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An objective approach for measuring intermittency in the transitional boundary layer

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Abstract

Laminar-turbulent transition in boundary layers occurs through the intermittent production of turbulent spots. Determining the intermittency of turbulent spots has been a challenge for several decades. One of the key parameters for the intermittency determination is the selection of a threshold value of turbulence intensity, which often involves a certain level of subjectivity. In this paper an objective method is proposed for choosing a threshold value, which in turn, aids in a more physical determination of intermittency in the transitional boundary layer. The proposed methodology is successfully implemented for a set of experiments involving the interaction of an upstream aerofoil wake with a downstream flat plate boundary layer. Furthermore, the obtained intermittency distributions are validated with the widely used dual-slope method.

Keywords: Laminar-turbulent transition, Intermittency, wake-boundary layer interaction.

1. Introduction

The intermittency factor (γ) is defined as the fraction of time the flow remains turbulent at a given point in the laminar-turbulent transition regime. The value of the intermittency factor varies from 0 to 1, where 0 represents a fully laminar region and 1 represents a fully turbulent regime. There are numerous techniques developed by many researchers [1,2,3,4,5,6] for the measurement of γ. However, the methods proposed in the literature do not seem to work for all type of flows, resulting in no universal procedure for measuring γ. Further, most of the available techniques follow the generic procedure conceived by [1] for measuring the intermittency in fully turbulent boundary layer.

In general, the procedure for determining the intermittency consists of a series of sequential steps involving detector, criterion, and indicator functions, illustrated in figure 1. The detector function can be obtained by processing the raw signal (most often the time derivative of the velocity signal) to make it easier to discriminate between laminar and turbulent portions in the signal: this is called 'sensitizing' the signal. In the second step, the criterion function (indicated as a red line in figure 1c) is obtained by smoothing the sensitized signal over a predefined time interval (usually of the order of the sampling interval); this is done to avoid the turbulent drop outs and spurious signals (laminar spikes) being taken into account during the analysis. As a final step, a threshold value (T_h) is chosen (the choice of this value varies for different methods) to detect the presence of turbulent spots in the signal, following which an indicator function, I(t) is obtained (indicated as a black coloured square wave, see figure 1d). In any part of the obtained signal, if the criterion function exceeds the threshold value then that region is considered as turbulent. Subsequently, the indicator function would be assigned a value of 1 for this turbulent condition, else it remains zero. Eventually, by averaging the indicator function over a given period of time, intermittency is calculated. This is the general procedure followed in many algorithms developed by several researchers for intermittency measurements using hot wires and hot films. Several investigators have proposed different techniques for choosing each function (detector, criterion, threshold and indicator function), and interested readers are referred to the first author's thesis, [7].

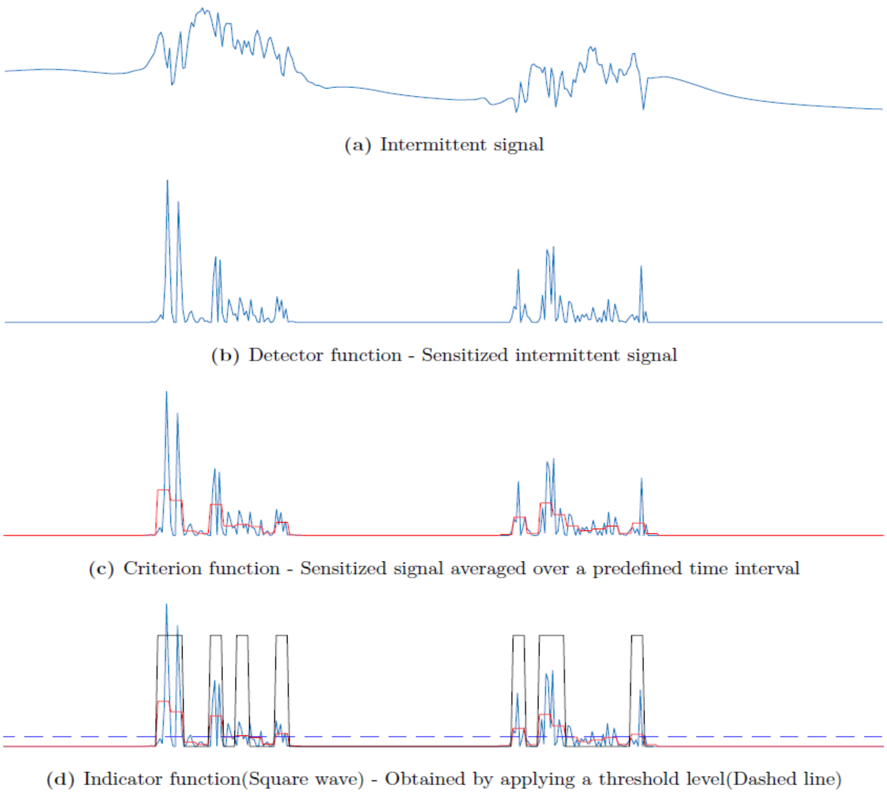

Figure 1. General procedure followed for the intermittency measurement.

