Boundary Layer Transition by Advese Pressure Gradient

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Abstract. For some cases of diferrent of boundary layer development conditions (roughness of surface, turbulence in main flow) by adverse pressure gradient was determined tranzitiom region. Boundary layer Tranzition region was found based on intermittency development of flow inside the boundary layer. Intermitency was evaluated using modiffied TERA method algorithm.

1 Introduction

Results of data analysis of experimental investigation of the transition of the laminar boundary layer to turbulence on a flat plate into a diffuser channel with and without adverse pressure gradient are presented. Different cases with a combination of some boundary layer development conditions were investigated.

It was studied cases with combination of different roughness of surface by different free stream turbulence intensity and by pressure gradient along boundary layer. This combination of conditions is usually common in real flow tasks.

Better understanding and description of effect of an adverse pressure gradient and another conditions like roughness of surfaces or turbulence of external flow on the boundary layer transition, location and size of the transition zone by transition from laminar boundary layer to turbulence, seems to be important.

The transitional intermittency represents by distribution of intermittency factor γ the boundary layer development. The distributions of an intermittency factor γ and on its based determination of onset and terminating of transition zone are presented in this work.

2 Pressure Gradient

The pressure gradient is often present in the free stream dependently on the changings of the mean velocity along the flow. An adverse (unfavorable) pressure gradient in the external flow is often present in technical tasks, so its a frequent phenomenon in internal and external aerodynamics. It can be identified for example along the diffuser walls or airfoil and blade profiles (tail part on the suction side), that means very serious cases. The unfavorable pressure gradient in the external stream has a strong destabilizing effect on the boundary layer.

3 Experiments

3.1 Experimental setup

The experiments were carried out in the closed type wind tunnel and the investigated boundary layers were developing on the smooth or rough flat plate. The orthogonal coordinate see Fig. 1.

Cross section of the test section of the wind tunnel was 0.9 m x 0.5 m. The length of a flat plate was of 2.65 m. Flat plates with different roughness of surface can be changed (aerodynamically smooth and sandpaper roughness P32 and P60 particles/cm^2). The flow acceleration begins about 1.2 m upstream the flat plate.

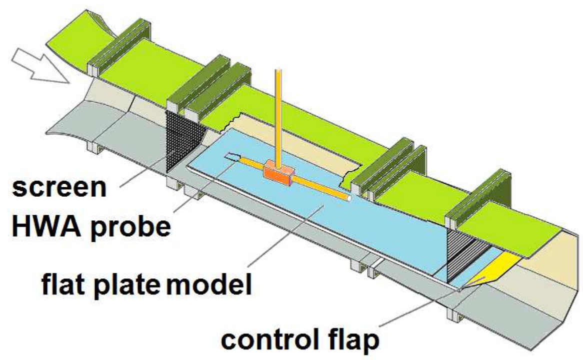

Fig. 1. Experimental setup - flat plate in the windtunnel test section

The flow deceleration starts at the level of the leading edge of the flat plate (x = 0) where the flow velocity is set to U_e = 10 m/s. Cases with adverse pressure gradient are provided by plane diffuser expanding part putted into test section. The diffuser channel was created in the test section for make the adverse pressure gradient in main flow belong flat plate. Length of this diffuser section is 1.4 m and opening angle was 5°. It was checked carefully that there was no flow separation on the deflected wall.

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The free stream turbulence was controlled by square plane mesh (grid) with cylindrical rods and square mesh holes. The free stream turbulence intensity Iu_e at the leading edge was naturally Iu_e = 0.005 or set by the special screen (square grid) to Iu_e = 0.03. The leading edge of the plate had a super-ellipse shape MSE6.

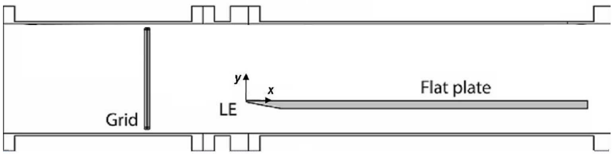

Fig. 2. Experimental setup - flat plate without diffusser part in the windtunnel test section.

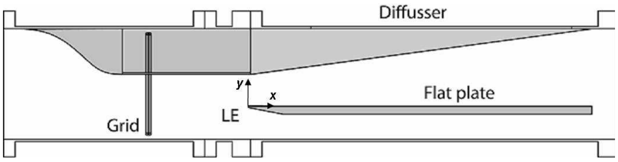

Fig. 3. Experimental setup - flat plate with diffusser along the model of flat plate in the windtunnel test section.

