Finally, in the model proposed in [3] for the unsteady flow of a gas into vacuum through a perforated plate it is assumed that the parameters p_m, ρ_m, u_m realized in the critical cross section of the perforation are the same as would occur for flow created by acceleration of the undisturbed gas in a transient rarefaction wave with subsonic velocity. To the left of the plate in this case is a region of subsonic flow with constant parameters. The intensity of the rarefaction wave propagation through the rest gas is determined from the condition of equality of the mass flow rates before the plate and in the critical cross section. In the region after the plate, as in [2], it is assumed that a flow region with constant parameters does not exist, i.e., $u_{\pm} = a_{\pm}$. The system of relations at the plate is formulated in two ways. The first presupposes satisfaction of the two conditions (1) relating the cross sections m and +. However, the total enthalpy in the cross sections − and + can differ. The second approach is based on replacement of the second Eq. (1) by the momentum conservation principle

$$\varepsilon(p + \rho v^2)_m - \varepsilon \Delta p = (p + \rho v^2)_+.$$

Here the influence of fluid friction of the plate is introduced by the formula $\Delta p = \beta q \sqrt{T_0}$ with the fluid friction coefficient β and the temperature of the undisturbed gas T_0.

We note that, in contrast with [1], in [2, 3] experimental confirmation is not given in support of the assumptions underlying these studies.

The author is grateful to A. N. Kraiko and V. T. Grin' for their interest and useful discussions.

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PRESSURE FLUCTUATIONS DURING FLOW AROUND BLUNT BODIES

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UDC 533.6.011

At subsonic flight speeds the most intense vibrations develop during flow separation and the formation of local supersonic zones, while at supersonic speeds they occur in the interaction of a shock with the boundary layer. The combination of intense pressure fluctuations and a relatively large velocity head at transonic speeds can lead to appreciable dynamic loads, and the abrupt rearrangement of the character of the flow changes the aerodynamic characteristics. We present data which illustrate some forms of fluctuating loads developing on aircraft components at both subsonic and supersonic flight speeds.

1. Experimental Procedure. A cylindrical model of diameter d = 50 mm and length l = 200 mm was tested by mounting it at right angles to the flow on thin side plates fastened to the lower perforated wall of a wind tunnel. Measurements were made when the model was rotated about its axis by an angle φ. A spherical model of diameter 70 mm mounted on a base 15 mm in diameter was tested also. Pressure fluctuations on the spherical model were measured with three inductive pressure transducers. The angle φ was measured by the rotation of the model support.

The tests were performed in an intermittent type wind tunnel whose test section was 600 × 600 mm in cross section. The Reynolds numbers, determined from the free-stream parameters and the diameter of the sphere, were in the range $Re_d = (0.6-1.5) \cdot 10^6$.

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 2, pp. 65-72, March-April, 1983. Original article submitted August 10, 1981.

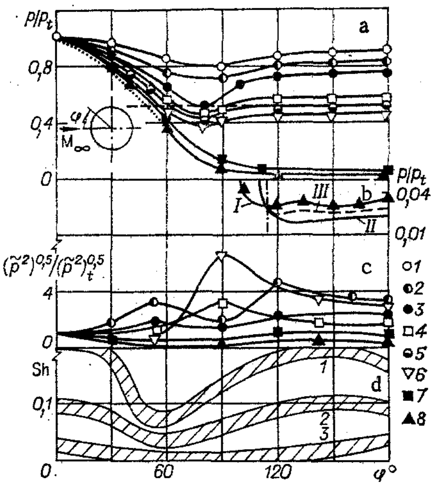

Fig. 1

The average pressure was measured with an inductive transducer, using the pressure measured with a Pitot tube as a reference. The transducer was located in a pneumatic pressure commutator to which tubes from the drain holes in the model were attached. The relative mean-square error in the pressure measurements was $\bar{\sigma}_p = \pm 2\%$. The pressure fluctuations were measured with a differential inductive transducer mounted on a damping chamber which communicated with the outside atmosphere through a tube 40 mm long and 0.3 mm in diameter. The pressure pulses acted on the diaphragm, and in passing through the tube were damped by hydraulic losses, establishing a quasisteady pressure p in the chamber. Thus, the transducer diaphragm perceived only the fluctuating component of the pressure $\tilde{p}(t)$.

