COEFFICIENT OF SKEWNESS IN THE DISTRIBUTIONS OF VELOCITY FLUCTUATIONS IN LAMINAR – TURBULENT BOUNDARY LAYER TRANSITION

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The process of transformation of the energy transfer mechanism from molecular to large eddies during transition from laminar to turbulent flow has attracted increasing attention of researchers in recent times. This interest stems from the hope that a knowledge of the transition mechanism would lead to a better understanding of the processes taking place in a turbulent boundary layer. Our earlier studies on transition in a flat-plate boundary layer revealed the presence of a number of zones across the thickness and along the transition region as a result of the variation in the nature of velocity fluctuations [1, 2]. Later studies on the probability density distribution of velocity fluctuations in the laminar–turbulent transition region made it possible to quantitatively estimate the different zones. An example of one of the distributions of velocity fluctuations is given in [3]. The latest studies on transition revealed an interesting nature of the variation of the coefficient of skewness of velocity fluctuations at distances less than the boundary layer displacement thickness. Results obtained in the two cycles of tests, widely separated in time, are reported in the present paper.

Studies on laminar–turbulent transition on a flat plate with an elliptic leading edge and zero pressure gradient were conducted in a low turbulence wind tunnel. Velocity measurement was made with a DISA anemometer with a linearizer, and an MP-5521 tape recorder was used to record signals in the 1 Hz to 10 kHz frequency range. Velocity realizations were analyzed on a Histomat statistical analyzer. Distributions were plotted for 100-124 points with a sample volume $\Sigma p(v_i) = 10^6$ and a total process time of 90 sec. Probability density was determined in the usual manner:

$$p_i = p(v_i)/\Sigma p(v_i),$$

where $p(v_i)$ is the instrument-indicated probability.

Subsequent mathematical analysis of distributions was carried out using the first and the second moments

$$E[V] = \Sigma v_i p_i, \quad E[V^2] = \Sigma v_i^2 p_i,$$

where V is the random variable being investigated, v_i are the possible values of the random variable with probability p_i, the dispersion

$$D = E[V^2] - (E[V])^2,$$

the central third moment

$$E[\overset{0}{V}{}^3] = \Sigma (v_i - E[V])^3 p_i,$$

where $\overset{0}{V}$ is the centered random variable, and the coefficient of skewness

$$\nu = E[\overset{0}{V}{}^3]/D^{3/2}.$$

The experimentally determined family of curves $\nu(\gamma^*; y/\delta^*)$ (γ^* is the maximum value of the intermittency coefficient at a given location along the plate length, y is the normal distance from the flat-plate surface, δ^* is the boundary-layer displacement thickness) made it possible to establish two facts: a) $\nu = 0$ when y is close to δ^*, for $0.1 \le \gamma^* \le 0.8$; b) the similar nature of the dependence of ν on y/δ^* with variation in the dimensionless distance from the flat plate in the range $0.1 \le y/\delta^* \le 1.2$. It has been suggested that the variation in the coefficient of skewness ν in the above-mentioned range can be expressed as a product of two functions:

$$\nu(\gamma^*; y/\delta^*) = f_1(\gamma^*; y/\delta^* = \text{const}) f(y/\delta^*). \tag{1}$$

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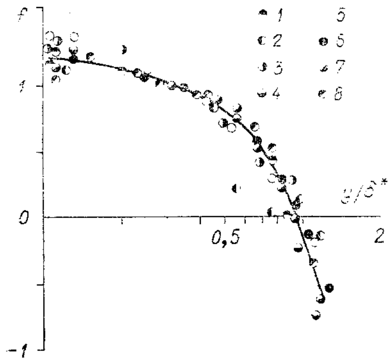

Fig. 1

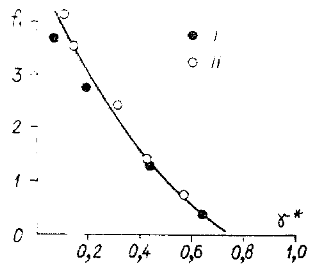

Fig. 2

All the values of ν obtained for different intermittency coefficients were normalized with respect to the coefficient of skewness at $y/\delta^* = 0.3$ for each value of γ^*. The results are plotted in Fig. 1 [values of γ^*: 1) 0.08; 2) 0.20; 3) 0.45; 4) 0.65; 5) 0.15; 6) 0.32; 7) 0.44; 8) 0.58]. Numerical analysis using the method of least squares showed that the function

$$f(y/\delta^*) = 2 - 0.709 \exp (1.088\, y/\delta^*) \tag{2}$$

(the solid line in Fig. 1) adequately expresses all the available experimental data. The high accuracy of the coefficients in Eq. (2) is retained since they have an appreciable influence on the curve. In computations using Eq. (2), the result obtained has to be rounded off in accordance with the accuracy of experimental data.

The apparatus described in [4] was used to determine the values of the intermittency coefficient $\gamma(x, y)$, whose maximum value along y was found for each x (x is the coordinate along the flat plate). This value of γ^* was taken as the fundamental parameter characterizing the transition zone. The possibility of such an interpretation is discussed in [5]. Figure 2 shows experimental values of the coefficient ν for $y/\delta^* = 0.3$ at each location of the boundary layer along x [point 1 is from cycle I, point 2 is from cycle II, and the solid line is expressed by the function

$$f_1(\gamma^*;\, y/\delta^* = 0.3) = 2.20 - 3.16\gamma^* + 3.05 \exp (-3.8\, \gamma^*), \tag{3}$$

obtained by the method of least squares using, unfortunately, very few experimental points].