3.2 Measurement techniques

Flow in the boundary layer was studied by constant temperature anemometer technique. It was used a hot wire anemometry equipment CTA system Dantec Streamline.

The hot-wire probe was put into defined positions by the computer controlled traversing device. The distance y from the wall was checked manually by cathetometer with accuracy ±0.02 mm relative to the surface or to peaks of roughness (used fine control plate with area 5mmx20mm below the hot-wire probe).

The reference value of the free stream velocity was measured by a Prandtl pressure probe (diameter 6 mm) at the inlet of test section. Prandtl probe signal and barometric pressure was connected to pressure transducer Druck DPI 145 (range 7 kPa, accuracy ±0.005% FS). The flow temperature was measured by thermometer Pt100. Output voltage from the transducers were read by Data acquisition unit HP 34970A.

A single hot-wire probe was used for HWA measurement. A sensor of the probe was tungsten wire. Diameter of the wire was d_w = 5e-06 m and length of the wire was l_w = 1.25e-03 m. Operating wire temperature during measurement was set T_w=493 K. Hot wire sensor was oriented parallel to leading edge of flat plate. The output anemometer signal was digitalized using the A/D transducer National Instruments data acquisition system and recorded by the PC using the LabVIEW scripts (sampling frequency 75 kHz, 16 bit, time of every measurement was set to 20 s).

A cooling law for heated sensor of Koch and Gartshore (1972), was used for hot-wire measurements.

Data analysis TERA method [2] was performed using the LabVIEW scripts, results were organized using MS EXCEL.

3.3 Measurement uncertainties

The experimental uncertainties Δ are estimated based on calculated root mean square errors of interpolations and observed repeatability. The upper limits of relative errors of evaluated quantities depend mainly on precision of location of the probe (the distance y from surface of flat plate) and accuracy of hot-wire local instantaneous velocity U measurement:

$\Delta U/U = \pm 0.005$; (U_e = 10 m/s);
$\Delta y = 0{,}001$m ;
$\Delta H_{12}/H_{12} = \pm 0.01$;
$\Delta\, \gamma\, /\, \gamma = \pm 0.2$.

3.4. Determination of the intermittency

The transitional intermittency is describing the laminar to turbulence transition process development in the boundary layer along the surface of the flat plate, see Fig.4.

Boundary layer starts from leading edge of the flat plate in stream wise direction and in specific distance from leading edge starts the process of laminar to turbulent flow transition. It relates to the generation and propagation of turbulent spots, turbulent spots are detected using TERA method. The transitional intermittency factor $\gamma(x)$ is one of the key parameters in physically right recognition of the transitional boundary layer state.

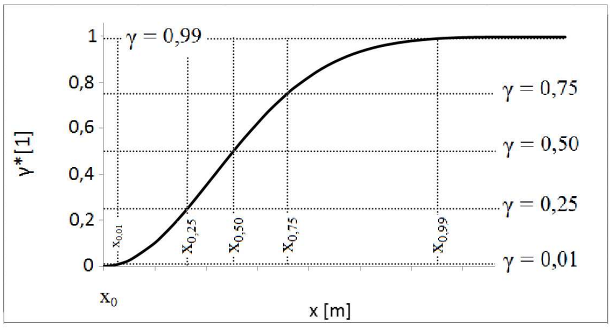

Fig. 4. Boundary layer tranzition – process mdescription using intermittency coeffitient.

Onset of transition corresponds to minimum of its value (ideally $\gamma \approx 0$) and the end of transition region is indicated by1 $\gamma \approx 1$. Increasing value of the intermittency coefficient upstream the transition onset could be explained by disturbances penetrated from outside the boundary layer and interactions with particless of fluid from boundary layer. [3]

The intermittency factor computed by a direct method is defined as time ratio of turbulent flow occurrence time over whole measurement time

$$\gamma\ (x\ )=\sum_{i=1}^{N}\frac{I(\mathrm{x},\mathrm{t}_i)}{N}, \qquad (1)$$

where $I(x,t_i)$ is indicator function in point x and time t_i, derived from digitalized instantneous velocity record captured close to the surface of flat plate in distance x from leading edge of the flat plate, see below and Fig. 4 - Fig. 6.

Determination of onset and terminating of transition zone is usually covenanted. The transition onset is covenanted in $x_{0,99}$, where $x_{0,99j}$ is a point, where $\gamma(x_{0,01}) = 0{,}01$; the transition terminating is covenanted in $x_{0,99}$, where $x_{0,99j}$ is a point, where $\gamma(x_{0,99}) = 0{,}99$.

