National Conference with International Participation
ENGINEERING MECHANICS 2003
Svratka, Czech Republic, May 12 – 15, 2003

paper no.
219

CONDITIONAL ANALYSIS OF THE WALL FRICTION HISTOGRAMS IN TRANSITIONAL BOUNDARY LAYERS

P. Jonáš[1], O. Mazur[1], V. Uruba[1]

Summary: *The conditional analysis of the skin-friction was applied on time records made in transitional boundary layers originating under boundary conditions prescribed for the ERCOFTAC Test Case T3A+. Histograms evaluated from the whole records as well as those evaluated from the segments belonging to phases of flow with a non-turbulent or with a turbulent structure are analysed. It is shown that the development and features of a conditionally evaluated histogram depend on the flow structure remarkably. Some universal properties of histograms during laminar/ turbulent boundary layer transition are indicated.*

1. Introduction

The distinctive periods of the boundary layer transition process are well pronounced from the distribution of the skin friction coefficient. So it appears, that the analysis of some statistical characteristics of the wall friction, during transition process, can add to the knowledge on the flow structure and to the refinement of computational methods which involve combining laminar and turbulent solution for the mean flow quantities (e.g. Jaňour [1]) according to the superposition model proposed by Emmons [2] or more sophisticated methods accounting more over for the interaction between the laminar and turbulent phases (e.g. Steeland and Dick [3].

2. Experimental apparatus and procedures

The presented results are based on experiments made at the Institute of Thermomechanics AS CR during the last decade. The experimental facility and measurement technique, used in the current study, are given in Jonáš at al. [4]. The flat-plate boundary layer was developed in the close circuit wind tunnel (0.9 x 0.5 x 2.7 m^3). The outer stream turbulence was controlled by means of plane grids/screens of different geometry and porosity located upstream the flat

[1] RNDr. Pavel Jonáš, DrSc., Oton Mazur, prom. fyzik, Ing. Václav Uruba, CSc.: Ústav termomechaniky AV ČR; Dolejškova 5; 182 00 Praha 8, tel.: 266052025; fax: 286584695; e-mail: jonas@it.cas.cz

plate leading edge (the origin of boundary layer, x=0) in such distance as to produce the turbulence level $Iu_{x=0}$ = 3% with three different turbulence dissipation length parameters L_{e} = 0.0038, 0.0059 and 0.0334 m (COST/ERCOFTAC Test Case T3A+, e.g. Savill [5]). The mean velocity of the free stream was preserved U_e= 5 m/s.

The method and procedure of the employed conditional analysis are fully described in Jonáš et al. [6]. The digital records of the instantaneous velocity measurements, made using a single hot-wire anemometer working in CTA mode, were analysed. Special procedures of measurement and evaluation were derived which allowed transforming the output signal records into records of the wall-friction τ_w [Pa]. Next filtering of this records, detector function computation, threshold setting, determination of the indicator function I(t) followed as customary; the function I(t) = 0 if the flow structure is laminar/non-turbulent and I(t) = 1 if the flow structure is turbulent. The long time average of the indicator function I(t) is equal to the intermittency factor γ(x) at the investigated section. Having determined the indicator function I(t), the probability that a flow with turbulent features is passing over the space of observation, the intermittency factor γ(x) can be calculated. Next turbulent and non-turbulent periods of the skin friction record are defined

$$\begin{aligned} \left(\tau_w(t)\right)_{tot} &= \tau_w\left(t\right) = (\tau_w)_i; \quad i = 1, 2, ..., 1500\,000 \\ \left(\tau_w(t)\right)_{lam} &= \left(1 - I(t)\right).\tau_w\left(t\right) = \left(lam\,\tau_w\right)_i \\ \left(\tau_w(t)\right)_{tur} &= I(t).\tau_w\left(t\right) = \left(tur\,\tau_w\right)_i \end{aligned} \tag{1}$$

Apparently any kind of the statistical analysis of each of the above mentioned records could be done as customary. We decided to start with the analysis of histograms within the preliminary study. The reasons to start with the evaluation of histograms are not only to determine the rate of change of probability with data value – the probability density function and consecutively the moments in future, but also to identify qualitative physical features of the wall friction afterwards. In the authors opinion histograms are more illustrative then the probability density function as they include also the indication on the proportion of the occurrence of the “laminar” or “turbulent” events. Due to this the length of records has been kept identical during each measurement.

