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UNSYMMETRIC CORNER FLOWS

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Streamwise flow past corners is characterized by the development of secondary flows in the neighborhood of the bisecting plane [1-4]. These streamwise vortices in the boundary layer were determined by Prandtl [5] as secondary flows of the second type, i.e., flows where the velocity gradients $\partial/\partial y$ and $\partial/\partial z \gg \partial/\partial x$. Such flows are caused by Reynolds stress gradients along the y and z axes, which induce v and w components in the interaction region of the boundary layers. The extent of this wall region in the transverse direction is on the order of (2-4) times the boundary-layer thickness at the given section [6]. Conditions for the appearance and development of such flows with the transition of laminar to turbulent boundary layers in the case of symmetrically developing boundary layers in a straight two-sided corner are studied in detail in [7]. However, in a number of practical cases there is an unsymmetric interaction of boundary layers. Such flows are realized, e.g., in the wing–fuselage junctions and other flight vehicle components. They are characterized by different growth history of the boundary layers on the sides of the corners which leads to asymmetric flow in the neighborhood of the bisecting plane. This type of boundary-layer interaction is the most complex and least studied, and as yet there is no acceptable model for computing such flows. Even experimental data describing the physical picture of the phenomenon are also very limited. The only known investigations are in [8] in which the flow characteristics were studied in the neighborhood of the junction of a slender wing profile mounted on the wall of a wind tunnel test-section of a rectangular cross section. Here the wing leading edge was a semiellipse with $b/a = 1:6$. This paper presents results of experimental studies on the structure of turbulent flow at the junction of two plane surfaces which can be schematically considered as an idealized joint of the wing–fuselage type. A sufficiently wide variation was made in asymmetry which can be conditionally characterized by the ratio of the thicknesses of interacting boundary layers δ_B/δ_A. This made it possible to analyze the variation in the structure of such flows as it transforms from a simple pattern in which symmetrically developing boundary layers ($\delta_B/\delta_A = 1$) interact to form a more complex structure where there is an interaction of boundary layers with different growth histories ($\delta_B/\delta_A > 1$).

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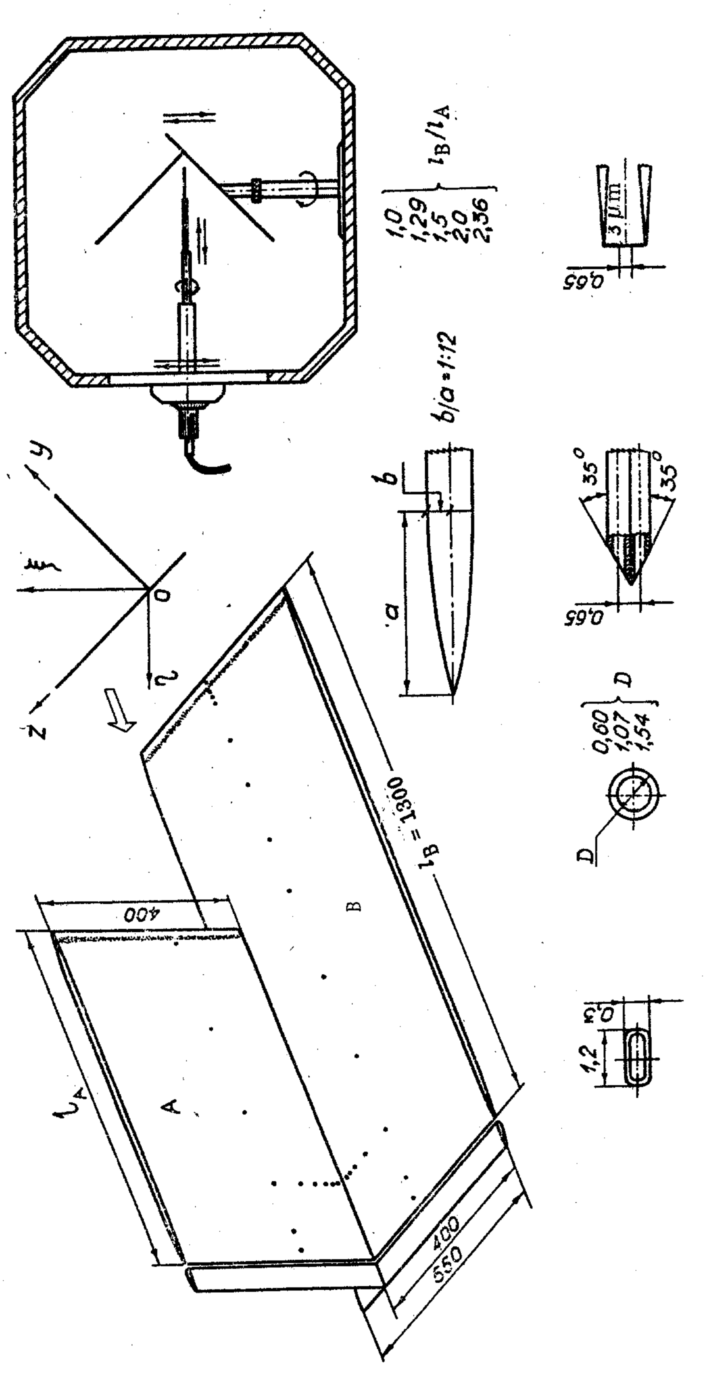
400
400
550
$l_B = 1300$
l_A
A
B
x
y
z
o
a
b
b/a = 1:12
l_B/l_A
1,0
1,29
1,5
2,0
2,36
35°
35°
0,65
0,65
3 μm
D
0,60
1,07
1,54
1,2
0,3

