MEASUREMENTS OF FLUCTUATIONS FOR HIGH SUBSONIC VELOCITIES USING A HOT-WIRE ANEMOMETER

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The fluctuating processes for high subsonic and supersonic stream velocities play a significant role in flows past a body. Studying the unsteady characteristics of the flow is of special interest in aerodynamic setups because of the appearance of resonant effects and the influence of the stream fluctuations on the boundary-layer development on models and the boundary-layer separation [1, 2]. Hence, questions concerning methods of examining the fluctuations and equipment selection and construction are of current interest.

Hot-wire anemometers are successfully used for both subsonic and supersonic flows. Because of their good service characteristics, constant-temperature hot-wire anemometers are used mainly for subsonic flows. For supersonic flows, however, constant-current hot-wire anemometers are preferred (primarily because the frequency range is independent of the heating level of a sensing element, which allows one to separate fluctuations of pressure, temperature, and velocity).

The purpose of this study is to determine the degree of applicability of constant-temperature and constant-current anemometers in compressible subsonic flows and some peculiarities in the interpretation of hot-wire anemometry data. The fluctuation-diagram method of Kovasznay is used as a basis. The fundamentals of this method are described in [3].

The change in voltage e across the sensing element under working conditions depends on the change in the mass flow rate m and on the stagnation temperature T_0:

$$de = \frac{\partial e}{\partial m} dm + \frac{\partial e}{\partial T_0} dT_0. \tag{1}$$

Here and below, the values of e, m, T_0, etc. are normalized by their averages. After some simple transformations, the linearized equation relating the instantaneous values of fluctuations m' and T_0' to the fluctuations of voltage across the sensing element e' can be written as

$$e' = -Fm' + GT_0', \quad F = |\partial e/\partial m|, \quad G = |\partial e/\partial T_0|. \tag{2}$$

The methods of determining the sensitivity coefficient for the mass flow rate F and the stagnation temperature G are described in detail in [3-6].

Dividing (2) by G, raising to the second power, and averaging, we obtain Kovasznay's equation for the fluctuation diagram:

$$\begin{gathered} \vartheta^2 = \langle m\rangle^2 r^2 - 2rR_{mT_0}\langle m\rangle\langle T_0\rangle + \langle T_0\rangle^2, \\ \vartheta = \langle e\rangle/G, \quad r = F/G, \quad R_{mT_0} = \langle mT_0\rangle/(\langle m\rangle\langle T_0\rangle) \end{gathered} \tag{3}$$

where the angle brackets denote mean-square quantities. In the general case, Eq. (3) corresponds to the hyperbola $\vartheta(r)$ with the axis r and the line $r = R_{mT_0}\langle T_0\rangle/\langle m\rangle$ as the axes of symmetry. The part of the hyperbola within the first quadrant represents Kovasznay's fluctuation diagram.

In the presence of only the velocity fluctuations in the stream (see [3])

$$m' = u', \quad T_0' = \beta u', \quad R_{mT_0} = 1, \quad \beta(\mathrm{M}) = \alpha(k-1)\mathrm{M}^2,$$
$$\alpha(\mathrm{M}) = \left(1 + \frac{k-1}{2}\mathrm{M}^2\right)^{-1}$$

(where M is the Mach number and k the adiabatic exponent), the equation of the vortical mode takes the form

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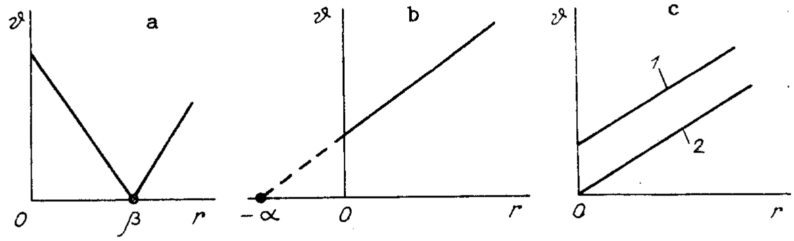

Fig. 1

$$\vartheta_u = |\beta - r| \langle u \rangle. \qquad (4)$$

It is shown in the same reference that the temperature nonhomogeneity corresponds to

$$\vartheta_T = (\alpha + r) \langle T \rangle. \qquad (5)$$

In this case $m' = \rho' = T'$, $T_0' = \alpha T'$, $R_{mT_0} = -1$.

For subsonic velocities of the stream, the diagrams for vortical and entropic modes are analogous to those for supersonic velocities:

$$\beta \to 0, \qquad \alpha \to 1 \quad \text{for} \quad M \to 0,$$

$$\beta \to 2(k-1)/(k+1), \quad \alpha \to 2/(k+1) \quad \text{for} \quad M \to 1.$$

The form of the diagrams corresponding to Eqs. (4) and (5) is presented in Figs. 1a, b.

