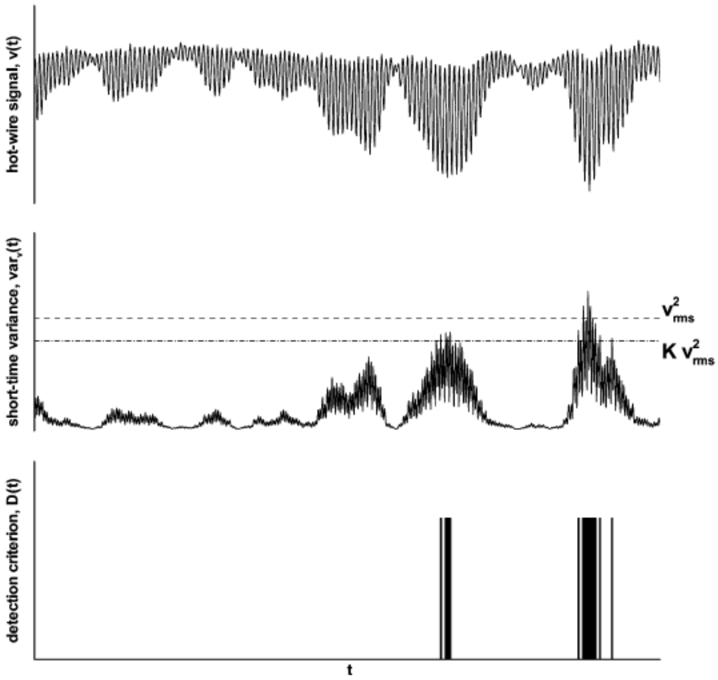


Figure 11: Graphical illustration of the variable interval time-averaging (VITA) technique.

Concluding Remarks

The intermittent nature of transition, both at low and high free stream turbulence intensity, has led to efforts to incorporate intermittency in transition models and to model the two zones of the intermittent flow separately. Moreover, the estimation of flow intermittency from a signal requires a discrimination between the turbulent and non-turbulent parts of the signal, and its choice depends on the method employed for finding the flow intermittency. In the literature, there are many methods used to quantify the extent of the transition region. In this report a few of them which are recently used are explained. However. due to the nature of transitional flow it is hard to decide which of these methods could be appropriate for an experiment. Further experiments in a variety of different conditions should be carried out to determine if the techniques discussed here can be extended to the general case.

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