Fig. 1

TABLE 1

δ_B/δ_A	1,0	1,23	1,5	1,98	2,3
$Re_{x_A}\cdot 10^{-6}$	2,17	1,62	1,26	0,68	0,69
$Re_{x_B}\cdot 10^{-6}$	2,17	2,17	2,10	1,73	2,17

Experiments were conducted in the low-turbulence wind tunnel of the Institute of Theoretical and Applied Mechanics of the Siberian Branch of the Academy of Sciences, USSR (ITPM SO AN SSSR) [9] with a free stream velocity u_∞ = 30 m/sec which corresponds to a unit Reynolds number $Re_1 = 1.95\cdot 10^6$/m. A sketch of the corner model is shown in Fig. 1. The corner model consists of two plane polished sides mounted at right angles to each other on a rigid steel body. The nose and the trailing edge region of the plates were made in the form of half-ellipses with b/a = 1:12. Here the length of the side A was successively varied but the length of the side B was kept constant at 1300 mm as a result of which a turbulent boundary developed even before the beginning of the junction. Variation in the degree of flow asymmetry whose value was varied in range δ_B/δ_A = 1.0-2.3 was also achieved in the same manner. The corresponding Reynolds numbers in the transverse section Re_{xA} and Re_{xB}, computed on the basis of the velocity outside the boundary layer u_δ and distances x_A and x_B from the beginning of the growth of turbulent boundary layer, are given in Table 1.

In order to measure the respective parameters of the incompressible boundary layer inside the two-sided corner such as total pressure, magnitude and direction of velocity, and the local skin-friction coefficient, a series of small aerometric transducers shown schematically in Fig. 1 were used. The measurement of the streamwise component of velocity fluctuations was made with a 55 D00 DISA constant temperature hot-wire anemometer. The probe was made of a 3-μm-diameter Wollaston wire (see Fig. 1).

A more detailed description of the model, experimental procedure, and instrumentation as well as some results of systematic studies are given in [7].

According to the data from numerous experiments, the relative value of the random error in the measurement of integral characteristics of the boundary layer, computed for the longitudinal velocity component, is 0.2%. The neglect of the transverse velocity component may introduce additional error not exceeding 2%.

One of the basic characteristics analyzed in this work is the streamwise vorticity component which was determined by graphical differentiation of experimental curves w(y) and v(z). It is known that this method may lead to considerable error in the determination of this quantity. However, computations made by using the small parameter technique showed that the absolute error in the nondimensional streamwise vorticity component $\Delta\omega_x$ does not exceed ±0.5.

In order to eliminate systematic errors, the possibility of the propagation of disturbances in the given section from the corner points of the leading edge of the side B was studied. Results obtained made it possible to choose relative location of the sides of the corner excluding the penetration of outside disturbances into the region under study [7]. The static pressure distribution on the surfaces of the sides was also measured in all configurations of the model. The pressure coefficient distribution was very uniform except in the neighborhood of the leading edge and certain regions on the side B within the zone of propagation of disturbances from the nose region of the side A [10]. Analogous variation in pressure was observed for all degrees of asymmetry δ_B/δ_A.