The acoustic disturbances satisfy the relations $m' = u' + \rho'$, $\rho' = p'/k$, $T_0' = \alpha(k-1)(\rho' + u'M^2)$, and $R_{up} = -1$, which lead to the equation $\vartheta_p = \alpha(k-1)(M^2 \langle u \rangle - \langle p \rangle /k) + r(\langle p \rangle /k - \langle u \rangle)$ [3, 7]. Using the relation between the pressure and the component of velocity normal to the acoustic wave front $\langle p \rangle = kM\langle u_n \rangle$ and taking into account that the sensing element of the hot-wire anemometer is positioned perpendicularly to the incoming stream and is sensitive to the velocity fluctuations in the streamwise direction, i.e., $u' = u_n' \cos\chi$ (χ is the angle between the normal to the wave front and the direction of the stream), an equation of the following form was obtained in [3]:

$$\vartheta_p = \langle p \rangle /k |\alpha(k-1)(1 + M\cos\chi) - r(\cos\chi/M + 1)|. \qquad (6)$$

It was found in the above works that, for a Mach wave, $\cos\chi \leqslant -1/M$, and the diagram takes the form shown in Fig. 1c (curve 1 denotes sources of disturbances moving with respect to the sensing element, and curve 2 denotes stationary sources).

The position of the front of acoustic disturbances can be arbitrary for subsonic velocities ($0 \leqslant \chi \leqslant 2\pi$). In order to determine the form of the diagram with respect to the orientation of waves, we use the expression for $r_0(M, \chi)$ (where r_0 corresponds to $\vartheta_p = 0$). From Eq. (6) we have

$$r_0 = \beta(1/M + \cos\chi)/(\cos\chi + M). \qquad (7)$$

Since for $M < 1$ the numerator is always positive and the denominator may be either positive or negative, r_0 is also either positive or negative.

Let us consider a source of acoustic disturbances stationary with respect to the sensing element D located in the subsonic stream (Fig. 2). If the origin of the frame coincides with the source and the x axis is directed along the velocity vector, the incoming disturbances at point D propagate at an angle χ with sonic velocity a and drift away with stream velocity u. Then, it follows from geometrical relations that $\cos\chi = \cot\varphi \sin\chi - M$ ($\cot\varphi = x/y$). Solving the above equation for $\cos\chi$, we find

$$\cos\chi = -\frac{M}{1+\mathrm{ctg}^2\varphi} \pm \sqrt{\frac{M^2}{(1+\mathrm{ctg}^2\varphi)^2} + \frac{\mathrm{ctg}^2\varphi - M^2}{1+\mathrm{ctg}^2\varphi}}.$$

The part of the graph $r_0(\cot\varphi)$ which corresponds to the position of the sensing element downstream from the source of the acoustic wave is shown in Fig. 3. For $\cot\varphi < 0$ the graph is symmetric to that mentioned above with respect to the origin. The case $\cos\chi = 0$ turns out to be important in applications which, for example, represent acoustic waves emitted perpendicularly to the stream by walls of a channel (dashed line). Then, $\cot\varphi = M$ and the values of r_0 vary from $(k-1) = 0.4$ for $M = 0$ to $2(k-1)/(k+1) \approx 0.33$ for $M = 1$.

