PRELIMINARY RESULTS ON TRANSITIONAL INTERMITTENCY IN THE ZERO PRESSURE GRADIENT BOUNDARY LAYERS

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Abstract

The paper concerns with the complex effects of free stream turbulence and surface roughness on the transitional intermittency inclusive of spot production rate in the zero pressure gradient boundary layer at weak k-type transient roughness and at low Reynolds number.

Introduction

The problem of joint action of wall roughness (WR) and free stream turbulence (FST) on the boundary layer development is very broad. The laminar turbulent transition plays a major role in boundary layer development so deserves a special attention. Its relevance is in changes of skin friction, heat transfer and of tendency to flow separation that are caused by increased momentum and scalar diffusion after the transition. The mechanism of how an originally laminar boundary layer on a smooth surface is forced by disturbances penetrating into the layer from environment and of the corresponding routes to turbulent layer were described elsewhere e.g. Jonáš, (1997). The opinion generally accepted is that the final phase of boundary layer laminar/turbulent transition starts with the occurrence of first turbulent spots regardless of the initial conditions.

The location of the laminar-turbulent transition region can be estimated from the distributions of characteristics derived from the mean flow measurements, especially if their course is known in laminar and turbulent states. This is the case of the flat plate boundary layer. The skin friction coefficient distribution seems most suitable for this purpose.

This paper is a follow up to the investigations of mean flow field in the zero pressure gradient boundary layers on plates with smooth surface and plates with surfaces covered by sandpapers (grits 60, 80 and 100) in turbulent free stream e.g. Hladík et al. (2010). The skin friction coefficient value was derived from the mean velocity profile. Then the location of transitional region was carefully estimated by the diversion of the skin friction coefficient distribution from the Blasius solution and by the attachment of the distribution to the Ludwieg and Tillmann curve. The accuracy of this procedure is generally weak because of the measurement scatter, of a

otherwise equal conditions?**Experimental facility and methods**

Investigations of boundary layers developing on smooth or rough plates were performed in the close circuit wind tunnel (0.5 x 0.9 x 2.7 m^3) of the IT AV CR, Prague.

Following boundary conditions were modelled:The mean velocity of external stream was constant, between 5.0 m/s and 5.2 m/s, during investigations of a boundary layer in the given configuration.

2. Boundary layers were developing either on the original smooth plate with the special shape of the leading edge (details see Jonáš et al. , 2000) or on the plate covered with sand paper grits 60 with the elliptic shape of the LE (details see Hladík et al., 2010). The maximum size of grains on sandpaper was chosen as the representative length of the sand paper roughness s = (0.435 ± 0.014) mm.

3. Free stream turbulence was either low – natural with the level 0.3 percent and the length scale of order the 0.1 m or it was intensified by means of square mesh plain grids/screens. Three types of FST were used, each with the intensity Iu = 0.03 and individually with three dimensions of the dissipation length parameter: Le = 3.8 mm, 5.9 mm or 33.4 mm at the plane of the L.E. (x = 0).

The mean flow boundary layer characteristics were evaluated from the mean velocity profiles measured in the investigated sections x (const). Two single wire probes working in the CTA mode were used in the smooth wall configuration. The first reference probe, placed in a fixed position in the outer stream, serves as the indicator of the *reference velocity* $U_r\left(t,\vec{x}_r\right)\approx U_e$. The second probe, the *profile probe,* was put into position by a traversing system in the streamwise direction x and in the direction y normal to the surface. The distance y was measured with an accurate cathetometer (accuracy 0.01 mm). Digital records of the output signals (25 kHz, 750000 samples, 16 bit) were acquired simultaneously and then records of the relevant instantaneous velocities were evaluated using data from the calibration measurements performed prior to the experiment. Next, the correction Jonáš et al. (1999) of the wall proximity effect on hot-wire cooling was applied. The instantaneous wall friction time series $\tau_w\left(t\right)$ are the by-product of wall corrections.