Analysis of the fields of streamwise velocity component u and velocity fluctuations u', and also stationary secondary flows characterizing the velocity components v and w indicates the complexity of the three-dimensional nature of the flow near the line of intersection of the two sides of the corner. As an example, in Fig. 2a-c the distribution of lines of equal velocity (isotachs) u/u_δ = const is shown corresponding to δ_B/δ_A = 1, 1.5, 2.3. Here curves 1-6 correspond to the relative velocity u/u_δ = 0.5, 0.7, 0.8, 0.9, 0.95, 0.99. The curves shown in Fig. 2a have been obtained for $Re_{xA} = Re_{xB} = 2.17\cdot 10^6$. In the remaining cases here and in what follows Reynolds numbers are given in Table 1.

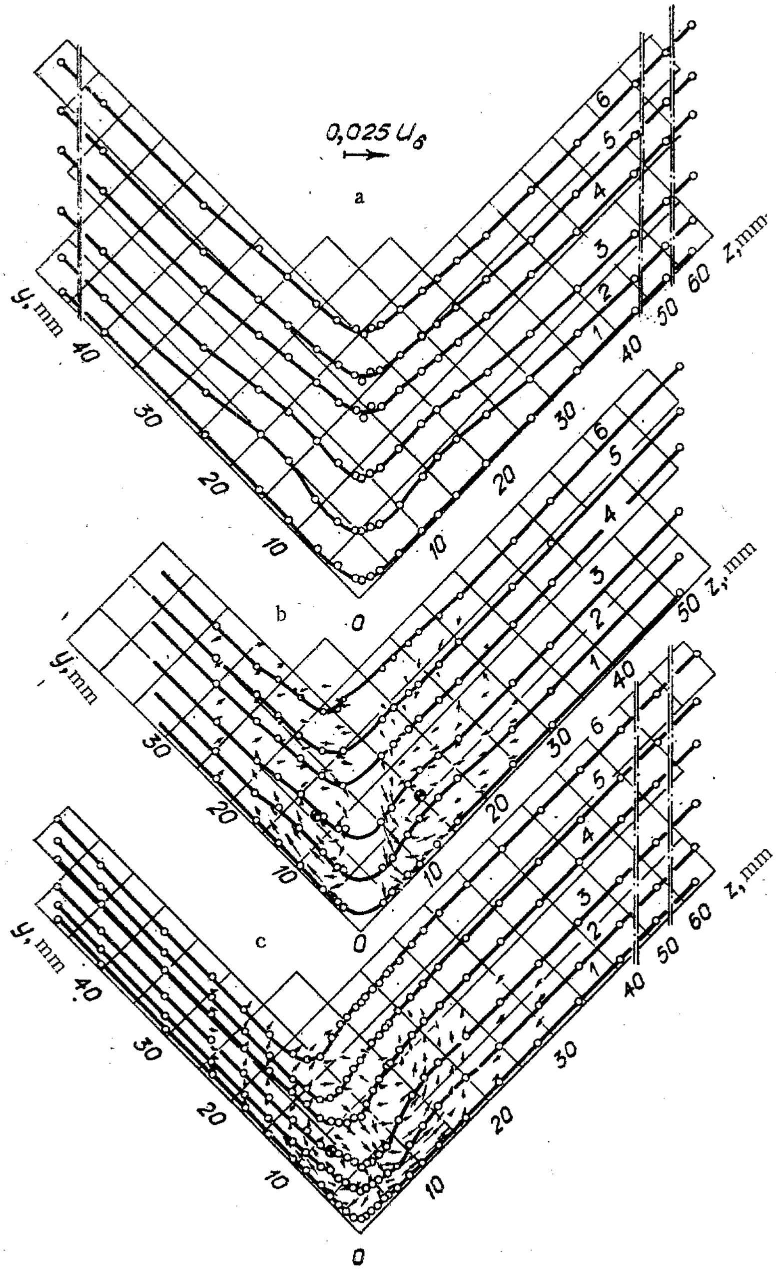

Fig. 2

If in the case $\delta_B/\delta_A = 1$ the flow is symmetric with respect to the bisecting plane of the corner, then with an increase in this parameter the symmetry is violated all the more. In this study, in practically the whole range of values of δ_B/δ_A in the interaction region of the boundary layers there is a twist in the contour of isotachs due to secondary flows.