3. **Results**

Histograms of the wall friction were determined either from the complete record (1500000 samples) entitled N_{tot} or from the passages corresponding to non-turbulent flow structure (I=0) - N_{lam} or from the record passages corresponding to the time periods with turbulent flow structure (I=1) – N_{tur}. The range of the wall-friction τ_w [Pa] was chosen from 5.10^{-4} Pa up to 1 Pa, divided into thousand portions. This choice ensures that no samples of the wall-friction τ_w will occur outside the range. The analysed wall-friction records were made at numerous distances x (from 0.025 m up to 1.8 m) downstream from the leading edge of the plate with the investigated boundary layers. The introducing of all data sets would cause an untransparency of the presentation. As to avoid this eventuality, only histograms interpolated from the measured distributions at selected sections x are shown: x=0.05m, $x=x_0$ (the section where the intermittency factor γ starts to grow from zero resp. minimum) and next the coordinates of sections where the intermittency factor attains the values γ = 0.25, 0.5, 0.75 and 1 (terminating of transition process). The triads of histograms N_{tot}, N_{lam} and N_{tur} are plotted for individual length scales L_e as functions of τ_w [Pa] and the coordinate x [m] in Figures 1, 2 and 3.

Histograms derived for the laminar phases illustrate that the remainders of outer stream turbulence disturbances penetrating into the boundary layer are not fully damped by the action of viscosity near the leading edge. The outer stream disturbances are attenuated downstream up to the region of small intermittency. Histograms N_{lam} are initially nearly symmetric. Their peaks are at first growing up to the section $x > x_0$, the transition onset, or little bit downstream. They are simultaneously shifting to lower values of τ_w. After the culmination of growth, the peaks are decreasing in the streamvise direction, their shifting is finished and the histograms become more and more asymmetric. Finally the histograms originated during non-turbulent phases of flow vanish still before the termination of the transition process. The “laminar” events contribute to the total record of τ_w predominantly up to the value of $\gamma \approx 0.25$. It should be mentioned that some histograms originated during non-turbulent phases of flow mark out with signs similar to the histogram of a process with superposition of random and sine wave components. Such signs are not evident from histograms originated during turbulent phases of flow.