Experimental data obtained in the two cycles of tests I and II for the coefficient of skewness ν are given in Fig. 3a and b [a is from cycle II; values of γ^* are: 1) 0.15; 2) 0.32; 3) 0.44; 4) 0.58; b is from cycle 1; values of γ^* are: 1) 0.08; 2) 0.20; 3) 0.45; 4) 0.65; 5) ~0; 6) 0.90]; the solid lines are plotted using Eq. (1) with functions $f(y/\delta^*)$ and $f_1(\gamma^*;\, 0.3)$ [Eq. (2) and Eq. (3)]. It is seen that in the laminar–turbulent transition zone, these functions describe very well the dependence of the coefficient of skewness of velocity fluctuations in the wall region of the boundary layer on the dimensionless distance from the flat-plate surface and on the maximum intermittency coefficient across the thickness.

It is necessary to note yet another experimental fact. The values of the coefficient of skewness in the pre-transition region of the boundary layer ($\gamma^* \sim 0$) and the post-transition region ($\gamma^* = 0.9$) are plotted in Fig. 3b. In the pre-transition boundary layer almost symmetrical velocity fluctuations are observed, and their character changes fairly rapidly when the intermittency coefficient is of the order of 0.1. Farther downstream, the velocity fluctuations across the boundary layer in the given zone tend to be symmetrical but at the end of the transition zone the sign of the coefficient of skewness is changed. Even when $\gamma^* = 0.9$ the nature of variation of the coefficient of skewness is reminiscent of a turbulent boundary layer in which $\nu > 0$ is observed only in the viscous sublayer [6] close to the wall.

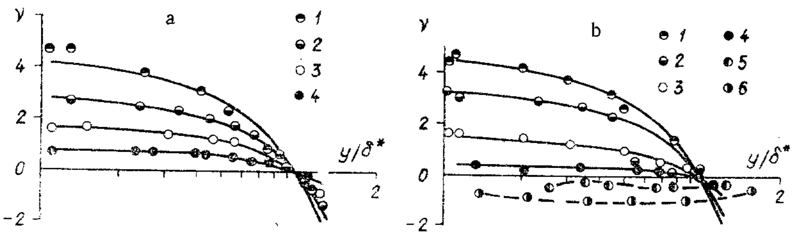

Fig. 3

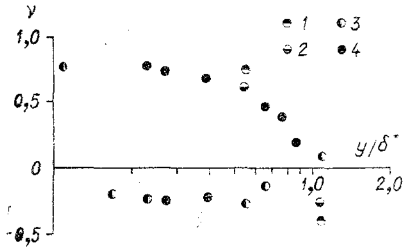

Fig. 4

In order to determine the frequency distribution of velocity fluctuations that make a fundamental contribution to the variation in the coefficient of skewness in the transition region, ν was measured for the same initial signal with the help of different high-pass and low-pass filters. Values of ν for the three frequency ranges are plotted in Fig. 4 for the case $\gamma^* = 0.58$ (points 1 are for the range 1 Hz to 10 kHz; 2, for 1 Hz to 1 kHz; 3, for 1 to 10 kHz; 4, for overlapping points). It is seen that the fundamental contribution to the sign and magnitude of the coefficient of skewness is made by low-frequency velocity fluctuations associated with the production and passage of turbulent spots with different lifetimes.

The above experimental data on the coefficient of skewness of velocity fluctuations in the region near the wall of the laminar–turbulent transitional boundary layer and their numerical analysis indicate the presence of certain statistical similarities during transition. The coefficient of skewness in the given flow is determined by the low-frequency velocity fluctuations associated with the production and passage of turbulent spots. These results could be used to explain the mechanism of transition of the laminar boundary layer into a turbulent one.

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LITERATURE CITED

1. G. S. Migirenko, V. A. Tétyanko, and Yu. V. Shtatnov, "Certain general characteristics of laminar–turbulent transition," in: Heat Physics and Physical Hydrodynamics [in Russian], Nauka, Novosibirsk (1974).
2. V. A. Tétyanko and Yu. V. Shtatnov, "Studies on the characteristics of laminar–turbulent transition," in: Turbulent Boundary Layer, Proc. of the Eighteenth Siberian Heat Physics Seminar [in Russian], Part II, S. S. Kutateladze (ed.), Novosibirsk (1975).
3. V. A. Tétyanko and T. A. Sharapova, "Laminar–turbulent transition and the development of turbulent boundary layer," in: Transition from Laminar to Turbulent Boundary Layer. Two-Phase Flows [in Russian], Izd. Inst. Teplofiz., Sibirsk. Otd., Akad. Nauk SSSR, Novosibirsk (1978).
4. A. N. Voitenko and V. A. Tétyanko, "Determination of intermittency coefficient in laminar–turbulent transition," in: Studies on Boundary Layer Control [in Russian], Izd. Inst. Teplofiz., Sibirsk. Otd., Akad. Nauk SSSR, Novosibirsk (1976).
5. A. A. Ginevskii, E. V. Vlasov, and A. V. Kolesnikov, Aeroacoustic Interactions [in Russian], Mashinostroenie, Moscow (1978).
6. E. U. Repik, Yu. P. Sosedko, and N. S. Tronina, "Studies on the structure of turbulent boundary layer close to the wall," in: Turbulent Boundary Layer, Proc. of the Eighteenth Siberian Heat Physics Seminar [in Russian], Part II, S. S. Kutateladze (ed.), Novosibirsk (1975).