Among the steps given in the procedure, the choice of threshold value plays a crucial role in determining the intermittency distribution. Nevertheless, it has been defined subjectively for several decades, for instance using a graphical approach [2], or an arbitrary percentage of mean velocity, as proposed in [6]. Moreover, for streamwise intermittency distribution, different threshold values are chosen for each streamwise stations which in turn intensifies the subjectivity involved. Motivated by this problem, in this paper we have proposed a new rational method for choosing a threshold value. The advantage of the proposed approach over those reported in the literature are (i) the choice of threshold value is rational, simple and automatic (ii) a single threshold value is enough for determining the streamwise intermittency distribution in the transition zone, (iii) the threshold values are quantitatively reproducible by other investigators, given the same data set or a similar experimental setup is considered.

The proposed method is investigated in a wake-induced transition experimental setup, involving an upstream aerofoil wake and its interaction with a downstream flat plate boundary layer. In this setup, the aerofoil wake acts as an upstream disturbance and it induces laminar-turbulent transition on the downstream flat plate. Further, by varying the upstream aerofoil height (above the flat plate), the robustness of the proposed intermittency determination method is investigated.

2. Experimental setup

The experiments reported in this paper were performed in the low-speed wind tunnel at City, University of London. This is a closed-circuit wind tunnel with a test section dimension of $0.924 \times 0.915 \times 3.66$m The aluminum flat plate used for the experiment was mounted vertically and had a total length (l) of about 2255 mm and a thickness of 10 mm. In order to maintain a zero pressure gradient over the flat-plate, a trailing edge flap was employed for finer adjustment of the circulation around the plate. To induce the laminar-turbulent transitional boundary layer on the flat plate an aerofoil was introduced ahead of, and above, the flat plate at zero degree angle of attack, shown schematically in Figure 2. The chord length (c) of the aerofoil was 250 mm.

The streamwise and wall-normal stations are defined using a coordinate system, x-y having its origin at the leading edge of the flat plate. The vertical separation between the aerofoil and the flat-plate is denoted as the 'height' (h_w) and the horizontal separation is denoted as the `overlap' (x_w). It is well-known from the literature [8,9,10,11,12] that these two parameters play a crucial role in determining the aerodynamic performance of a multi-element aerofoil system. In the present paper, the overlap distance was fixed, $x_w = 0.25c$, and by varying the height of the aerofoil, the length of the transitional regime was altered and used to investigate the robustness of the proposed intermittency determination method. The experiment was conducted at a free-stream velocity (U_0) of 20 m/s, the corresponding Reynolds number based on the aerofoil chord being $Re_c = 3.4x10^5$. Free-stream turbulent intensity measured at an upstream location of the aerofoil was 0.015%.

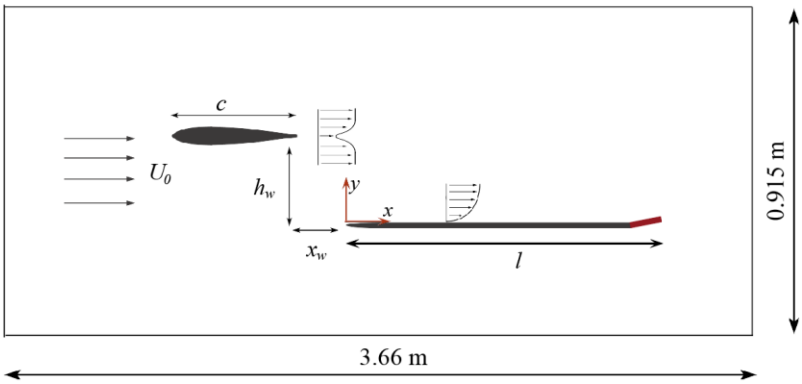

Figure 2. Schematic representation of the experimental setup, with the flat plate and the upstream aerofoil

To avoid vortex shedding from the aerofoil and to stimulate a turbulent wake, a sandpaper roughness strip (average roughness height = 425 μm) was used for tripping the boundary layer at around 25% chord. Furthermore, the wake profiles follow the universal shape proposed by Wygnanski et al. (1986). All the velocity measurements in this experiment were obtained using hot-wire probes with Dantec DISA 55M01 constant Temperature Anemometry unit, at a sampling rate of 10 KHz for 30s.