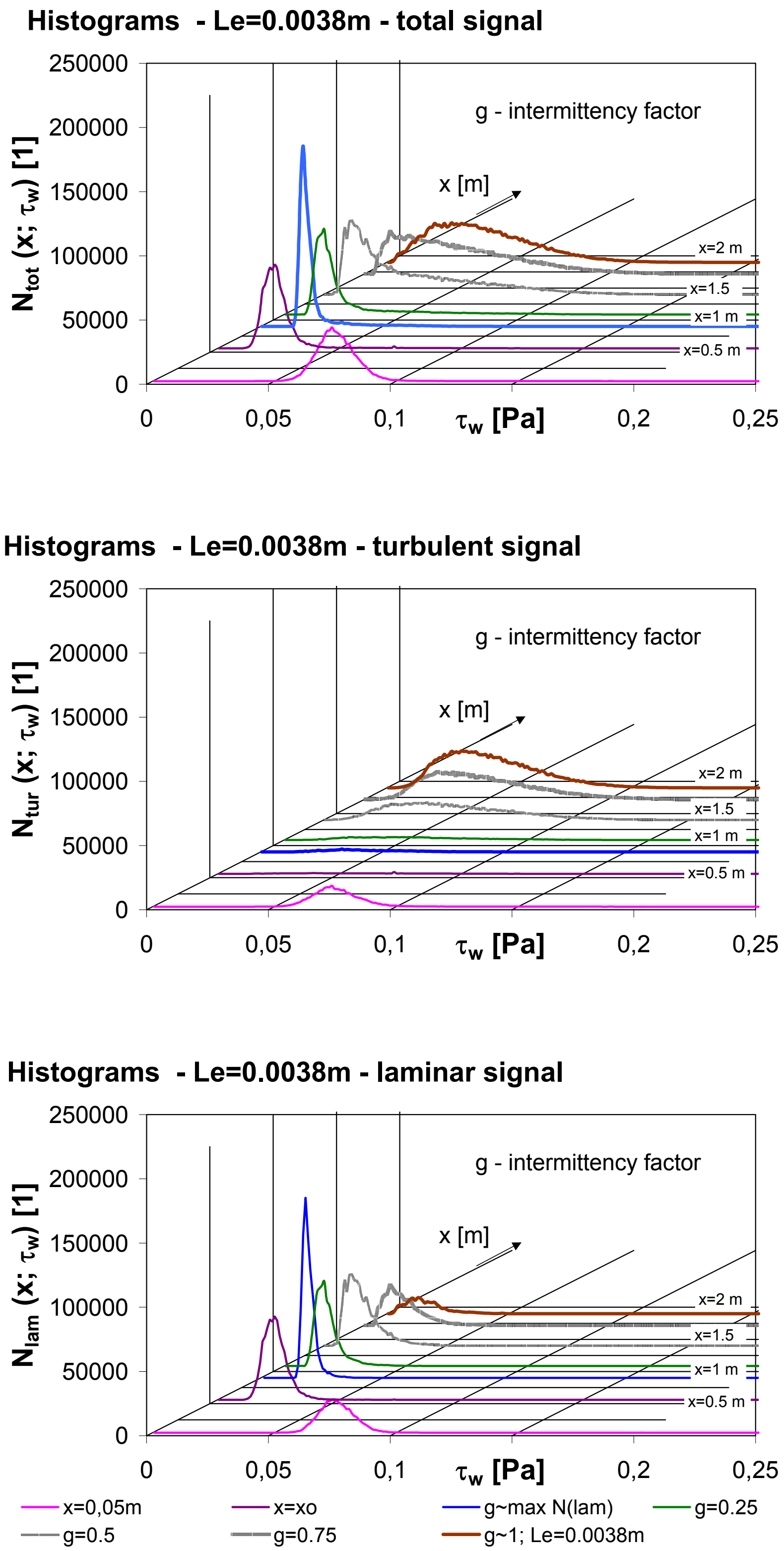

Figure 1 Histograms of the wall friction in transitional boundary layer under turbulent free stream with Iu = 0.03 and L_e = 0.0038 m at the onset of boundary layer, x = 0 m.

