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BASE PRESSURE FLUCTUATIONS

A. I. Shvets

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INTRODUCTION

Acoustic loading of aircraft due to fluctuating pressures leads to problems associated with strength, vibration, and noise. At present, there are no reliable methods for calculating pressure fluctuations in separation flows and the efforts of experimentalists are directed toward the acquisition of data making it possible to estimate the fluctuation levels for different classes of bodies and finding the main sources of fluctuation.

The known individual results on base pressure fluctuations [1-8] do not enable one to construct generalizing dependences. With the aim of determining the influence of the body profile and the Mach number on the base pressure fluctuations we have investigated some model configurations in the range M = 0.4-3. The pressure fluctuations were measured by inductive sensors with preliminary amplification in a plant with carrier frequency 36 kHz working in the range 50-4 000 Hz. In the process of the experiments, we measured the total levels of the pressure fluctuations:

$$L_\Sigma = 20\lg[(\langle p^2\rangle)^{0.5}/L_0], \qquad \left(\langle p^2\rangle = \int_0^\infty \langle p^2(f)\rangle df\right)$$

(where $\langle p^2(f)\rangle$ is the spectral density, f is the frequency, and $L_0 = 2\cdot10^{-5}$ Pa is the fluctuation zero level), and an analyzer was then used to obtain traces with a two-coordinate recording instrument of the fluctuation level in a 7 Hz band.

1. Rms Value of the Fluctuations

We studied cones with half-angles θ = 10, 20, 40, and 60° (Fig. 1a, the numbers 1-4,

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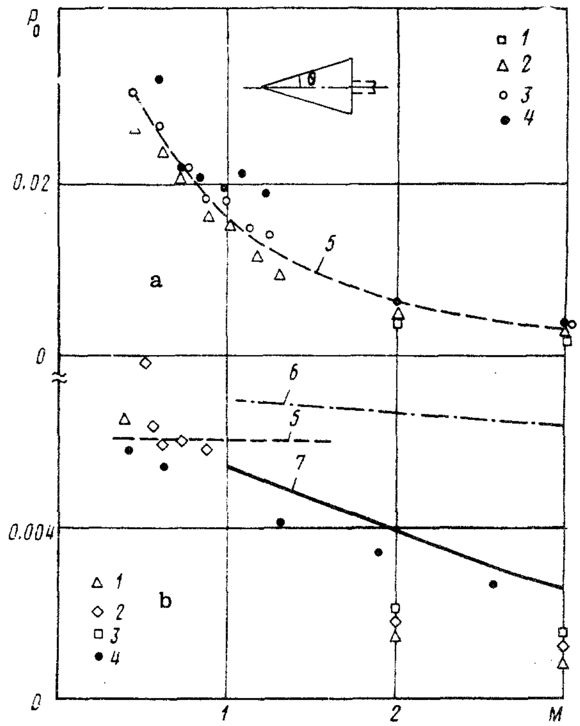

Fig. 1

respectively) and a short cylinder (of length L = 50 mm) with elliptic front part (semi-axis ratio 0.2 (Fig. 2), number 1) set up on the base support. The diameter of the middle section of the models was D = 130 mm, and the diameter of the base support 30 mm. The fluctuations of the base pressure were also measured on a cylindrical body (L = 250 mm, D = 60 mm) with conical (θ = 30°) rounded front part (rounding d/D = 0.25) set up along the flow, and on a cylinder (L = 200 mm, D = 40 mm) placed across the flow and fixed on thin lateral plates (2 and 3 in Fig. 2). The pressure sensor was at distance 0.5R from the center.