3. An objective approach for measuring intermittency

To overcome the subjective selection of the threshold value in determining the intermittency distribution, an objective approach is proposed in this paper. The basic idea behind this approach is explained in Figure 3 using the streamwise fluctuating velocity signals obtained at four different points (designated as 1, 2, 3 and 4) on the flat plate whose fluctuating velocity signals are shown by $u_1(t)$, $u_2(t)$, $u_3(t)$ and $u_4(t)$ respectively. The points 1 and 2 are chosen in the upstream region where the flow tends to be laminar, and the points 3 and 4 are located further downstream, generally falling in the transition region. It is known that, as the boundary layer thickness increases, then the magnitude of the perturbations in the flow also increases. This is clearly demonstrated in the perturbation signals plotted in Figure 3, where the magnitude of the perturbation increases from the laminar region to the downstream end of the transitional zone (from points 1 to 4). It is important to note that the flow remains laminar (points 1 & 2), even in the presence of increasing perturbations, until we reach point 3 where we observe turbulent spots. By observing the signal at the transition onset (point 3) and the middle of the transition zone (point 4), it becomes clear that the perturbations due to the turbulent spots (spiky signals) are distinct from the so-called 'laminar' perturbation (a persistent, lower-amplitude component lying within the red dashed lines). An interesting fact is that these lower-amplitude perturbations do not increase in magnitude between the transition onset point (point 3) and the middle of the transitional zone (point 4), in contrast to the increasing amplitude of these perturbations in the laminar region (points 1&2). This observation prompts an assumption that the magnitude of the 'laminar' perturbations remains constant throughout the transition region. In this regard, it is proposed to choose the magnitude of the laminar perturbations at the transition onset point as a threshold value for intermittency estimation. Naturally, it would then be easy to distinguish the turbulent perturbations from the transitional signals. Such an approach has been adopted and applied to the present measurements to estimate the intermittency.

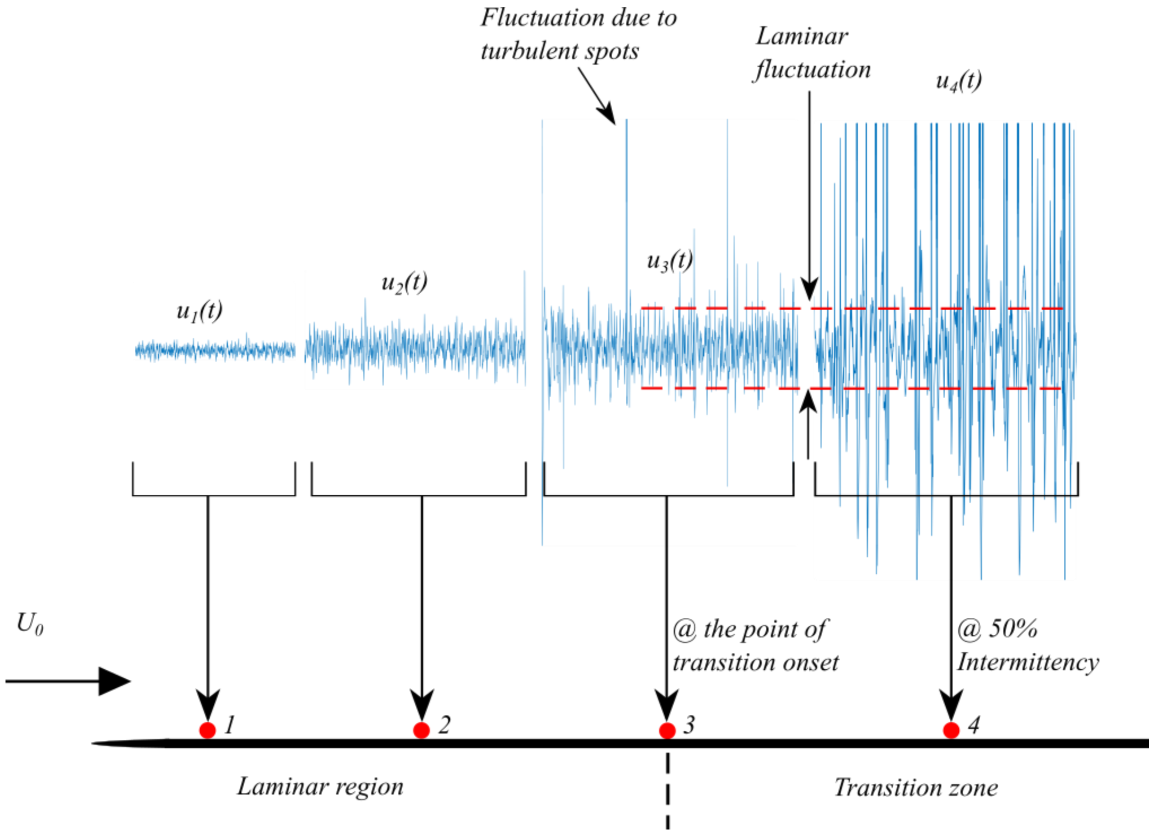

Figure 3. An objective approach to choose the threshold value for intermittency estimation