Direct method TERA of determination of the intermittency factor is very effective in detecting the start and the end of transition with proper choice of parameters for signal processing and analysis. A lot of methods of determination γ is available [1, 2], the TERA (Turbulent Energy Recognition Algorithm) method [2] was chosen.

The TERA method consists of several consecutive steps, with modify raw hot wire signal of instantneous velocity to the criterion function, see [x1, x2].. At the first, the raw instantaneous velocity fluctuations signal from CTA anemometer is filtered to $\tilde{u}$(t) by Butterworth filter with low pass frequency 1 kHz to eliminate parasitic noise from the signal. Sensor HWA was sensitive to stream wise velocity component and to vertical velocity component.

The second step is derivation of the signal to the detector function $D(t)$. Time derivation of signal makes the differences of the signal time behaviour during turbulent and non-turbulent periods more recognizable. Detector function is defined as

$$D(t)=\left|u\frac{\partial u}{\partial t}\right| \qquad (2)$$

where u is fluctuations of the instantaneous velocity.

Then the HWA signal (Fig. 2) is filtered (Fig. 3) and derived to the detector function (Fig. 4). Then is detector function smoothed to criterion function (Fig. 5). The threshold value K_P is applied onto criterion function $K(t)$, Fig. 5, and a its result is an indicator function I (t), Fig. 6, details are presented in [x4]). The threshold value K_P is in base TERA method given by

$$K_{\mathrm{P}}\left(x\right)=\mathrm{C}_2(\tilde{u}\left(x,t\right)\mathrm{d}\tilde{u}\left(x,t\right)/\,\mathrm{d}t)_{\mathrm{RMS}}\,), \qquad (2).$$

index RMS means the standard deviation evaluated during a time of measuement of one data point. [1, 2]

The disadvantage of TERA algorithm is well known. It is necessary manually find the "right value" of threshold constant C_2 in equation (2).

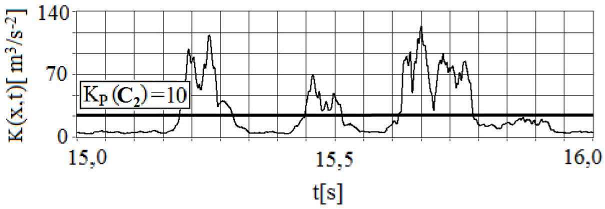

Fig. 5. Criterion function K(t) with threshold value $K_P(C_2)=10$.

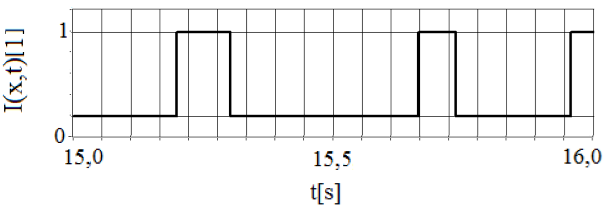

Fig. 6. Indicator function I(t), [3].

It was discussed different ways, how to find an optimal and objective value C_2^* of threshold constant.

The most successful is a criterion using quality of interpolation of evaluated experimentally data points γ with universal intermittency function γ^* [7]

$$\gamma^*\left(x\right)=1-exp\left(-0{,}412\left(\frac{x-x_{0,01}}{x_{0,75}\ -x_{0,25}}\right)^2\right). \qquad (3)$$

First step is calculation of a group of γ_j^* functions for different values C_{2j} from (empirically recomended) interval

$$C_{2j}\in(0{,}05;0{,}6)\,. \qquad (4)$$

where $j = \langle 1, M\rangle$, M is a number of iterations for evaluation C_2^* .

Universal intermittency function γ_j^* for C_{2j} is expressed

$$\gamma_j^*\left(x\right)=1-exp\left(-0{,}412\left(\frac{x-x_{0,01j}}{x_{0,75j}-x_{0,25j}}\right)^2\right), \qquad (5)$$

where $x_{0,25j}$ is a point, where $\gamma_j(x_{0,25j}) = 0{,}25$; $x_{0,75j}$ is a point, where $\gamma_j(x_{0,75j}) = 0{,}75$, for given C_{2j} .

Values *of* $x_{0,25j}$ and $x_{0,75j}$ (for given C_{2j}) should be found using TERA method from only locally interpolated data points of $\gamma_j(x)$.