For some bodies, high fluctuation levels are realized at transonic and small supersonic velocities of the external flow. In this range of velocities, the combination of strong pressure fluctuations and a comparatively large dynamic head can lead to appreciable

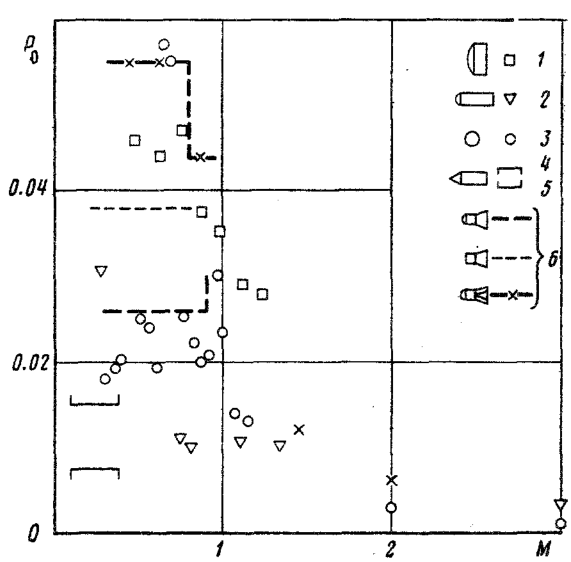

Fig. 2

dynamic loading, and rearrangement of the nature of the flow radically alters the aerodynamic characteristics.

For cones, a reduction of the rms fluctuation level $p_0=(\langle p^2\rangle)^{0.5}/q$ (where q is the dynamic head of the oncoming flow) was obtained in the range of Mach numbers M from 0.4 to 3 (Fig. 1a). When the half-angle of the cone is increased, a local rise in the fluctuations is observed near M ≈ 1.1. In the investigated range of M, the base pressure fluctuations for cones with $\theta < 40^\circ$ can be determined approximately from the empirical dependence $p_0=0.06(1+M)^{-2}$ (5 in Fig. 1).

In the transonic range of velocities, a decrease in the fluctuations occurs for the short cylinder (1 in Fig. 2); for the long cylinder (2), the fluctuations change little. A sharp increase in the fluctuations is observed for the cylinder placed across the flow at subsonic velocities (M > 0.5), this being explained by the transfer to the base region of disturbances from the embedded shock waves behind the local supersonic regions on the lateral surface of the cylinder.

Figure 2 also shows the results of [1] for a cylindrical body with ogival shape of the front part (L/D ≈ 4) with sensors placed at the center of the base section and at distance 0.65R from the center (4 and 5, respectively) and the data of [4] for three blunt bodies with tail fairings and sensor at 0.65R (6). In the experiments of [1] in the range M = 0.065-0.32, the relative rms value of the fluctuations remained constant, while a difference was observed in [4] at M ≈ 0.9, which was attributed to the different nature of the flow in the separation region in front of the fairing. The investigations of [7] showed that the base pressure fluctuations at subsonic velocities change little up to M = 0.9 and are p_0 = 0.013-0.015 for a long cylinder and 0.06-0.07 for a disk; however, a reduction in the fluctuations by a factor 1.4 was noted at M = 1.

In measurements of the base pressure fluctuations, it is necessary to have information about the fluctuations in the oncoming flow and their influence on the distribution of the fluctuations over the investigated model. Measurements were made of the fluctuations on the lateral surface of a cone with half-angle 7° set up on the base support and of the pulsations at the nose of a blunt cone placed across the flow. These models were fixed on thin lateral plates. Figure 1b shows the dependences of p_0 on the Mach number M of the oncoming flow (1 is for the lateral surface of the $\theta = 7^\circ$ cone; 2 for the nose point of the blunt cone, $\theta = 20^\circ$, d/D = 0.1, D = 130 mm). Besides data from the present investigation, Fig. 1b contains the measurement of [9, 10] of the fluctuations on a plate (3 and 4) and the results of tunnel [11] and flight [12, 13] tests, in which the value $p_0 \approx 0.006$ (5) was obtained on a smooth wall in the range M = 0.3-1.5. The semiempirical predictions of the acoustic loads at moderate supersonic velocities based on the data of flight tests [14] and tunnel experiments [15] at low supersonic velocities differ appreciably (6 and 7 in Fig. 1b).