The signal was recorded on a five-channel magnetic tape recorder with a 36-kHz carrier frequency. The transducer measures pressure fluctuations in the frequency range 50-4000 Hz [1]. The relative mean-square error of the measurements of the amplitudes of the whole recording-measuring channel was $\bar{\sigma}_L = \pm 15\%$, with a reliability of 70%. The error in the determination of the frequencies was $\bar{\sigma}_f = \pm 3.5\%$.

In the course of the experiments, the integrated levels of pressure fluctuations were measured:

$$L_\Sigma = 20 \lg \frac{(\tilde{p}^2)^{0.5}}{p_0} \text{ [dB]}, \quad \tilde{p}^2 = \int_0^\infty \tilde{p}^2(\tilde{f})\, df,$$

where $\tilde{p}^2$ is the mean square of the pressure fluctuations, $\tilde{p}^2(\tilde{f})$ is the spectral density, f is the frequency, and $p_0 = 2 \cdot 10^{-5}$ Pa is the reference pressure. From the sequential spectrum analyzer a trace of the level of pulsations was made on an XY recorder in a band of width $\Delta f = 7$ Hz.

2. Cylinder. In order to analyze the pressure fluctuations on the surface of a cylinder it is necessary to have an idea of the steady flow pattern around it. This information is particularly important in the range of transonic speeds where unstable local supersonic zones develop. Flow around a cylinder has been rather thoroughly studied over a wide range of Reynolds and Mach numbers. It is known that an increase in Re at low speeds is accompanied by a rearrangement of the flow with a nonmonotonic displacement of the separation point. The pressure distribution over the surface of a cylinder is shown in Fig. 1a, where M = 0.32, 0.44, 0.54, 0.68, 0.81, 0.88, 2, and 3 for points 1-8, respectively. The pressure p measured on the surface of the cylinder is relative to the pressure p_t at the forward point. At subsonic speeds an increase in the Mach number decreases the pressure on the base of the cylinder, and for $M \approx 0.5$ local supersonic zones appear on the lateral surface. Starting from the foremost point of the body ($\varphi = 0$) the pressure decreases up to $\varphi = 80°$, and then increases, leveling off on the bottom part of the cylinder. In Fig. 1a the test data for M = 3 are compared with results calculated in [2] (dotted curve).

In supersonic flow the base pressure is a very small fraction of p/p_t, and therefore in Fig. 1b (curve I) the test data for M = 3 are presented on a considerably larger scale to illustrate the pressure distribution on the bottom part of the cylinder. The stream is overexpanded in flowing around the lateral surface of the cylinder, which corresponds to the first pressure minimum. An increase in pressure from the overexpanded value to the base pressure causes separation of the boundary layer. The position of the separation point determined from Topler photographs coincides with the minimum and is equal to 115° (dash—dot curve of Fig. 1b). The second pressure minimum at φ = 145-155° is related to circulatory flow directed at this place along the surface of the cylinder from the rear point (φ = 180°).

Measurements of the pressure distribution over the bottom section of a wedge with θ = 15° at M = 3 showed that the pressure remains almost constant and equal to p/p_t = 0.027 [3]. The base pressure behind the wedge depends strongly on the Reynolds number [4]. For a laminar boundary layer the base pressure decreases with increasing Re. In contrast with a wedge, the base pressure behind a cylinder increases negligibly with increasing Reynolds number (Fig. 1b; I, experimental data; II, M = 5.8, Re = $1.4 \cdot 10^3$; III, M = 5.8, Re = $8 \cdot 10^3$ [4]). Under the assumption that the mixing occurs at constant pressure, i.e., the pressure on the surface of the body behind the separation region is constant and equal to the pressure on the outer boundary of the mixing layer, it is clear that the constant pressure region on the bottom surface of a cylinder decreases with decreasing Reynolds number, and accordingly the separation point is displaced toward the rear point of the body.