The pressure measurements took priority over CTA method for the mean velocity measurements in the rough wall configuration because of easy breakability of hot-wires by the spikes of roughness grains, difficult/risky set of the smallest distance y from the surface and the increase of dust presence near the sand paper surface. The couple of flattened Pitot tube (probe tip: 0.18 mm x 2.95 mm) and round nosed static pressure probe (dia. = 1.8 mm) serves as the *profile probe* and the Pitot-static probe (dia. = 6 mm) is the indicator of the reference velocity. The basic measurement of the instantaneous wall friction series is carried out by means of a wall hot wire probe step-wise moving in the stream wise direction in the distance from the rough surface y_0 ~ 0.3 mm. The probe (calibrated in advance) is attached to the three wheels truck connected to the traversing system. The probe is working in the CTA mode and the output voltage is recorded (25 kHz, 750000 samples, 16 bit). Next these records are digitally transformed using calibration parameters into the records of the local nominal instantaneous velocity. The CTA output signals processing follows assuming the adjusted y_0 like that in the smooth wall case with one important difference. Irregular variations of the true distance y_w from the adjusted one y_0 in hundred millimetre with the location x occur and we are not able to remove them. Thus an auxiliary local correction of y_w must be made. The correction equals the time averaged skin friction coefficient determined from the mean velocity profile with the mean value of skin friction coefficient calculated from the CTA measurement in the given location x_j. The instantaneous wall friction is evaluated in the vicinity of x_j using the corrected distance y_w.

The instantaneous wall friction records (25 kHz, 750000 samples, 16 bit) were utilized in a statistical analysis of the wall friction in the rough wall boundary layer like in the smooth one.
The applied method of the transitional intermittency analysis is Turbulent Energy Recognition Algorithm-Method, (TERA-method) e.g. Zhang et al. (1996) and the procedure of is very similar to that described in Hedley and Keffer (1974) and Elsner and Kubacki (2000). The method consists of several consecutive steps. At the first, the obtained records of the instantaneous values of wall friction fluctuations τ'_w are filtered by Butterworth filter with low pass frequency 1 *kHz* to eliminate noise from the signal. At the second step, the detector function $D(t)$ is derived as to emphasize the differences of the signal time behaviour during turbulent and non-turbulent periods. The detector function is computed after the formula:

$$D(t) = \left|\tau'_w \cdot \partial^2 \tau'_w / \partial t^2\right| \tag{1}$$

Then the detector function is smoothed to eliminate the scales much smaller than those to be recognized, thus the criterion function $K(t)$ is created. The criterion function, the threshold and the indicator function $I(t)$ are evaluated successively. The indicator function allows assort the whole record in the time intervals with turbulent structure (I = 1) and those with laminar/non-turbulent structure (I = 0). Finally the transitional intermittency factor $\gamma(x)$ is calculated (details are presented in Hladík and Uruba, 2009). This procedure was verified (Jonáš et al.2009) comparing the dimensionless turbulent spot production rates $n^*\sigma$ evaluated by using both the intermittency analysis and the wavelet analysis after Elsner et al. (2006).
At first the authors applied the method within the investigation of the smooth flat plate boundary layer developing in the FST with turbulence intensity Iu = 0.03 and different values of the FST length parameter Jonáš et al (2009). The records of measured data have been made already during the experiments performed within the COST Action F5 and the thematic network TRANSPRETURB (e.g. Jonáš et al. 2000).

Results

Distributions of the transitional intermittency factor γ against the local Reynolds number Re_x are shown in the Figure 1. They clearly illustrate the significant effect of FST, WR and their joint action. Results related to smooth wall layers are marked with triangles, circles mark results related to rough wall layers and various colours/shades of grey differentiate FST after the intensity *Iu* and the length parameter L_e. Data on FST and WR are given in square brackets in captions.

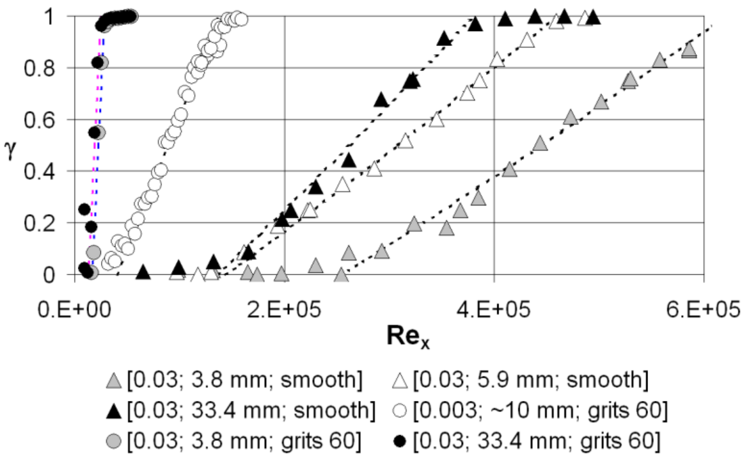

Figure 1 – Distributions of the transitional intermittency factor.