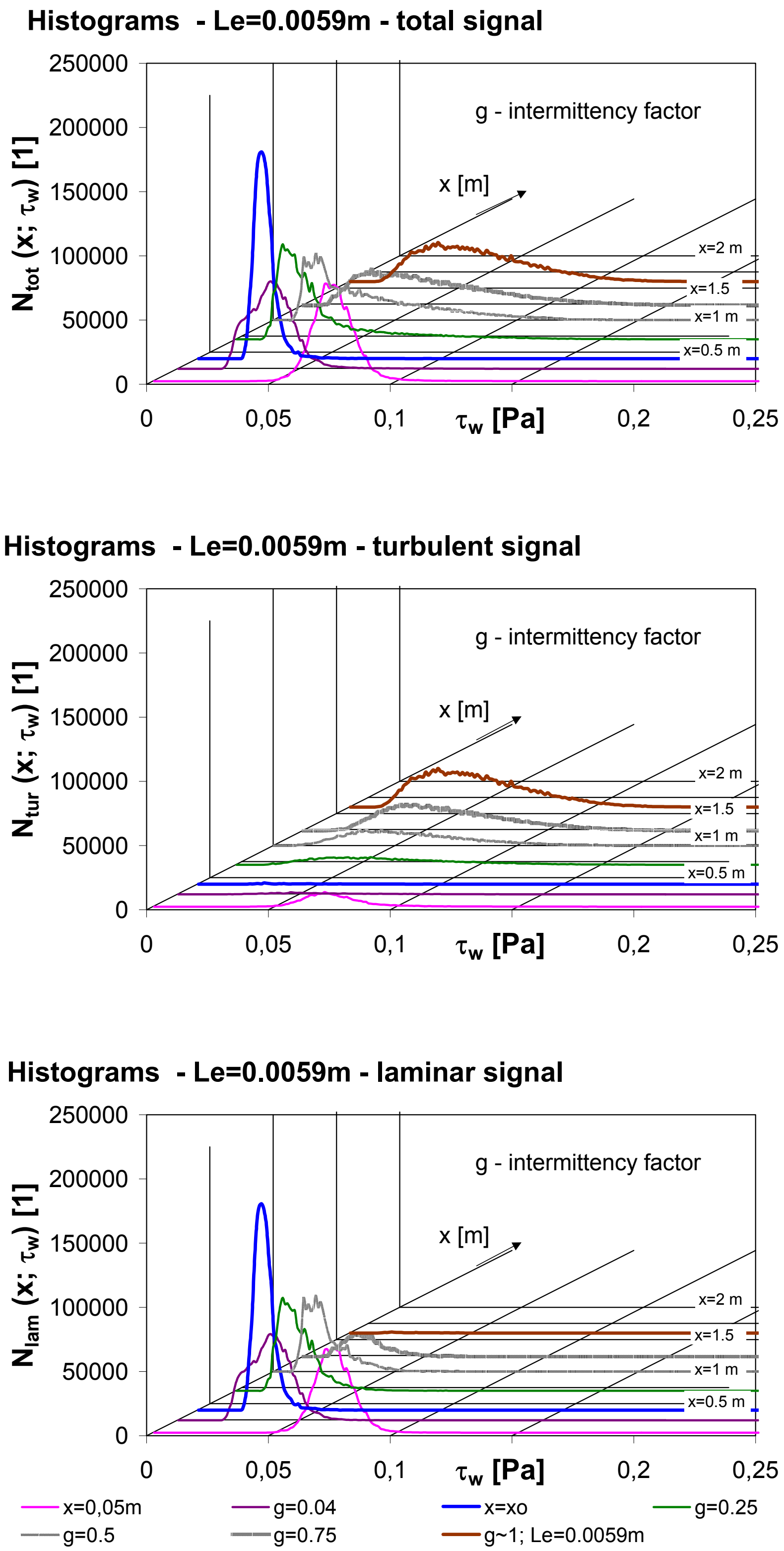

Figure 2
stream with Iu = 0.03 and L_e = 0.0059 m at the onset of boundary layer, x = 0 m.