3.1 Determining the transition onset point (x_o)

To execute the proposed method, the primary task is to locate the point of transition onset , so that the magnitude of the laminar perturbation from that point can be determined. In general, onset is defined as the point where the first turbulent spot occurs. Several methods, such as surface Pitot tubes, hot-wires, surface hot-films, china-clay and other flow visualisation techniques have been employed to detect the transition onset and breakdown points. Despite the availability of several methods, the point of transition detection is still subjective. For instance, in hot-wire techniques, the point at which the transition occurs is usually determined visually from the perturbation signal. While it is logical to use such an approach, it does not necessarily guarantee an accurate point of transition. Here we have used a rational technique, using a skewness parameter to reliably detect the transition onset point (x_o) and breakdown point (x_b). Skewness distributions in the transitional zone of turbomachinery flows and multi-element aerofoils have been already explored in [13, 14]. However, the way they have defined the skewness (third moment normalised with its maximum value, $\overline{u^3}/\max(\overline{u^3})$) did not identify the onset and breakdown points, rather it just gave the region of transition. To obtain the precise location of those points, the skewness parameter must be defined in a way that the third moment is normalised with the cube of the root mean square of the fluctuating velocity, given by $\overline{u^3}/u_{rms}^3$, which definition is generally followed in turbulent research [15].

Skewness distributions based on the present definition are plotted in Figure 4 for all aerofoil heights. It shows that, for all heights, the skewness distribution follows a similar trend, where the skewness initially attains a positive maximum, then gradually drops to the negative side and eventually reaches a plateau. By comparing the skewness and the corresponding time series of the velocity perturbation signal, it can be seen that the streamwise station corresponding to the positive maximum skewness is considered as transition onset, and beyond that, the point where it starts to attain a constant value (plateau) is considered as breakdown point (x_b). To substantiate, fluctuating velocity signal for the h_w = 30 mm at various streamwise stations are given in Figure 5, where the existence of abrupt spikes

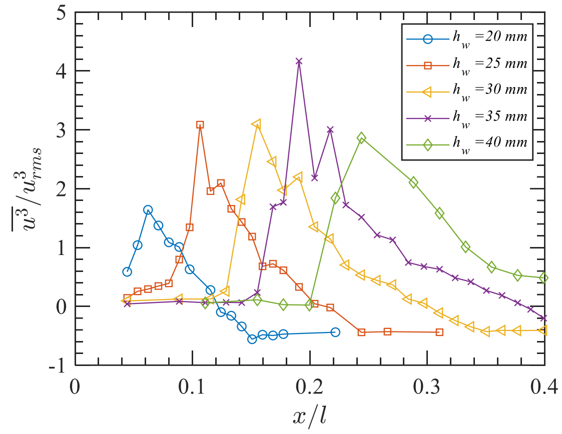

Figure 4. Skewness distribution for various aerofoil heights, measured at y/δ^{*} = 0.5.

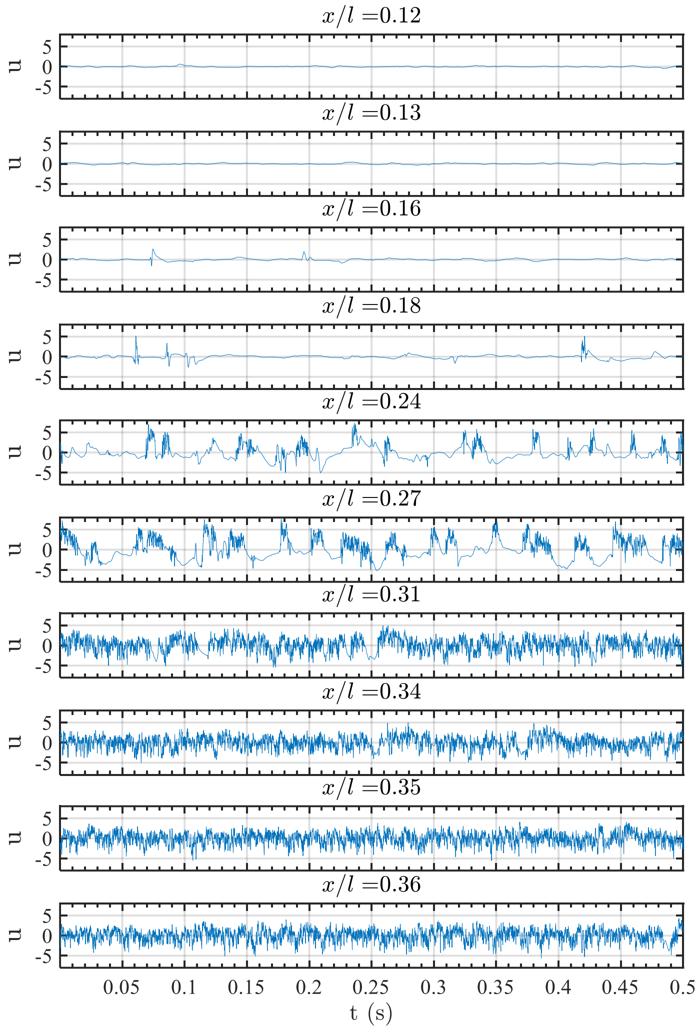

Figure 5. Streamwise fluctuating velocity signals exhibiting turbulent spots in the transitional regime for h_w = 30 mm, measured at y/δ^{*} = 0.5.

