Estimating of turbulent velocity fluctuations in boundary layer with pressure gradient by Smoke Image Velocimetry

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Abstract. The results of the experimental estimating of the velocity profiles and turbulent pulsations in the boundary layer for adverse and favorable pressure gradients are presented. The profiles of characteristics based on the dynamics of two-component instantaneous velocity vector fields measured by the field optical method of Smoke Image Velocimetry are estimated. The measurements are performed with a large spatial and temporal resolution, the measurement results are relevant for estimating the terms of the conservation equation of turbulent energy in the boundary layer and for improving semiempirical turbulence models.

1. Introduction

Flows with pressure gradient are often encountered in technical systems, especially the airfoil flow has a practical value in this problem. The presence of pressure gradient exerts a significant influence on the development of boundary layer. Experimental studies of the turbulent boundary layer (TBL) with adverse (APG) [1-16] and favorable (FPG) [1, 3, 12, 15, 17-25] performed with the use of instantaneous velocity measurement by point methods quite fully explained the physical basis of mechanics of such flows.

The study in detail the interaction of large-scale vortex structures with the wall turbulence zone only with the advent of field methods for measuring the instantaneous velocity has become possible. Over the past 10 years, field optical measurement methods have often been used in studies of flows with APG [26-33] and FPG [34, 35]. However, the problems of the PIV and PTV methods described in the works on the study of the zero-gradient boundary layer [36-40] obviously remain relevant for flows with a pressure gradient. The growth in the uncertainty of PIV and PTV measurements with a reduction in scale does not allow to estimate with sufficient accuracy the spatial small-scale turbulent characteristics that are necessary for a more complete understanding of the mechanisms of generation and dissipation of turbulence and for improving semiempirical turbulence models. In part, this problem was solved in two new spatial measurement techniques, "Shake-The-Box" (STB) [41] and VIC+ [42]. However, these two approaches have not yet been tested for the boundary layer under conditions of a pressure gradient.

In the technique of high-speed optical measurement of instantaneous velocity fields (Smoke Image Velocimetry - SIV) [43, 44] used by the authors of this article, in contrast to the classical methods of PIV and PTV, the multiply higher concentration of tracers is used. Particles due to a higher concentration on the video image look like smoke with a continuous distribution of brightness. The studies of the zero-
gradient boundary layer carried out using the SIV method showed that with a sufficiently good temporal resolution (of the order of 10 kHz), the use of a high tracer concentration contributed to a reduction in measurement noise with an increase in the spatial resolution to 1.6-2.0 of the Kolmogorov scale. This allowed to evaluate small-scale characteristics, such as dissipation of turbulence energy and higher-order moments of velocity fluctuations with an acceptable degree of accuracy.

An estimate of the velocity profiles and its turbulent pulsations in the boundary layer under conditions of adverse and favorable pressure gradients in the coordinates of the wall law based on SIV-measurements of flow velocity vector fields is obtained in this paper. The results of these measurements performed with large spatial and temporal resolution are relevant for estimating the terms of the conservation equation of turbulent energy in the boundary layer, which has not yet been experimentally obtained for the flows with pressure gradient.

2. Experimental setup
The air flow in a smooth plane expanding and convergent channels has been studied. Experimental setup for study the flow structure using the optical method of Smoke Image Velocimetry (SIV) is shown for APG in figure 1 and for FPG in figure 2. The test section 1a for boundary layer with APG, figure 1, was an asymmetric diffuser channel of rectangular cross-section with 5 degrees angle of expansion, a 150 mm width, a 410 mm length, 27 mm entrance section, 60 mm output. Before the diffuser there was a prewired section 13a which was a rectangular 27×150 mm2 channel with the length of 350 mm and a smooth inlet 10 with 12:1 contraction. The test section 1b for boundary layer with FPG, figure 2, was an asymmetric confusor channel of rectangular cross-section with 5 degrees angle of expansion, a 150 mm width, a 410 mm length, 60 mm entrance section, 27 mm output. Before the confusor there was a prewired section 13b which was a rectangular 60×150 mm2 channel with the length of 350 mm and a smooth inlet 10 with 6:1 contraction.

A turbulence generating grid 9 with 5 mm cell size, 1.6 mm steel wire diameter was mounted downstream of the smooth inlet 10. Abrasive P24 (ISO 6344-2) 12 was glued onto the channel perimeter along a 50 mm section. This provided fully developed turbulent boundary layer in the measurement area during the experiments. Channel walls were made of transparent materials (glass and polycarbonate). Stable air flow rate downstream of the test section was provided by a regulating gate 11 and a 1.3 m3 receiver tank 2 mounted downstream of the latter. Flow rate was measured by an ultrasonic flowmeter 3 IRVIS RS4-Ultra mounted downstream of the receiver tank. The relative error in flow rate did not exceed 1%.

To visualize the flow pattern, the air-aerosol mixture (MT-Gravity fluid with medium fog density and average particle size of 0.1…5 μm; Safex aerosol generator 5) was supplied from the preparation chamber 4 to the channel inlet. The measurement area 6 was illuminated by a continuous diode-pumped solid-state laser KLM-532/5000-h 7. The flow pattern in the channel symmetry plane at the distances of L=5, 135 and 270 mm from the inlet was recorded by a monochrome high-speed camera Fastec HiSpec 8 with the frame resolution of 665×110 pixel (scaling factor of 0.054…0.0625 mm/pixel), frame rate f = 9578…12526 1/s. The scaling factor and frame rate in each section were selected based on preliminary estimates of the boundary layer thickness and the average velocity at the measurement area. The camera was equipped with a Navitar 1”F/0.95 lens (focal length 25 mm, manual focus).