These are confirmed by the velocity profiles w and v for which it is characteristic to change sign as one moves away from the surface of the sides [10]. These profiles show that transverse flows in the wall region are directed away from the bisecting plane along the span of the corner, but in the outer region the direction of these flows changes in the opposite manner, i.e., toward the plane of symmetry of the corner. Thus, in the neighborhood of the bisecting plane counterrotating streamwise vortices are developed, which is more clearly established by the distribution of transverse velocity vectors, shown with arrows on the background of the lines of equal velocities (see Fig. 2b, c). The transverse flow to the surface of the model with displacement from the plane of symmetry in the direction of the greater length of the side B is clearly observed. Unlike the symmetric case these vortices are distinguished by their intensity and are located asymmetrically with respect to the bisecting plane, the asymmetry being the greater, the greater the value of δ_B/δ_A. Here the dividing line of

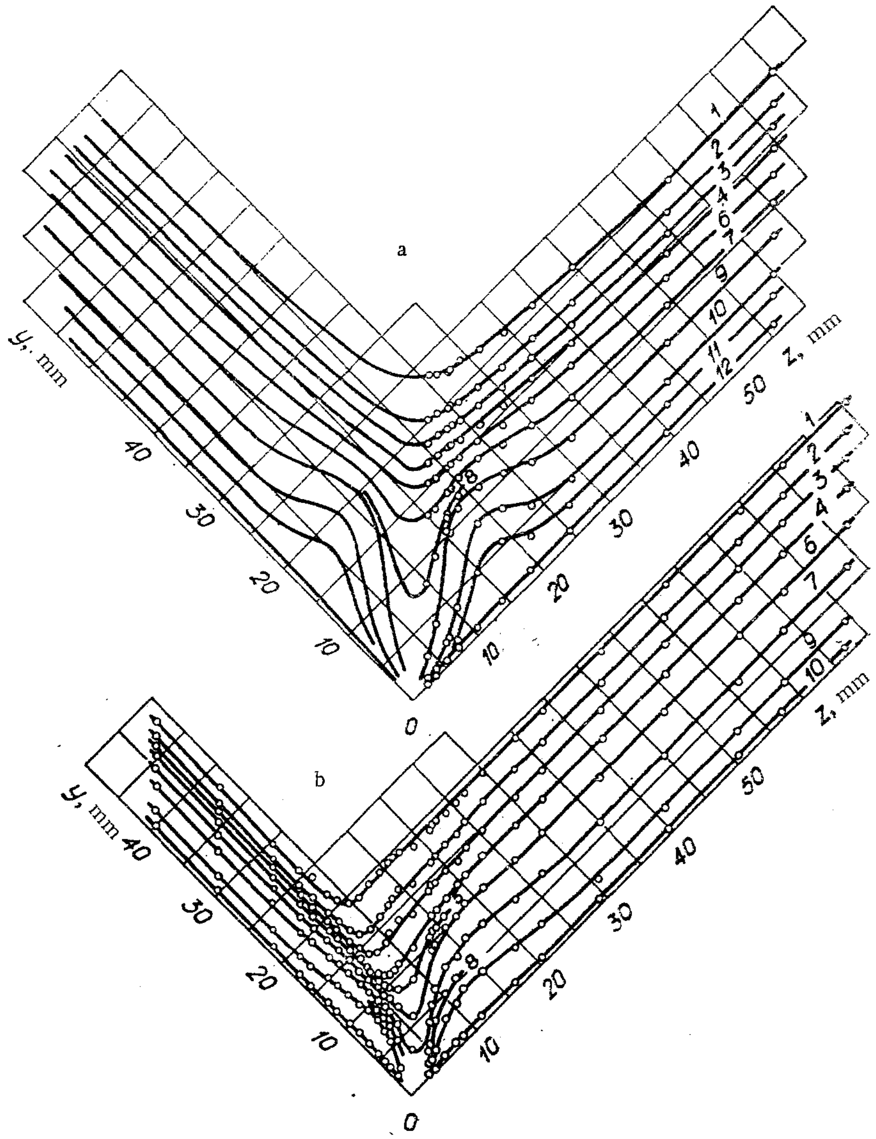

Fig. 3

these two vortices located on the layer side is clearly seen. A similar picture was observed even in the compressible case for $M_\infty = 3$ [11].