Pressure Fluctuations. In processing the test data on pressure fluctuations on a cylinder we used the quantity $(\tilde{p}^2)^{0.5}/(\tilde{p}^2)_t^{0.5}$, where $(\tilde{p}^2)^{0.5}$ and $(\tilde{p}^2)_t^{0.5}$ are respectively the mean-square values of the pressure fluctuations measured on the lateral surface and at the foremost point of the cylinder. The distribution of pressure fluctuations over the surface of the cylinder is shown in Fig. 1c. For a low free-stream speed (M = 0.44) there are two regions of increased fluctuations: at 40-60 and 110-130°. The presence of the first extremum on the graph of the distribution indicates the formation of the primary separation region on the lateral side. First the laminar boundary layer begins to separate as a result of the negative pressure gradient, and then the layer becomes turbulent and is subsequently reattached to the surface.

One of the reasons for the formation of high levels of fluctuations at the separation and reattachment points is the oscillatory character of the displacement of these points and the related change in the distribution of the mean pressure. In [5] a separation region was observed on a smooth cylinder in a uniform flow at a Reynolds number $Re_d = 10^5$ with the separation point at 77°. This same position of the separation point was observed at the first extremum of the fluctuations on a cylinder for $Re_d = 1.1 \cdot 10^5$ [6].

An increase in the free-stream speed smooths out the fluctuation distribution somewhat (M = 0.54), and for M = 0.68 the fluctuations near φ = 90° begin to increase and reach a maximum at M = 0.88. Strong pressure fluctuations on the surface of a cylinder at the critical flow velocity are associated with oscillations of terminal shocks behind the local supersonic zones.

For M = 2 and 3 the fluctuations decrease somewhat from the foremost critical point up to φ = 90°, and behind the separation point (M = 3, φ = 115°) the fluctuations increase and then decrease with increasing distance from the separation point, but increase somewhat near 180°. The increase in fluctuations near the separation point is related to oscillations of this point; this was studied in [7] for the separation zone ahead of a step. An increase of the fluctuations near the rear critical point depends on the dynamical effect of the reverse wake [8].

It is clear from the relation $(\tilde{p}^2)^{0.5}/(\tilde{p}^2)_t^{0.5} = f(M)$ that when the subsonic flow speed is increased from M = 0.32 to M = 0.63 the fluctuations decrease over the whole surface of the cylinder except at φ = 90° where there is a sharp increase in the fluctuations as the sound speed is approached. At a supersonic flow speed a change from M = 2 to M = 3 decreases the fluctuations over the whole surface of the cylinder including the base region. Data on the base region of the cylinder correspond to results of studies of pressure fluctuations behind axisymmetric bodies [8].

From the fluctuation spectra it was possible to determine approximate values of the Strouhal numbers Sh = fd/V (where f is the frequency, d is the diameter of the cylinder, and V is the free-stream speed) corresponding to the maximum amplitudes of the spectrum. Figure 1d shows the Strouhal numbers Sh which characterize the frequency distribution over the surface of the cylinder (points 1-3 correspond to M = 0.54, 0.88, and 3.0). As the flow spreads out from the forward point, the speed increases, and the frequencies of the fluctuations

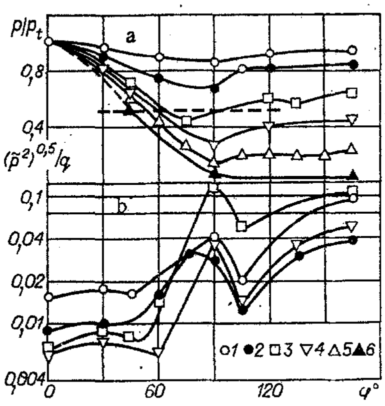

Fig. 2

decrease. At subsonic speeds there is a sharp decrease in the Strouhal number at φ = 30-50°. At M = 0.54 the frequencies increase up to φ = 120° and then decrease slightly. There is a similar distribution of the Strouhal numbers at M = 0.88. At supersonic speeds the Strouhal numbers reach a minimum near φ = 90°.

3. Sphere. Pressure Distribution. At subsonic and transonic speeds the pressure distribution on a sphere is qualitatively similar to that on a cylinder (Fig. 2a). Starting from φ = 0 the pressure decreases on the front part and then increases at the rear point. For M = 0.3, 0.5, 0.7, 0.9, 1.2, and 3 (points 1-6 on Fig. 2) the minimum pressure occurs near φ = 80° except for M = 0.7 for which the minimum is at φ = 70°. At this Mach number, and also for M = 1.1, there is another pressure minimum at $\varphi \approx 135°$.