Figure 1. Experimental setup for APG TBL
Figure 2. Experimental setup for FPG TBL

Flow velocity fields were measured by optical SIV technique based on digital processing of flow pattern video recordings. Velocity vector fields here were estimated by the analysis of turbulent structure displacements visualized by smoke. Interrogation window size was 16×6 and 16x16 pixel. Velocity vectors were calculated from the digital images at the nodes of Cartesian grid with grid spacing of 2 pixels. Maximum displacement of turbulent structures between two consecutive frames was 12 pixels (at the boundary layer edge). Image resolution in Y+ coordinates was 1 pixel = 0.7...1.0 Y+.

Profiles of velocity and turbulent fluctuation intensity are written in wall coordinates y+. The presence of the pressure gradient obviously increases the parametric dimension to describe the similarity laws. In addition to the classical the Re number for ZPG turbulent boundary layers, in the case of APG and FPG the dimensionless pressure gradient parameter β=δ* (∂p/∂x)/τ proposed by Francis Clauser in 1954 [2] is usually considered. This parameter describes the ratio of the pressure force to the friction force where dp/dx is the static pressure gradient. During the experiment pressure measurement was not performed, therefore the static pressure gradient was estimated according to the Bernoulli’s equation for the adverse gradient of the dynamic pressure calculated from the average velocity.

3. Results and discussion

Table 1 presents the main characteristics of the investigated turbulent boundary layer with the APG and FPG calculated from the results of measuring the instantaneous velocity field by the SIV method. The numbering of sections is given in the flow direction.

A velocity profile described by the logarithmic law of the wall for a non-gradient turbulent boundary layer (figures 3A, 4A) at the entry sections of the diffuser and confuser channels is observed. The level of turbulent pulsations in the boundary layer also corresponds to the level for ZPG (figures 3B, 3C, 4B, 4C).

The velocity profiles in section 2 and 3 obtained by the SIV measurements for APG and log law in the coordinates of the wall law y+ correspond to the coordinate of y+≈50. Starting from y+>50 the deviation from the logarithmic distribution is clearly traced on the velocity profile with APG: the region appears with a shape similar to the influence of the wake law. The effect of the evolution of turbulent pulsation profiles is described along the length of the diffuser channel [45, 46]: the peak of the turbulent pulsation profiles shifts from the coordinate y+≈10-20 to the region of the middle of the boundary layer thickness and this process is evolutionary along the channel length. It should be noted that the level of turbulent pulsations u'u' in the coordinate region y+≈150 exceeded the level of turbulent pulsations in the region of y+≈15 only in the third section, for which β=5.88, figure 3B. This is consistent with the results of [9, 16, 25], in which this effect was noted for β>5. A similar appearance of the peak near the coordinate y+≈150 at β=5.88 is observed in the profiles v'v' and u'v', figure 3C.

Similar velocity profiles U+ for same β in the boundary layer with FPG in sections 2 and 3, figure 4A, are obtained. It is evidence of the equilibrium state of the boundary layer [25]. In the profiles of turbulent pulsations of the boundary layer with FPG, figures 4B, 4C, the effect of flow laminarization along the length of the boundary layer is visually observed.

4. Conclusions

The results of estimating the characteristics along the length and thickness of the boundary layer under the conditions of APG and FPG based on SIV-measurements of flow vector fields completely agree
with the conclusions of the works in which point methods of measurement were used. The high spatial and temporal resolution achieved with the SIV-measurements allows using these results for the estimation of small-scale spatial characteristics of turbulence.

**Table 1. Results of the main measured characteristics of turbulent boundary layer**

| Section number | APG | FPG |
|----------------|-----|-----|
| Freestream velocity, $U_\infty$ (m/s) | 7.49 | 6.14 | 4.58 | 3.55 | 4.36 | 4.94 |
| Thickness TBL, $\delta_{99\%}$ (mm) | 7.70 | 13.4 | 26.0 | 28.1 | 21.9 | 4.86 |
| Displacement thickness TBL, $\delta^*$ (mm) | 1.18 | 2.81 | 7.09 | 3.22 | 2.04 | 0.95 |
| Momentum thickness TBL, $\theta$ (mm) | 0.73 | 1.76 | 3.94 | 2.07 | 1.33 | 0.43 |
| Dynamic velocity, $u_\tau$ (m/s) | 0.40 | 0.26 | 0.16 | 0.18 | 0.22 | 0.26 |
| $\beta$ | 1.02 | 2.68 | 5.88 | -1.2 | -0.9 | -0.9 |

**Figure 3.** Profiles of characteristics of boundary layer with APG: A) velocity profiles; B) $u'u'$ turbulent pulsation profiles; C) $v'v'$ and $u'v'$ turbulent pulsation profiles

**Figure 4.** Profiles of characteristics of boundary layer with FPG: A) velocity profiles; B) $u'u'$ turbulent pulsation profiles; C) $v'v'$ and $u'v'$ turbulent pulsation profiles

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