The exact value of $x_{0,01j}$ (point of start of the transition proces) is very difficult to find directly from locally interpolated data points of $\gamma_j(x)$, function γ is here very flat and experimental data are usually not enough smooth. Value of $x_{0,01j}$ can be better found using another form of universal intermittency function $\gamma^{**}\left(x\right)$, see eq. (6), [8]. This form uses experimentally data points $\gamma_j(x)$ from the middle part of transition zone, function γ is here » *well shaped* ». The value of $x_{0,01j}$ is the last searched value in eq. (5)

$$\gamma_{0,01j}^{**}\left(x\right)=0{,}01=1-exp\left(-0{,}412\left(\frac{x_{0,01j}-x_{0,5j}}{x_{0,75j}-x_{0,25j}}+1{,}3\right)^2\right), \qquad (6)$$

where $x_{0,5j}$ is point, where γ_j = 0,5. Values of $x_{0,25j}$ and $x_{0,25j}$ are known, see before, the value of $x_{0,5j}$ can be found as the local interpolated value from experimental data point of $\gamma_j(x)$ too. This is analytical algorithm, how to find the γ^* or γ^{**} in every "j- iteration".

Another possibility how to find parameters of $\gamma_j(x)$ function consist in direct using of a simple optimization process internally in every "j-iteration" using interpolation of experimentally data points of $\gamma_j(x)$ by γ^* or γ^{**} function.

Experimental data points, which appears to be sure inside the transition zone of the boundary layer, $\gamma^*(x_i, C_{2j}) \in (0,2;0,8)$ or $\gamma^{**}(x_i, C_{2j}) \in (0,2;0,8)$, is necessary take with some higher weight-coefficient into internal optimizing process to supress influence of the data points, which appears to be far outside the transitional zone.

The quality of approximation ϕ_j of (from experimentally data evaluated) intermittent factor γ_j with universal intermittency function γ_j^* can be expressed (for N points of γ and γ_j^*)

$$\phi_j(C_{2j}) = \frac{1}{N}\sum_{i=1}^{N} \sqrt{\gamma(x_i, C_{2j})^2 - \gamma^*(x_i, C_{2j})^2} \,. \qquad (7)$$

Function $\phi_j(C_{2j})$ depends on the value of the threshold value C_{2j}. Optimization criterion to find the optimal and objective value of the treshold value C_2^* can be expressed

$$\min(\phi_j(C_{2j})) \to C_2^* \,. \qquad (8)$$

This process of experimental data points postprocessing seems be capable and simple improvement of the known TERA method. Now is it possible set the founded optimal value C_2^* into (up to now unknown) constant C_2 in equation (2) and the objective distribution of intermittency factor $\gamma(C_2^*)$ or in the form of the universal intermittency function γ^* can be now clearly expressed.

Another classical and historically older and undirect way musing Emmons hypothesis, how to evaluate the intermittency factor, consit in observing of some integral boundary layer parameter X development along boundary layer, such a boundary layer shape factor, skin friction coeffitient, etc.

$$X = (1-\gamma) X_{\mathrm{L}} + \gamma X_{\mathrm{T}} \qquad (9)$$

where δ_1 is a displacement thickness of boundary layer and δ_2 is a momentum thickness of boundary layer. For some basic cases, such as flat flate boundary layer, are values of X_L and value of X_T for turbullent boundary layer known. For example, shape factor H_{12} can be used

$$H_{12} = \frac{\delta_1}{\delta_2}\,, \qquad (10)$$

4 Results of the experiment

It was carried out a lot of hot wire measurement. It was made fine measurement in whole boundary layer region and its neighbourhood with good space and time resolution for cases of combination different conditions of boundary layer development (Tab. 1).

Table 1. List of the test cases. Combination of the external conditions of the development of the boundary layer along flat plate.

label	α [°]	surface	Iu_e [1]
0-S-0,005	0	smooth	0,005
0-S-0,03	0	smooth	0,03
0-R-0,005	0	rough P32	0,005
0-R-0,03	0	rough P32	0,03
5-S-0,005	5	smooth	0,005
5-S-0,03	5	smooth	0,03
5-R-0,005	5	rough P32	0,005
5-R-0,03	5	rough P32	0,03

Especially in cases with adverse pressure gradient it is not easy find a point of velocity profile (or a distance of the probe from the surface of the flat plate), where to investigate transitional intermittency, see Fig. 7. Position and size of identified transitional zone is in different points different. The best results seems to be for distance about 1,5 mm from the surface or peaks of surface roughness (corresponds to $y^+ \approx 100$), more precise criterion was not found yet. In cases without adverse pressure gradient is possible use signal from the position of probe in the mean velocity profile, where the sign of the skewness parameter $S(u)$ is changing (maximum of turbulent spots generation).