In conformity with Narasimha (1985) the transitional intermittency factor gamma can be expressed in the form involving the spot production rate n (the number of spots occurring per unit time and space distance) and the Emmons (1951) dimensionless propagation parameter σ (including both the stream wise and lateral spot growth -, effect of drift)

$$\gamma(x) = 0,\ x \le x_t; \quad \gamma(x) = 1 - \exp\left[-(x - x_t)^2 n\sigma / U_e\right] \tag{2}$$

Introducing the local Reynolds number into the expression (2) we can define the dimensionless spot production parameter $n^*\sigma$

$$\gamma(\mathrm{Re}_x) = 1 - \exp\left[-(\mathrm{Re}_x - \mathrm{Re}_t)^2 n^*\sigma\right], \quad \mathrm{Re}_x = xU_e/\nu, \quad n^*\sigma = n\sigma\nu^2/U_e^3. \tag{3}$$

Following Narasimha, working on the formulae (3) we can introduce the function that is suitable for the statistical estimates of the transition start $x_s(\gamma = 0)$ and the value of parameter $n^*\sigma$

$$F(\gamma) = \sqrt{-\ln(1-\gamma)} = \sqrt{n^*\sigma}\,(\mathrm{Re}_x - \mathrm{Re}_{xs}) = a_0 + a_1 \mathrm{Re}_x \tag{4}$$

The linear interpolations of the discussed examples are shown in the Figure 2. Obviously both the FST and WR shift the start of transition (γ = 0) and change the dimensionless turbulent spot production rate (slopes of interpolated straight lines).
The distributions of intermittency factor can be expressed in the universal form derived by Narasimha (1985) who introduced a new variable ζ

$$\zeta = (\mathrm{Re}_x - \mathrm{Re}_{tr})/\Delta\mathrm{Re}_{tr};\ \Delta\mathrm{Re}_{tr} = \mathrm{Re}_x(\gamma = 0.9) - \mathrm{Re}_x(\gamma = 0.1);\ \mathrm{Re}_{tr} = \mathrm{Re}_x(\gamma = 0.5) \tag{5}$$

Then the formulae is valid

$$\gamma(\zeta) = 1 - \exp\left[-a(\zeta + b)^2\right] \tag{6}$$

The empirical parameters a and b take the values a = 1.42 and b = 0.72 after model proposed by Narasimha (1985) or the values a = 0.6 and b = 1.05 according to the model proposed by Johnson and Fashifar (1994). Regardless of the established

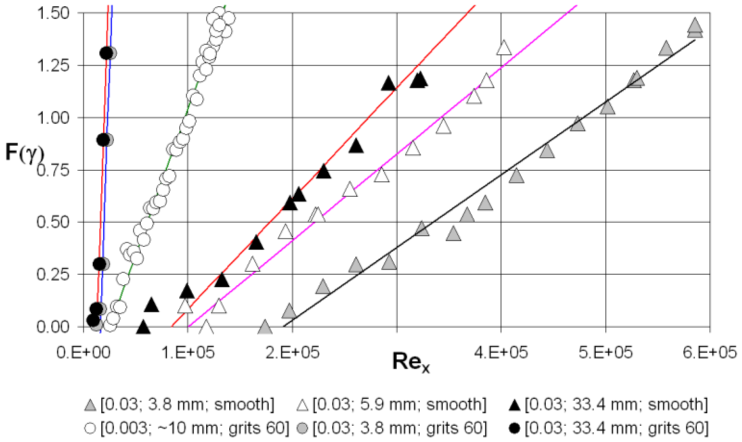

Figure 2 – Distributions of the function F(γ).

differences, the presented data plotted in the Figure 3 demonstrate the compatibility with the universal form (6).