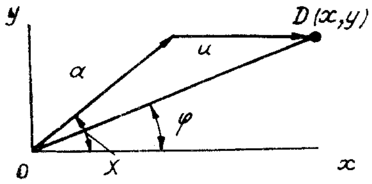

Fig. 2

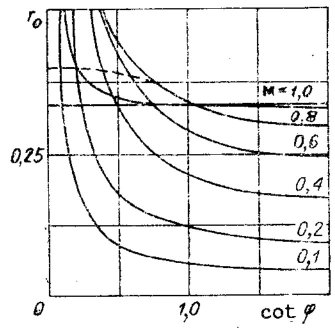

Fig. 3

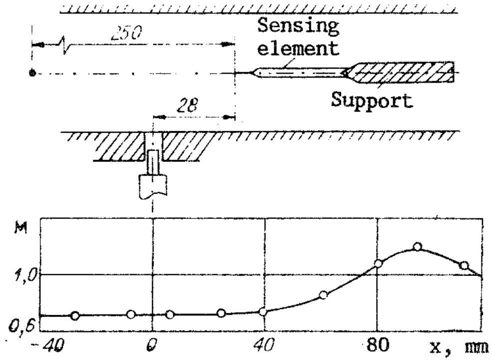

Fig. 4

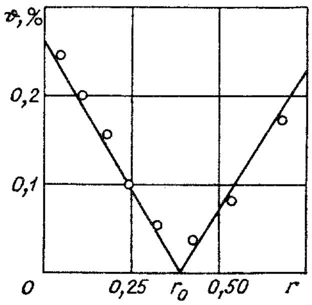

Fig. 5

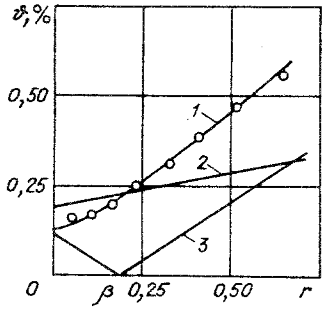

Fig. 6

An experimental examination of the characteristics of fluctuations for high subsonic velocities was performed in a wind tunnel with a test section of 4 × 4 cm (Fig. 4); M was determined by the geometry of the supports on which the sensing element of the anemometer was mounted; the value 0.72 was assumed instead of the measured one. The distribution of M along the test section found on the basis of the static pressure is presented in Fig. 4. The fluctuations were measured for some values of the wire temperature using the constant-current hot-wire anemometer TPT-2 [8] and sensing elements with a 6-μm-diameter wire. This allowed us to vary the relative coefficient of sensitivity r from 0.05 to 0.7. The thermal inertia of the sensing elements was compensated by an electric circuit using square-wave signals. This ensured that the frequency range was independent of the heating level of the wire during measurements.

In order to generate acoustic disturbances, a 6-mm-diameter hole in the upper part of the test section was used (Fig. 4). The hole was about 6 mm deep, which corresponds to the maximum level of fluctuations and the frequency f = 10.8 kHz. The excess of the discrete component over the background level approached 18 dB. The fluctuation diagram corresponding to the above conditions, obtained in the 316-Hz-wide range with the frequency of the center f = 10.8 kHz, is shown in Fig. 5. The parameters of the hyperbola [Eq. (3)] which satisfy the experimental data were calculated using the least-squares method. The correlation coefficient is $R_{mT_0} = 1$, with an accuracy of about 1%. From this it follows that the fluctuation diagram represents a degenerate hyperbola consisting of two straight lines intersecting at the abscissa at $r_0 = 0.39$. The proximity of the sensing element and the source of disturbances, and the influence of reflected waves do not allow one to carry out a quantitative comparison with the calculated values of r_0, but one can fully explain the propagation in the 20-30% range from the value of r_0 calculated based upon the geometric lengths according to expressions (7) and (8).

Disturbances of the second kind (moving with the stream velocity) were generated by the 0.5-mm-diameter wire stretched along the axis of the tunnel upstream of the test section. Here, the distance to the sensing element is 250 mm (see Fig. 4) and the Reynolds number based on the wire diameter Re = $10.5 \cdot 10^3$.

The fluctuation diagram for artificial disturbances of the type mentioned is presented in Fig. 6. The hyperbola 1 which corresponds to the experimental points was calculated using the least-squares method, and the values of the parameters defining the hyperbola are [see Eq. (3)]: $\langle m \rangle = 0.80\%$, $\langle T_0 \rangle = 0.13\%$, $R_{mT_0} = -0.29$.

Assuming that the acoustic disturbances are, in this case, small in comparison with the vortical (3) and entropic (2) ones, from the diagram (Fig. 6) one can determine the intensity of the vortical mode $\langle u \rangle = 0.64\%$ and entropic mode $\langle T \rangle = 0.20\%$ with a correlation coefficient between them $R_{uT} = -0.73$. The measurements with the constant-temperature anemometer (for one overheat ratio) do not allow one to obtain any information about fluctuations except approximate values of the intensity of the mass flow rate fluctuations $\langle m \rangle \approx \vartheta(r)/r = 0.87\%$. Consequently, for high subsonic velocities, it is advisable to use constant-current anemometers in order to obtain fluctuation diagrams and to separate modes of disturbances. Then, the form of the diagrams for the vortical and entropic modes is analogous to the diagram for supersonic velocities, and the diagram of acoustic disturbances may consist of two elements of a straight line intersecting at the abscissa.

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ASYMPTOTIC ANALYSIS OF FLOW INSTABILITY IN A COMPRESSIBLE BOUNDARY LAYER ON A CURVED SURFACE

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A nonviscous instability mechanism exists in a two-dimensional boundary layer on a curved surface, as a result of which there appear pairs of vortices oriented along the flow and rotating in opposite directions. These are commonly termed Görtler vortices (Fig. 1). With increase in intensity of these vortices down the flow they may cause a transition of the laminar boundary layer into a turbulent one. In experiments in the boundary layer transition region they manifest themselves as periodically distributed thermal fluxes, shear stresses, etc., in a direction transverse with respect to the direction of the main flow in the boundary layer (see, for example, [1, 2], and the bibliography presented in [3]). There is interest in boundary layer stability on a curved surface because the supercritical profiles which have been designed in the past have segments with quite large curvature, so that a transition to a turbulent boundary layer develops under the action of centrifugal forces [4]. Aside from this, the effect of surface curvature on the character of the flow in the boundary layer requires special attention in design of nozzles for low noise supersonic tubes [5]. Reviews of preceding studies of boundary layer instability on curved surfaces were presented in [3, 6, 7]. In our opinion, the main unique feature of this problem is that in comparison to Tollmin–Schlichting wave instability or instability of secondary flows in a boundary layer in the vicinity of an edge in arrowlike wings, Görtler vortices are characterized by a weak intensity of motion and relatively slow intensification down the flow. Hence in analyzing the flow stability in the general case it is necessary to preserve those terms

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