denotes the turbulent spots. Beyond *x/l* = 0.16, frequent occurrence of turbulent spots can be seen, while upstream of *x/l* = 0.16 these spiky signals are rare. At the same time, a skewness peak occurs at *x/l* = 0.16 for the h_w = 30 mm case. On the other hand, for *x/l* >0.35 in Figure 5, intermittent spiky signals are not seen, therefore *x/l* = 0.35 can be considered to be the breakdown point(x_b), and the corresponding skewness distribution also attains a plateau from *x/l* >0.35. Similar behaviour can be seen for other aerofoil heights considered in the experiment. Hence this confirms the approach that the location of maximum skewness *x/l* = 0.16 (for h_w = 30 mm) corresponds to the transition onset and x/l = 0.35, where the skewness plateaus, is considered as breakdown. A similar observation was made by Gomez et al. [16], where surface hot films were used for obtaining the fluctuating velocity signals. They observed that, when the skewness parameter (using the present definition) is determined from their signals, the transition onset point occurred around the initial peak of the skewness. Thus it can be concluded that the definition of skewness used in this work can be used effectively to identify the transition onset point.

By employing the above technique for detecting the transition onset and breakdown points in figure 4, the variation of x_o and x_b with respect to aerofoil height (h_w) is obtained, shown in figure 6. This figure demonstrates that the length of the transition regime increases with aerofoil height.

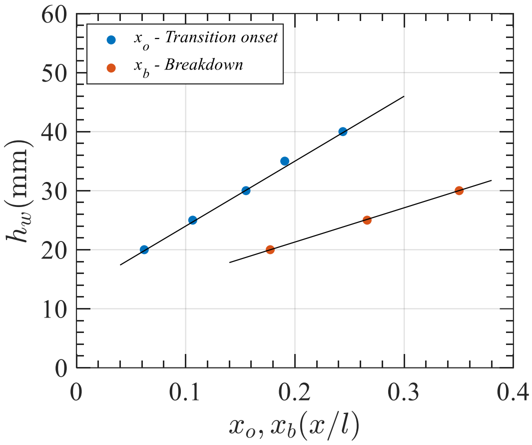

Figure 6. Transition onset (x_o) and breakdown (x_b) points for various heights of the aerofoil (h_w)

3.2 Identifying the threshold value (T^h) and determining the Intermittency

Having identified the transition onset point, the next task is to extract the magnitude of the laminar perturbations alone at that point. Nevertheless, extracting the laminar perturbation directly from the raw signal is difficult due to the presence of occasional turbulent spots at the onset point. To remove the perturbations due to the turbulent spots at the onset point, raw fluctuating signals from y/δ^* = 0.5 are first sensitized by double differentiating with respect to time and then squaring, $D(t)_{x_0} = (d^2u/dt^2)^2|_{x_o}$. By doing so, the high frequency fluctuation part alone is sensitised, thus easily distinguishing the laminar and turbulent perturbations. Furthermore, the time interval (Δt) of the high frequency signals is identified by applying the condition $D(t)_{x_0} > 2D(t)_{x_0\,,rms}$, where $D(t)_{x_0\,,rms}$ is the root mean square of $D(t)_{x_0}$. Eventually, by discarding the signal at Δt from $D(t)_{x_0}$, the laminar perturbation alone is extracted, $D(t)_{x_0,\ L}$, and its rms value is taken as the threshold value, $T^h = T_o^h = D(t)_{x_0,\ L,\ rms}$.

Once the threshold value is obtained, then the intermittency distribution is determined using the procedure conceived by [1]. Firstly, the fluctuating velocity signals obtained at y/δ^* = 0.5 for all the streamwise stations are sensitized using $D(t)_x = (d^2u/dt^2)^2|_x$. Then the sensitized signal is smoothed (moving average) within the sampling time interval of 7Δt (here $\Delta t = 0.7ms$, approximately 230 times the Kolmogorov time scale). Subsequently, the chosen threshold value is applied to the smoothed signal, which in turn yield the indicator function, *I(t)* given in equation. 1. Eventually, by integrating the indicator function for the whole signal, the intermittency γ is determined.

$$I(t) = \begin{cases} 0, & D(t)_x \le \boldsymbol{T^h} \\ 1, & D(t)_x > \boldsymbol{T^h} \end{cases} \quad (1)$$

$$\gamma = \frac{1}{T}\int_0^T I(t)dt \quad (2)$$

Based on the above proposed technique, the threshold value is obtained for h_w = 30 mm and used to determine the intermittency distribution, shown in figure 7 (red markers) along with the results obtained from the dual-slope method (black markers) which are slightly higher than those obtained using the current method. By considering the subjectivity involved in the dual slope method, this variation can be considered insignificant.