For flow around blunt bodies of ellipsoidal or spherical shape the largest pressure gradients occur near the sonic points. The position of a sonic point on the surface of a sphere was determined by assuming that the total pressure at the edge of the boundary layer ahead of the body is equal to the total pressure behind the normal shock. Then for $\varkappa$ = 1.4 the quantity p/p_t = 0.528 (dashed curves of Figs. 1a and 2a). A discrete change of the Mach numbers in our experiments did not permit a determination of the free-stream critical Mach number. For M = 0.7 the sound speed close to the surface of the sphere began near φ = 65°, while for M = 0.9 it began near φ = 55°.

The pressure distribution at M = 0.3 is similar to that for the flow of an incompressible stream around a sphere with a turbulent boundary layer [9]. In the latter case the flow separates from the surface of the sphere on the rear portion, and this decreases the resistance ($c_x \approx 0.1$) in contrast with laminar separation when the boundary layer separates from the spherical surface near the largest cross section ($\varphi \approx 90°$) and the pressure behind the sphere is decreased, producing a high resistance ($c_x \approx 0.48$) in spite of the decrease in frictional resistance.

Schlieren photographs of the flow pattern around a sphere clearly show the beginning of the separation of the boundary layer and the density gradient formed by the outer boundary of the free viscous layer. Figure 3 shows the dependence of the position φ_0 of the separation point on the free-stream Mach number. For subcritical flow (M = 0.3) the separation point is near φ_0 = 100°, and the initial portion of the rectangular boundary of the wake is inclined to the axis of symmetry. For incompressible laminar flow around a sphere the separation point is near 90° (small square on Fig. 3). A comparison of results for a sphere with those for the flow of an incompressible fluid around a cylinder shows that for laminar flow the separation point φ_0 is between 80 and 85°, while for turbulent flow φ_0 = 110°. If the free-stream speed is increased (M = 0.5), the separation point is displaced forward and passes through the middle cross section onto the front part of the sphere (φ_0 = 82°). At the same time the initial portion of the near wake is displaced from the axis of symmetry. The flow patterns for M = 0.5 and 0.7 are characterized by the formation of a region of accelerated flow on the front part of the sphere near the middle cross section. This is recorded on the photographs as a dark zone.

The transition to supercritical flow changes the flow pattern qualitatively. The region of accelerated flow noted on the photographs is displaced forward in the form of a narrow supersonic zone which is propagated away from the sphere and is terminated by a shock. The

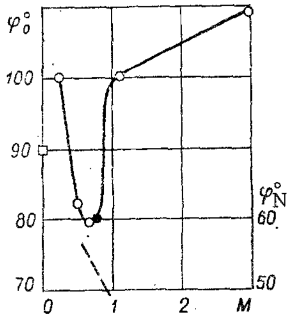

Fig. 3

position of the shock for M = 0.7 and φ_0 = 79° corresponds to experimental data for a sphere at M = 0.7 and Re = $7 \cdot 10^5$ [9] (solid circles on Fig. 3). At high subsonic speeds the separation boundary is again displaced toward the rear part of the sphere. This is related to the broadening of the supersonic zone and the displacement of the terminal shock, and accordingly, of the separation point which, as for a low subsonic speed, is near φ_0 = 100°. For a low supersonic speed (M = 1.1) the overexpansion of the flow behind the middle cross section of the sphere leads to the formation of a shock wave in front of the separation point similar to a lip shock [1]. Flow at M = 3 is accompanied by a similar detached shock wave which is inclined to the axis of symmetry.

Levels of Fluctuations. In our experiments, as in all studies of fluctuations in wind tunnels [7, 10, 11], pressure fluctuations on models correlate with acoustic radiation of the set-up, and therefore the measurements are of a qualitative character. Yet, the relations between pressure fluctuations and the shape of the model and the Mach number were duplicated in the tests.