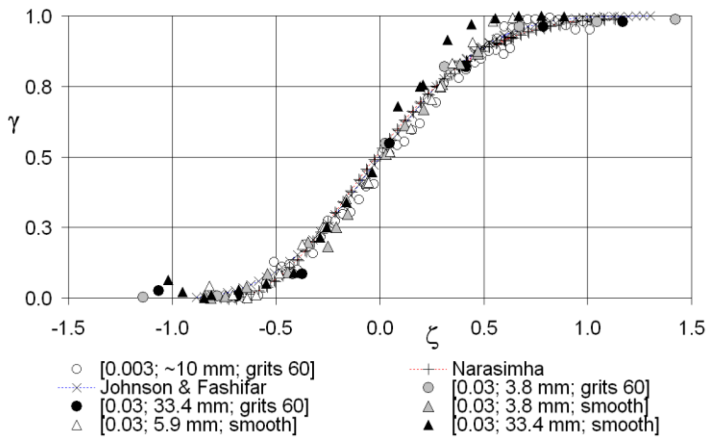

Figure 3 – Universal intermittency function.

Starting from the equation (4) the relation can be derived between the dimensionless spot production rate and the Reynolds number defined with the length of transition region. Let the start of transition relates to $\gamma = \gamma_1$ and $Re_x = Re_1$ and similarly the end relates to $\gamma = \gamma_2$ and $Re_x = Re_2$. Substituting into equation (4) we derive after some formal adaptations

$$n^*\sigma = \left(\sqrt{-\ln\gamma_2} - \sqrt{-\ln\gamma_1}\right)^2 \Big/ \Delta\,\mathrm{Re}_{tr}^2 ; \quad \Delta\,\mathrm{Re}_{tr} = \left(\mathrm{Re}_2 - \mathrm{Re}_1\right)^2 \tag{7}$$

The selection of values $\gamma_1 = 0.1$ and $\gamma_2 = 0.9$ results in the formula

$$n^*\sigma = 1.42 \big/ \Delta\,\mathrm{Re}_{tr}^2 \tag{8}$$

The received results agree with the relation (8) between the dimensionless spot production rate and the Reynolds number value, defined with the length of the transition region. This is shown in the Figure 4. Triangles denote the results received during the

investigation of the smooth surface layers under turbulent free stream with intensity of fluctuations 3 percent and three different values of the length parameter: 3.8 mm, 5.9 mm and 33.4 mm. The circles represent results evaluated from the rough wall boundary layers (sandpaper grits 60) under FST with natural/low intensity of fluctuations 0.3 percent and with two different FST, both with the intensity of fluctuations 3 percent values and with the length parameters 3.8 mm and 33.4 mm.
Apparently turbulent spot production grows and the width of transition region shortens with increasing WR and with growing FST.

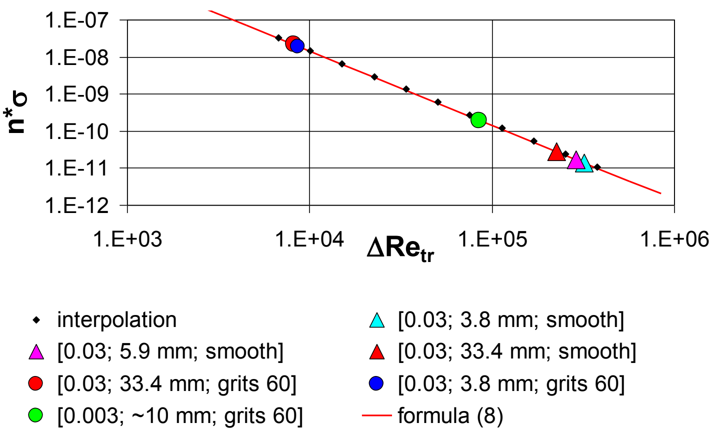

Figure 4 – Dimensionless spot production rate as function of Reynolds number defined with the length of transition region. Black rhombi mark results read/interpolated from Fransson et al. (2005).

Conclusions

The developed procedure of the transitional intermittency measurement and analysis proves successful also in rough wall boundary layers investigation.

The measurements of transitional intermittency factor are the promising tool to make exact determination of the start and the end of laminar-turbulent boundary layer transition region.

External flow turbulence accelerates the development of boundary layer on a rough surface so that the initial region with pseudo-laminar flow remains but shortens and as well the transitional region becomes shorter.Effect of the surface roughness on the boundary layer development is predominating but the impact of turbulence intensity is also significant and as well the effect of turbulence length scale is not negligible.

Turbulent spot production starts sooner and with higher intensity in the rough wall boundary layer than in the smooth one at otherwise equal conditions. The increase of the free stream turbulence intensity and turbulence length scale amplify this process.

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