One concern is that determining the threshold value T^h from the disturbance time history at the transition onset point would introduce subjectivity, owing to the processing to eliminated the signals corresponding to the turbulent spots (spiky signals). To alleviate this concern, we can choose T^h using time-history data from one station upstream of the onset point (x_{o-1}), where the turbulent spots are not seen, which would eliminate this source of subjectivity. The threshold value at $x_{o-1,}$ is determined from $T^h = T^h_{o-1} = D(t)_{x_{0-1},\ rms} = \mathrm{rms}[(d^2u/dt^2)^2|_{x_{o-1}}]$. The obtained intermittency distribution, based on T^h_{o-1}, is shown in figure 7 (blue markers). It is very similar to the T^h obtained at x_o. This observation confirms that a threshold value chosen close to the transition onset location results in a repeatable estimate for the intermittency.

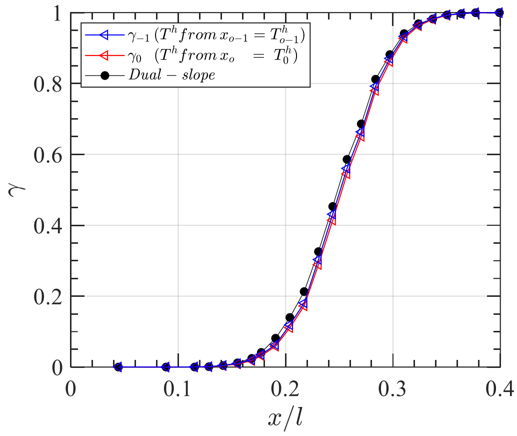

Figure 7. Intermittency distribution for h_w = 30 mm, based on the threshold value chosen at the streamwise measurement station corresponding to the onset point (x_o) and at the measurement station immediately upstream (x_{o-1}). Results are compared with the dual-slope method (black markers).

The reliability of the proposed method to detect the presence of turbulent spots is demonstrated by plotting the sensitized signal and the indicator function on the same plot in figure 8 for h_w = 30 mm. It can be seen that the indicator function accurately captures the turbulent bursts, leaving out any spurious laminar spikes. These observations confirm that choosing the threshold at the transition onset is an effective way to determine the intermittency, performing particularly well for the current experimental data.

Finally, the intermittency is determined for various different h_w using the threshold value ($T^h_o = D(t)_{x_{0,L,rms}}$) chosen at the transition onset point. The results obtained are shown in figure 9, which shows that the increase in h_w shifts the onset location downstream. Also the intermittency calculations are compared with the intermittency distribution obtained using Narasimha's hypothesis of concentrated breakdown [17], which agrees well with the present results.

The onset and breakdown points, obtained by interpolating the curves in figure 9, can be used to determine the length of the transition zone (figure 10) . Figure 10 also shows that the transition zone lengths obtained from the skewness and intermittency distributions do not differ significantly, which again supports the validity of the idea of determining the transition region from the skewness distribution. Additionally, the method proposed for the threshold selection perfectly captures the intermittent nature of the flow.

Further research [18,19] beyond that presented here has revealed that the pre-transitional region (between the leading edge and x_o) of the present experimental configuration exhibits an unusual transition mechanism, where both the natural and bypass transitional characteristics coexist. Furthermore, the transitional intermittency distributions are found to scale with aerofoil height.