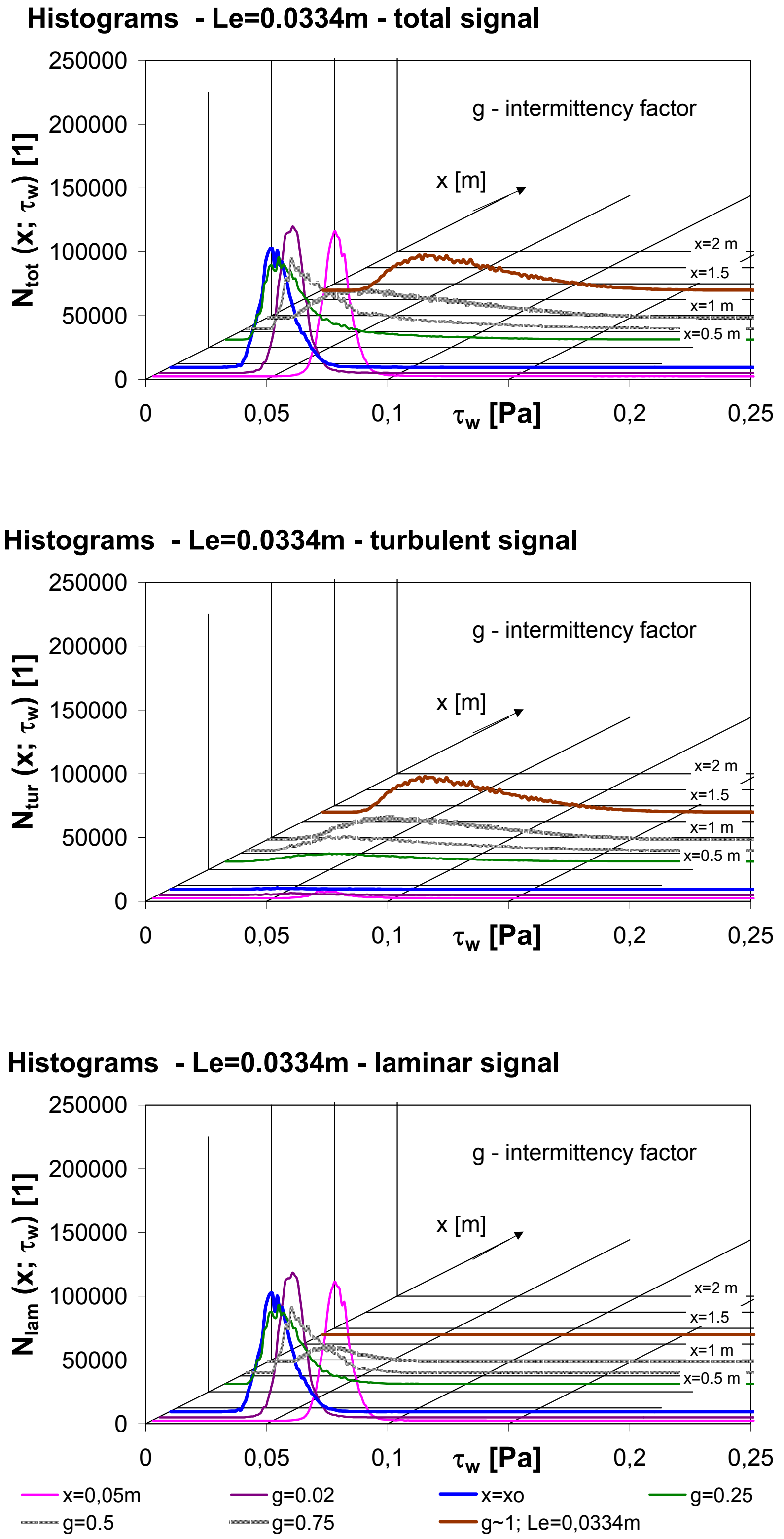

Figure 3 Histograms of the wall friction in transitional boundary layer under turbulent free stream with Iu = 0.03 and L_e = 0.0334 m at the onset of boundary layer, x = 0 m.

The development of the histograms derived for the turbulent phases is approximately opposite. They are recognized closely at the leading edge – at the onset of boundary layer, x = 0.05 m. Unexpectedly they are more obvious in the case with outer stream turbulence with the smallest length scale. Then motions considered as turbulent disappear downstream up to the surrounding of the section $x \approx x_0$.

Histograms of the wall friction during turbulent phases get to amplify, increase their volumes and became very asymmetric further downstream from the section where the intermittency factor $\gamma \sim 0.25$. Their mean values slightly decrease.

4. Conclusions

Histograms evaluated from series of 1.5 million samples of the wall-friction τ_w are evaluated in the course of laminar/ turbulent boundary layer by-pass transition at boundary conditions relevant to the ERCOFTAC Test Case T3A+.

Each series of the total signal is assorted into passages with laminar or turbulent character of flow and conditioned histograms are derived. It is shown that the developments of conditionally evaluated histograms depend on the kind of the flow structure remarkably. Some universal properties can be indicated.

During laminar phases of the flow structure: the histograms N_{lam} are broadly symmetric closest the boundary layer origin and their peaks are growing with the dissipation length parameter L_e. This observation illustrates that the remainders of outer stream turbulence disturbances penetrating into boundary layer are not fully damped by the action of viscosity near the leading edge – the origin of the boundary layer.

Farther downstream, the histograms N_{lam} are shifting to the lower values of τ_w. At first their peaks are growing in the streamvise direction up to the section little bit downstream from the onset of transition. Then the peaks are decreasing, the histograms become more and more asymmetric and weaken. Week signs of the presence of harmonic fluctuations (TS waves?) inside the analysed signal are visible up to the section where the intermittency factor γ draws to the value 0.5. Then the histograms during laminar periods lower and even disappear towards the end of transition region.

The development of the histograms N_{tur} derived for the turbulent phases is approximately opposite to the development of the histograms derived for the non-turbulent/laminar phases of flow. There are not observed signs of harmonic components in the wall friction record. This fact can support the notion that the above-mentioned occurrence of such components in “laminar” periods can be attributed to wavy motions in the flow field.

The turbulence length scale L_e does not affects qualitatively the appearance and development of the wall friction histograms in the transitional boundary layer. However its effect on the essential characteristics of transitional boundary layer is very remarkable. The larger is the scale L_e the faster is the progress of laminar turbulent transition although the turbulence intensity is equal at the onset of the boundary layer for all compared cases.

Acknowledgements

This work was funded by the Grant Agency of the CR, the grants #101/98/k001, #101/00/1057 and #101/03/0018. The support is gratefully acknowledged.

References

[1] Jaňour Z. /1995/: Two-layer model for by-pass boundary layer transition. ERCOFTAC Bulletin No. 24, 42-43.

[2] Emmons H. W. /1951/: The laminar turbulent transition in boundary layer. J. Aero. Sci. 18, 490-498.

[3] Steelant J., Dick E. /1996/: Modelling of by-pass transition with conditioned Navier-Stokes equations coupled to an intermittency transport equation. Intern. J. Num. Methods in Fluids, 23, 193-220.

[4] Jonáš P., Mazur O., Uruba V. /2000/: On the receptivity of the by-pass transition to the length scale of the outer stream turbulence. Eur. J. Mech. B – Fluids 19, 707-722.

[5] Savill A.M. /1995/: COST-ERCOFTAC transition SIG COST Action Workshop IT AS CR Prague. ERCOFTAC Bulletin No. 25, 36-37.

[6] Jonáš P., Mazur O., Uruba V. /2002/: Preliminary results of conditional analysis of the wall friction during boundary layer transition. In: Proc. Colloquium Fluid Dynamics 2002(Eds. P. Jonáš, V. Uruba), IT AS CR Prague (ISBN 80-85918-77-3), 77-80.