The turbulent boundary layer on the walls of supersonic tunnels leads to the generation of pressure fluctuations on the walls and the emission of sound into the free flow. For example, for the walls of wind tunnels the values of p_0 reported in [16, 17] reach 0.027 and 0.021, respectively, at M = 0.75 and decrease to 0.013 and 0.01 at M = 1.2. In the measurements of [18], the ratio of the fluctuations in the free flow to the fluctuations on the four walls increased from 0.08 to 0.4 as M increased from 0.5 to 4. Thus, one can estimate qualitatively that at subsonic and low supersonic velocities the emission from the walls into the free flow is p_0 = 0.002-0.004. Comparison of the data in Figs. 1 and 2 shows that the base pressure fluctuations are appreciably higher than those on the wall and at the nose.

The influence of lengthening the body on the relative level of the fluctuations is indicated in Fig. 3 (M = 0.6, 0.9, 1.2, 2, 3 for 1-5; the data of [1, 4, 7] are denoted by 6-8). The results for different bodies make it possible to estimate the influence of the body shape and M on the base pressure fluctuations. It can be seen that at subsonic and low supersonic velocities the fluctuations behind short bodies are appreciably greater than behind elongated shapes parallel to the flow, whereas the fluctuations depend weakly on the elongation of the body at M = 2 and 3. A change in the body elongation L/D from 0.5 to 5 at M = 0.6 reduces p_0 from about 0.5 to 0.015, whereas for M = 3 the fluctuations are approximately equal ($p_0 \approx 0.05$) for bodies of different elongations.

To determine the influence of the Reynolds number on the pressure fluctuations, the

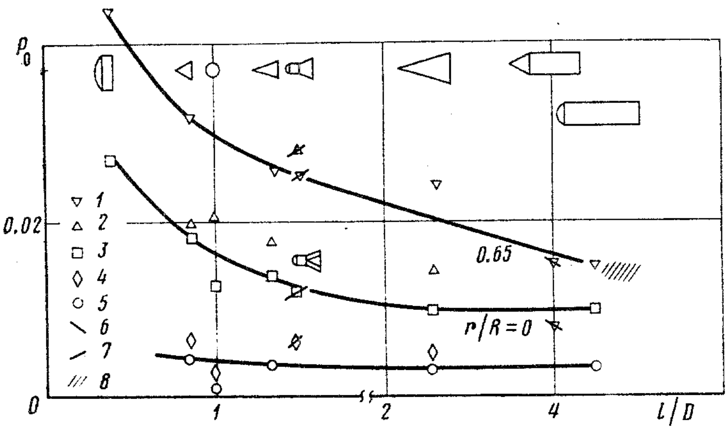

Fig. 3

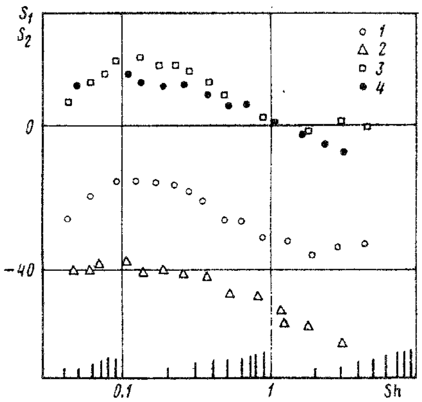

Fig. 4

parameters of the undisturbed flow and the dimensions of the models were varied [2]. With increasing size of the models, the rms fluctuations increased, as did the range of frequencies in which the maximum of the fluctuation spectrum is observed. The experimental data show that an increase in Re causes the fluctuations to grow for a turbulent boundary layer.

2. Fluctuation Spectra

Figure 4 shows a plot of the dimensionless spectral density of the base pressure fluctuations

$$S_1 = \frac{\langle p^2(f)\rangle}{q^2}\frac{u}{D}, \quad S_2 = \frac{\langle p^2(f)\rangle}{\langle p^2\rangle}\frac{u}{D}$$

against the dimensionless frequency Sh = fD/u for a cone with $\theta = 30^\circ$ (in Fig. 4: 1) S_1, M = 0.4; 2) S_1, M = 2; 3) S_2, M = 0.4; 4) S_2, M = 2). The main energy of the base pressure fluctuations is concentrated at low frequencies. For the test models at small subsonic velocities, the spectral density at low frequencies is higher near the trailing edge, while at supersonic velocities it is higher in the center of the base section. In the experiments of [1, 4] the similarity between the fluctuation spectra at high frequencies was explained by the fact that in the subsonic range of velocities the shape of the body does not have a large influence on small-scale eddies. At Sh < 0.1, the distribution of the spectral density $\langle p^2(f)\rangle$ changes little, while for Sh > 0.3 it is inversely proportional to Sh^2 [1].