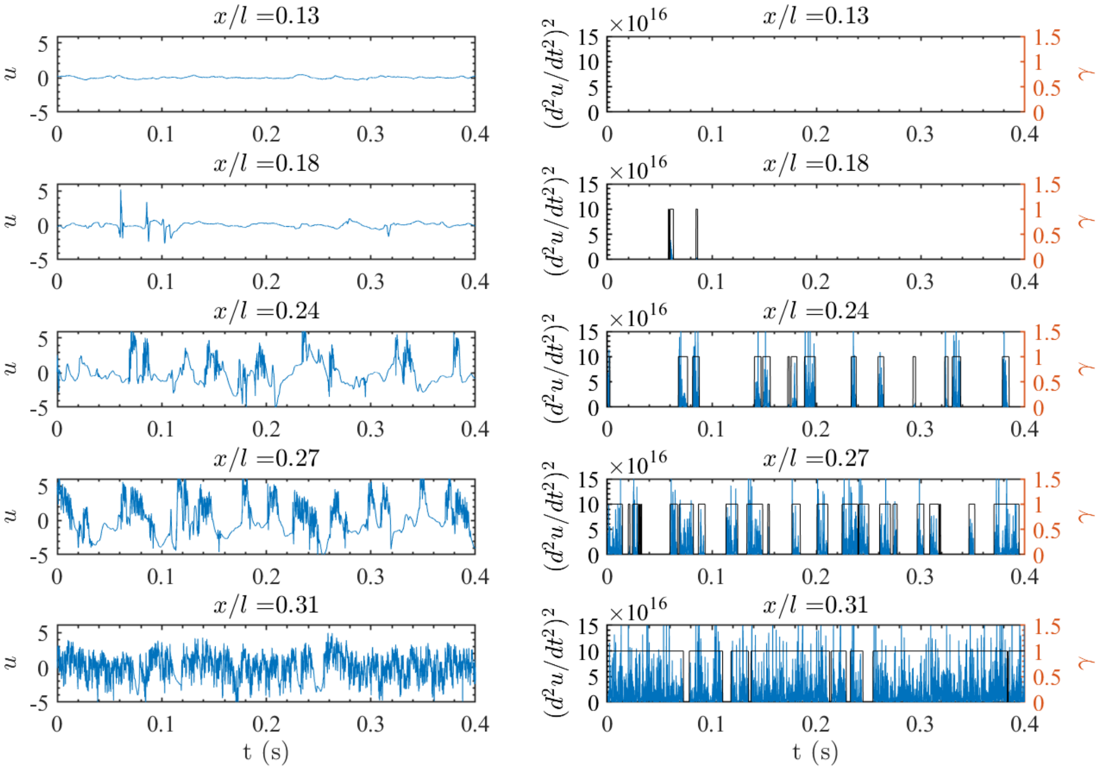

Figure 8. Raw fluctuating signal and its corresponding sensitized signal and indicator function, for h_w = 30 mm

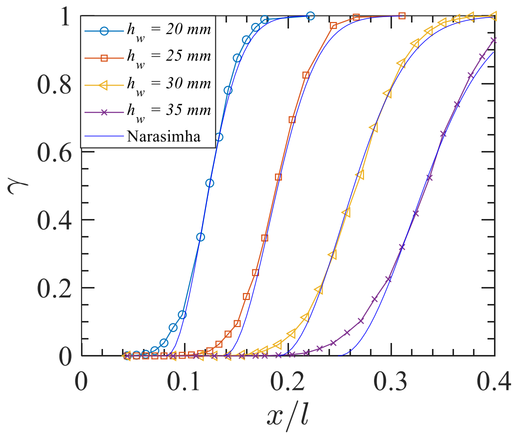

Figure 9. Intermittency distribution for various h_w, compared with the hypothesis of concentrated breakdown in [17]

4. Summary

Most of the intermittency estimation methods presented in the literature are subjective, with some level of arbitrariness in choosing the threshold value. In the present work, a rational and objective technique is proposed which alleviates the shortcomings involved in the other methods. The underlying idea is to detect the peak amplitude of 'laminar' perturbation in the transitional flow and then to use it as the threshold for determining the intermittency. The key question is, how to detect the maximum laminar perturbation in the transitional flow? It can be seen from the development of the streamwise fluctuation signals along the transition zone (Figure 3) that the magnitude of laminar perturbation increases along the downstream direction. However, downstream of the point of transition onset, its magnitude remains approximately constant.

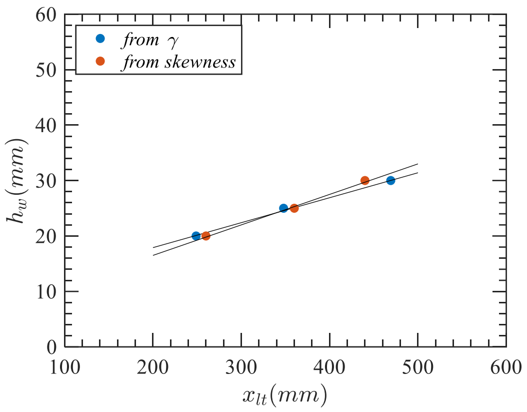

Figure 10. Length of the transition zone obtained from intermittency and skewness distribution.