The distribution of the relative mean-square value of the fluctuations over a sphere is shown in Fig. 2b. The curves for $(\tilde{p}^2)^{0.5}/q = f(\varphi)$ have qualitatively the same shape as those for $L_\Sigma = f(\varphi)$, but their relative location was changed. While in the first case for subsonic speeds an increase in the Mach number increased L_Σ on the front part of the sphere, in the second case the values of $(\tilde{p}^2)^{0.5}/q$ decreased. At Mach numbers from 0.3 to 1.2 the pressure fluctuations increase somewhat from the forward point to $\varphi \approx 30°$, decrease smoothly to φ = 45° (for M = 0.9 they decrease to φ = 60°), and then increase strongly up to φ = 90°. On the rear hemisphere there is also a minimum of the fluctuations at φ = 105°, and in the bottom region they reach approximately the same values as near a lateral point. The fluctuations were not measured in the immediate vicinity of φ = 180°, however, since it is known from measurements of fluctuations in the bottom region of axisymmetric bodies and on the rear part of a cylinder placed at right angles to the flow that the magnitude of the fluctuations varies slowly over the part of the surface adjoining the separated flow in the near wake.

The decrease of pressure fluctuations on the front hemisphere with increasing speed of subsonic flow up to the formation of local supersonic zones on the lateral surface is due to the increase of stability of the mean flow. It should be noted that measurements of pressure fluctuations on the surface of a fuselage at subsonic and low supersonic flight speeds ($0.5 \leqslant M \leqslant 1.6$) showed that $(\tilde{p}^2)^{0.5}$ is proportional to q with the proportionality factor k = 0.006 [12]. The same value of k was obtained in wind tunnels for $0.2 \leqslant M \leqslant 0.8$. As can be seen from Fig. 2b, the mean-square value of the fluctuations on the front part of the sphere at M = 0.7, 0.9, and 1.1 corresponds approximately to $(\tilde{p}^2)^{0.5}/q \approx 0.006$-0.008.

Flight test data [10] and wind tunnel measurements [12] of pressure fluctuations on the wall for a turbulent boundary layer showed that $(\tilde{p}^2)^{0.5}/q$ decreases with increasing Mach number, and the relation $(\tilde{p}^2)^{0.5}/q = f(M)$ can be approximated in the form $(\tilde{p}^2)^{0.5}/q = 3.25 \cdot 10^{-4}[5 + M - 4)^2]$ [10]. The values of the fluctuations on the wall calculated from this empirical relation correspond approximately to experimental data for points on the front of a sphere for transonic flow.

With an increase in the free-stream speed the fluctuations on the lateral surface increase to a maximum at M = 0.7. This results from the creation of supersonic zones and oscillations of terminal shocks. As the free-stream speed approaches the speed of sound, the fluctuations near a lateral point (φ = 90°) decrease.

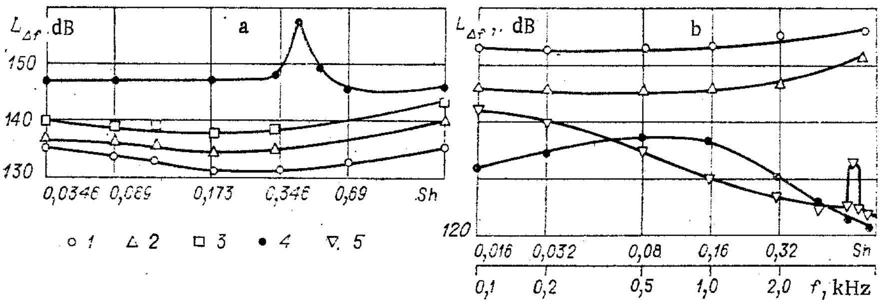

Fig. 4

Flow around a sphere at M = 0.7 leads to the creation of a local supersonic zone at φ = 70-90° in which the maximum underpressure reaches p/p_t = 0.42. An estimate of the local Mach number M_1 from the magnitude of the pressure in the supersonic zone and from M_∞ gave M_1 = 1.18. A comparison of the measured fluctuations in this zone with values calculated for a turbulent boundary layer from the empirical formula [13] $(\tilde{p}^2)^{0.5}/q = 0.006/[1 + (0.15M)^2 + (0.15M)^4]$ showed that the calculated values of $(\tilde{p}^2)^{0.5}/q$ = 0.0058 for a sphere are far smaller than the experimental values. For low supersonic speeds the fluctuation distribution has no abrupt changes up to $\varphi \approx 75°$, reaches a low minimum near φ = 90°, and then increases toward the bottom region.