The characteristic deformation of the lines of equal values of mean square fluctuation of the longitudinal velocity component $\sqrt{\overline{u'^2}}/u_\delta$ = const also confirms the significant asymmetry in transverse flows as shown in Fig. 3a, b for $\delta_B/\delta_A = 1$ and 2.3, respectively. Here the curves 1-12 correspond to the values of $\sqrt{\overline{u'^2}}/u_\delta$ equal to 0.01, 0.02, 0.03, 0.04, 0.045, 0.05, 0.06, 0.066, 0.07, 0.08, 0.085, 0.09. It is clearly seen even at $\delta_B/\delta_A = 2.3$ that there is a twisting of the contour of lines $\sqrt{\overline{u'^2}}/u_\delta$ = const due to transverse flows and, as a result, an appreciable gradient in the longitudinal fluctuating velocity component in the direction of the y and z axes.

It is known that the quantitative characteristic of the vortex can be represented by vorticity and, in particular, for secondary flows having the form of developing streamwise vortices by the component of mean vorticity along the x axis:

$$\omega_x = \left(\frac{\partial w}{\partial y} - \frac{\partial v}{\partial z}\right) \Big/ \frac{u_\infty}{L},$$

where L is the characteristic linear dimension assumed equal to 1 m; U_∞ is the free-stream velocity. Results of the measurement of transverse velocity components v and w made it possible to compute the isotachs of nondimensional vorticity ω_x = const, whose distribution is

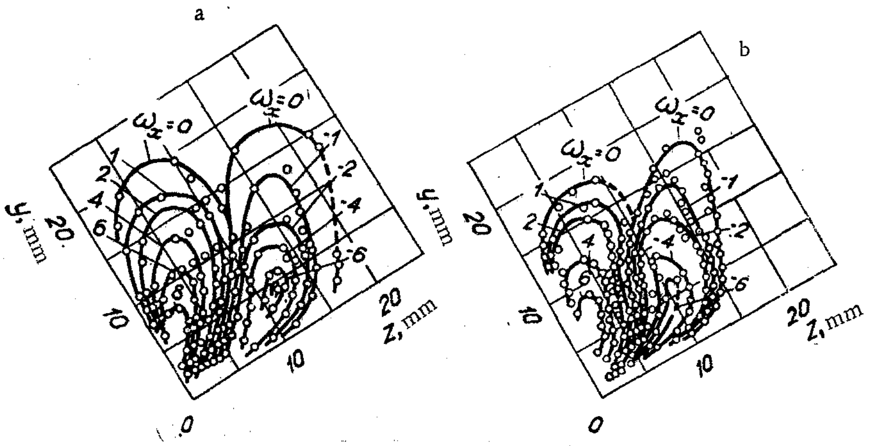

Fig. 4

shown in Fig. 4a, b for δ_B/δ_A = 1.5 and 2.3, respectively. The distribution of equivorticity lines makes it possible to consider that in the case of asymmetric interaction of boundary layers developing along the sides of a rectangular two-sided corner, a pair of counter rotating vortices is also formed with the direction of spreading from a certain dividing line (in the symmetric case it is the corner line) along the span of the corner. Judging by the maximum vorticity $\omega_{x_{max}}$ in the range of the asymmetry parameter δ_B/δ_A = 1.0-2.3, its increase leads to an insignificant reduction in vortex motion though there is no principal change in the flow structure.

Thus, for the streamwise flow past unsymmetric corners when the leading edge of the sides is a half-ellipse with b/a = 1:12, secondary flows, in all probability, are induced by gradients in Reynolds stresses in the direction of the y and z axes. Such complex turbulent flows cannot be described theoretically at present without a clear understanding of the mechanism of the generation and growth of secondary flows. A detailed study of such flows demands a knowledge of the distribution of Reynolds stress tensor components.

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