For the investigation of nonstationary flow in the wake, it is interesting to compare the value of Sh based on the frequency corresponding to the maximal amplitudes with the value constructed using the characteristic parameters. The flow in the base region depends on the flow parameters at the rim of the body [19], and since processes associated with the flow on the boundaries of the base region have a considerable influence on the fluctuations, it is expedient to take the velocity u_e in the exterior part of the free viscous layer as characteristic velocity.

To calculate Sh, one usually takes the diameter of the body as the characteristic scale in the case of axisymmetric bodies. With increasing velocity of the oncoming flow, the diameter of the near wake changes nonmonotonically [19]. In addition, bodies of different shape form wakes with different diameters. Therefore, in the case of a supersonic flow it is advisable to calculate Sh using the diameter of the wake rather than the diameter of the body generating the wake. Since we were investigating fluctuations in the base region in the present study, we took the throat diameter d of the wake as the characteristic scale. To estimate the effect of M on Sh for the fluctuations, we determined the frequency f_m corresponding to the position of the gentle maximum in the fluctuation spectrum: $Sh_m = f_m d/u_e$ (Fig. 5). Increasing M from 0.4 to 4 reduced Sh_m. In a subsonic flow, the maximal value in the fluctuation spectra of the pressure corresponded to Sh_m = 0.05-0.1 with M = 0.05-0.35 for a cylindrical body with ogival front part (L/D ≈ 4) [1], to Sh = 0.04-0.09 with M = 0.2-0.9, Sh = 0.09-0.11 with M = 1.4, and Sh = 0.1-0.12 with M = 2 for a blunt cylindrical body with expanding tail section [4], and to Sh = 0.1-0.3

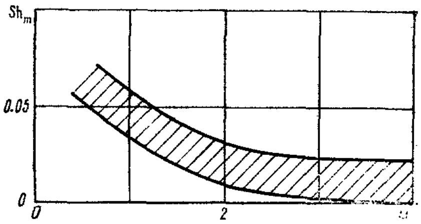

Fig. 5

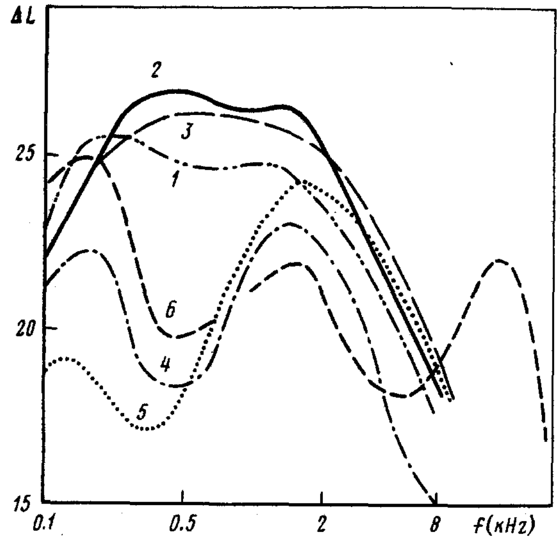

Fig. 6

with M < 0.1 for a sphere [6].

3. Fluctuations in the Near Wake

Besides investigating the base pressure fluctuations, we measured the fluctuations of the dynamic head in the return flow to the base section of the cone. Measurements were made by means of hot-wire and film anemometers of the firm Dis, and also a special sensor in the form of two parallel needles in the front converging part of which a glow discharge was set up. The sensors were placed on the wake axis at distance 0.3D from the base section of the cone. In Fig. 6 (cone with $\theta = 15^\circ$, D = 120 mm; 1-5 for the anemometer, 6 for the flow-discharge sensor; 1) M = 0.3, 2) M = 0.6, 3) M = 0.9, 4) M = 3, 5) and 6) M = 4) we have plotted curves based on photographs of the spectrum on the screen of a parallel one-third octave analyzer (the curves are therefore qualitative in nature). The level was not calibrated; ΔL is the scale on the analyzer screen (dB). In the range of subsonic velocities, large fluctuations are observed in a wide frequency range (f = 0.2-2 kHz). When the velocity of the subsonic flow is increased from M = 0.4 to M = 0.8, the maximum of the spectrum increases, but a subsequent increase in M (to $M \approx 1.1$) leads to a reduction of the maximum.