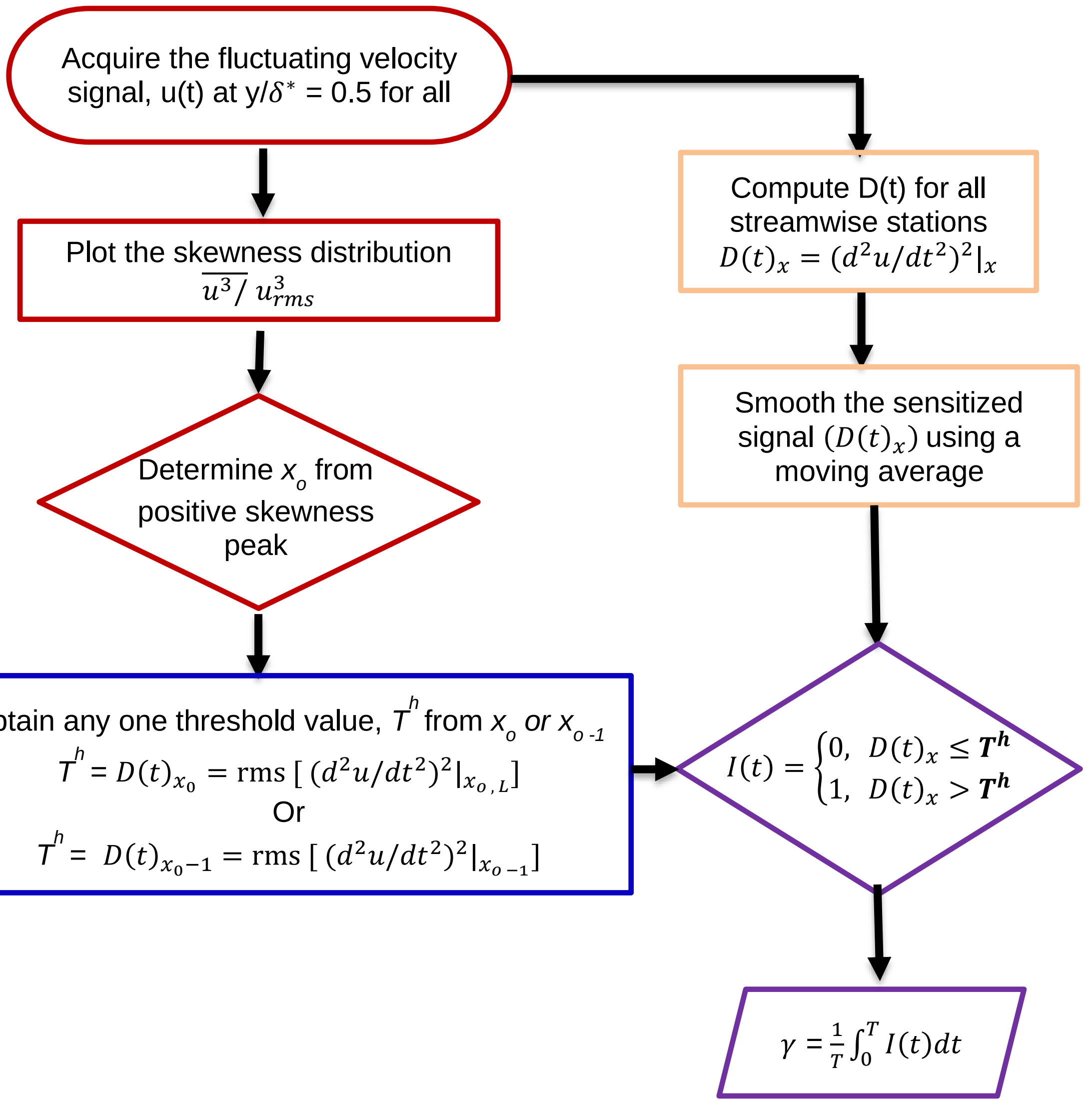

Figure 11.Flow chart of the proposed method for determining the intermittency distribution.

Therefore, it can be assumed that the level of laminar perturbation at the onset point is a clear detector of laminar and turbulent perturbation energy. Hence, in the proposed approach, the laminar perturbation level corresponding to the onset point is chosen as the threshold for determining the intermittency.

At this juncture, another question comes in: how to determine the onset point? And from there, how to extract the laminar perturbation alone from the raw signals? These questions were answered in this paper by proposing several steps, firstly detecting the onset point from the positive peak of the skewness distribution. Secondly, the magnitude of the laminar perturbation at the onset point is extracted by, removing the occasional turbulent spots and taking the rms of the sensitized velocity fluctuating signal ($T_o^h = D(t)_{x_{0,L,rms}}$). Based on the obtained threshold value, the intermittency distribution was obtained for various aerofoil heights and the results were comparable to those obtained with the dual-slope method. It was also demonstrated that choosing the threshold value at x_{o-1} (one station upstream of the onset point) yields the same intermittency distribution without any subjectivity error. For reference, the above procedure is illustrated in Figure 11 as a flow chart. The advantages of the proposed method are (i) a single threshold value is sufficient for the streamwise intermittency determination in the entire flow and (2) the approach reduces the level of subjectivity often involved in the selection of the threshold value. Moreover, the results from the present work suggest that the assumption of constant magnitude of laminar perturbation in the transition zone may be an inherent physical characteristic of the transitional boundary layer.

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7. Copyright Statement

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