Intermittency factor $\gamma(Re_x)$, shape factor H_{12} and pressure gradient or outer mean velocity decrease $\overline{U_\infty}/\overline{U_{\infty}}_0$ respectively was evaluated. Distributions for different conditions of developing of the boundary layer (Tab. 1) along the flat plate are plotted in Fig. 8 and Fig. 9, dependently on the distance x from the leading edge of the plate or on the local Reynolds number Re_x.

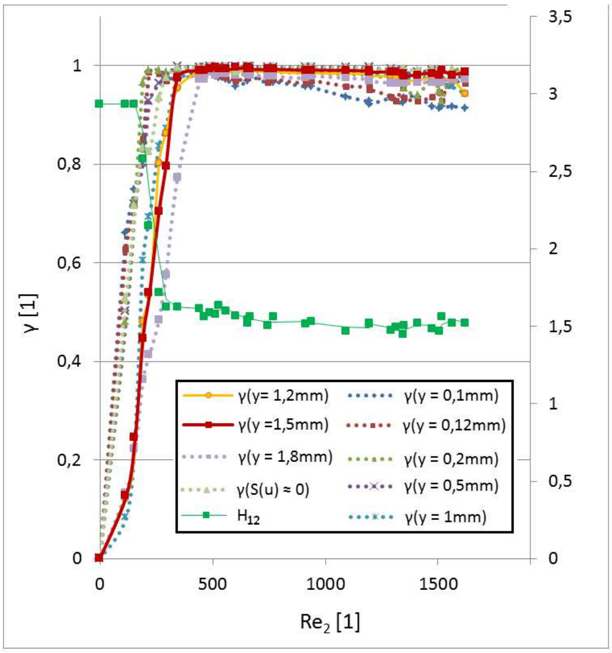

Fig. 7. Intermittency factor and shape factor in different points of mean velocity profiles of boundqary layer, example. Position and size of identified transitional zone seem to be different. Plotted usingn Reynolds number Re_2 related to the momentum thickness δ_2.

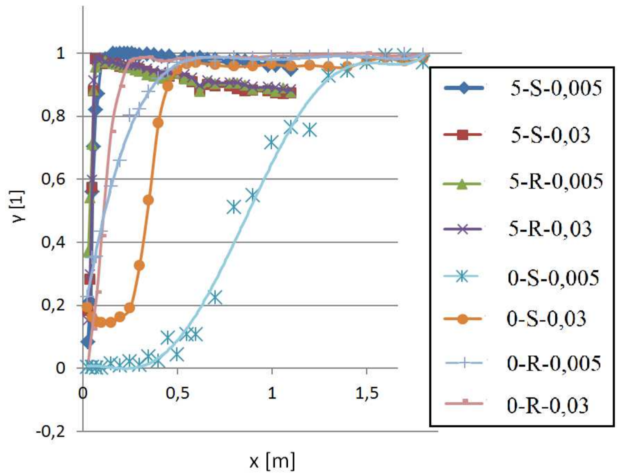

Fig. 8. Universal intermittency function γ^* describes boundary layer transition process, all cases.

5 Conclusions

Adverse pressure gradient accelerates the transition process to bypass transition of boundary layer. Transition starts much closer to the leading edge of the flat plate and the length of the transitional zone is much shorter. Higher free stream turbulence intensity and effect of and roughness of the surface are too recognizable and significant, but the separation of its influence is probably not possible, the process of bypass transition is nonlinear with significant nonlinear interactions in flow field in the boundary layer. Results can be used to numerical models validations.

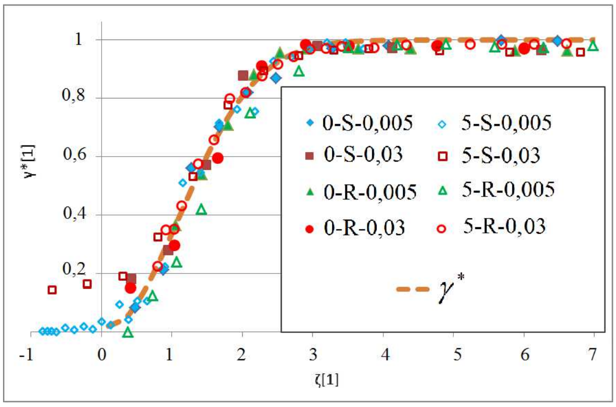

Fig. 9. Universal intermittency functionγ^* describes boundary. layer transition process, mcases without outer pressire gradient – influence of free stream turbulence and roughness of surface of the flat plate. Label explained in Tab. 1.

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