When a local supersonic zone is formed, a terminal shock may cause separation of the boundary layer. The extent of the supersonic zone (Fig. 3, dashed line, scale φ_N) was determined approximately from photographs of the flow and pressure measurements. The pressure fluctuations arising in the separation zone are transferred upward by flow through the boundary layer, and change the pressure drop across the shock. This leads to oscillations of the shock on the surface of the body. In studies of pressure fluctuations on a blunt cone model at transonic flow speeds [11] the change in average pressure and the mean-square value of the fluctuations were determined as functions of the Mach number. It was shown that a local supersonic zone terminated by a shock is formed near the blunt end. The level of fluctuations was estimated by assuming that the maximum level of fluctuations is produced by oscillations of the shock. The calculated value of the fluctuations for M = 0.8 and 0.9 was several times larger than the experimental value.

With increasing Mach number in the range of critical Mach numbers the upward propagation through the stream of a region of supersonic flow on the lateral surface of a sphere leads, on the one hand, to a decreae in the effect of the near wake on the front part of the body, and on the other hand to an increase in the strength of the shock terminating this region and the related fluctuations in the separation zone, particularly at the reattachment point. Studies of pressure fluctuations in a region of flow separation on an axisymmetric body with a step showed that the largest fluctuations occur in the region of maximum gradient of the static pressure formed by the shock ahead of the separated region. Data on the pressure distribution (Fig. 2a) and fluctuations on a sphere at M = 0.5 and 0.9 (Fig. 2b) show that maximum fluctuations also occur in the region of the maximum gradient of the static pressure (φ = 90°).

It should be noted that the relation $(\tilde{p}^2)^{0.5}/q = f(M)$ for the bottom region of a sphere differs from test results on elongated pointed bodies which showed that the fluctuations decrease monotonically with increasing Mach number, but are similar to results for a cylinder and for short bodies [8] which show a local increase of fluctuations at transonic speeds. Studies [14] showed that fluctuations of the base pressure at subsonic speeds vary little up to M = 0.9, and are described by $(\tilde{p}^2)^{0.5}/q$ = 0.013-0.015 for a long cylinder and 0.06-0.07 for a disk, but decrease by a factor of 1.4 at M = 1. A comparison of data on fluctuations in the bottom region with corresponding data for a turbulent boundary layer for separation ahead of and behind steps shows that at M = 1 the level of bottom fluctuations is comparable with that of fluctuations during separation of the boundary layer ahead of and behind steps, and for M > 2.5 the fluctuations in the bottom region are smaller [1].

Fluctuation Spectra. The spectral density of the signal was estimated from an XY recording from the sequential spectrum analyzer. Figure 4a shows pressure fluctuation spectra on the surface of a sphere for M = 0.64 (φ = 0, 30, 60, 90, and 150° for points 1-5, respectively). The frequency f and the Strouhal number Sh are plotted along the axis of abscissas, and the ordinate is the fluctuation level $L_{\Delta f}$ in a band with Δf = 7 Hz. The spectra at points from φ = 0 to φ = 90° are plotted one above the other for M = 0.64. The spectrum at φ = 90° shows a group rise of fluctuation levels at Sh = 0.35-0.6 which exceeds the average level of this spectrum by 10-15 dB. At M = 0.9 in the range φ = 0-60° the spectra are similar, but in this case, as for M = 0.64, there is a group rise of levels for Sh = 0.3 at a lateral point of the sphere. In addition, the latter spectrum is characterized by a preponderance of low-frequency components of the fluctuations.

Spectra obtained at a supersonic flow speed (Fig. 4b, M = 3) at the points φ = 0 and 30° are characterized by an approximately uniform frequency distribution of levels $L_{\Delta f}$, and at a lateral point there is a flat maximum (Sh = 0.1-0.15). The frequency distribution of fluctuation energy at φ = 150° is of interest. The fluctuation spectrum at this point has a preponderance of low-frequency components and a discrete component at high frequencies. In studies of fluctuations of the base pressure behind a cone [15] it was also noted that low-frequency oscillations predominate in the bottom region.

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