At supersonic velocities, the first maximum of the fluctuation spectrum of the dynamic head is observed at the same frequencies as for the pressure fluctuations. Like the pressure fluctuations, the transition from M = 3 to M = 4 reduces the fluctuations of the dynamic head at the first maximum. A feature of the fluctuation spectra of the dynamic head is that, in contrast to the pressure spectra, they have a further maximum, situated at frequencies $f \approx 1$-2 kHz. Note that the spectrum obtained with the glow-discharge sensor has a third maximum at $f \approx 15$ kHz.

It is of interest to investigate the fluctuations at not only the base section but also in individual regions of the near wake. The fluctuations near the wake axis were measured by means of gas-discharge sensors. The rms value of the fluctuations increased going downstream from the base section to the contraction region, and then decreased. In the circulation zone the spectral-density levels corresponding to low frequencies were higher, while the high-frequency levels were raised in the contraction region. The growth in the fluctuations over the section in front of the wake throat and subsequent decrease in their intensity behind the throat were also obtained in an investigation of the turbulence behind a wedge with turbulent layer at M = 4 [20] and behind an axisymmetric body with thick boundary layer [21]. The frequency distribution of the fluctuations behind the wedge exhibit a continuous shift of the fluctuation energy to lower frequencies with increasing distance from the wedge. In the case of flow over bodies with laminar layer up to the throat of the wake a second peak of the fluctuation intensity occurs in the region of the transition point in the wake [20, 22]. It follows from what we have said that the position of the wake throat and the transition point can be determined from the increase in the fluctuation intensity as one moves along the axis.

It has been suggested by G. Yu. Stepanov that when a strong disturbance is introduced into the base separation flow by, for example, the abrupt liquidation and subsequent formation of the flow, there could be strong damped fluctuations with varying frequency. To investigate this conjecture experimentally during the work in the wind tunnel with M = 3 a base plate was detached in the tail part of a cylindrical body (D = 130 mm). The experiments showed that there really is a characteristic time for the separation flow to be established and that in the initial period strong damped fluctuations with frequency 20-50 Hz occur.

With a view to elucidating the flow dynamics in the base region, we made a motion picture of the visualized flow using a high-speed cine camera working at 3-6 thousand frames/sec. These revealed fluctuations of the free viscous layer, periodic changes in the size of the toroidal eddy, and fluctuations of this eddy near the jet boundary. The region of circulation flow was surrounded by a flow with large pressure gradients, and these internal viscous layers were unstationary. Examination of the frames showed that the visualizing fluid periodically covers the jet boundary of the stagnation zone, the lower boundary of the colored fluid gradually being deflected toward the axial line, after which one observes a shift of this fluid from the throat to the base section. At a later time the darkening of the viscous layer disappears, and the colored fluid can be noted only near the drainage opening. These pulsations are due to flow-rate fluctuations of the fluid in the base zone and correspond to the frequencies of the maximum in the fluctuation spectrum of the base pressure. Measurements of the turbulence in the wake behind a thin slab and behind a wedge with tripped boundary layer [20] indicate that the intensity of the turbulence in the transverse section of the near wake has a maximum in the free viscous layer, and the intensity of the longitudinal fluctuations is almost two times greater than that of the transverse fluctuations near the trailing edge.

The high-speed motion picture of the visualized flow, and also plates with wires revealed the presence of regions in which the strongest low-frequency pulsations occurred. The regions are the stagnation position of the flow in the region of the throat and the region near the center of the base. It can be assumed that the large-scale variations of the flow in these regions make an important contribution to the low-frequency components of the spectrum of the base pressure fluctuations.

The base pressure fluctuations are produced by a number of interconnected factors, in particular, by the realization of quasistationary regimes with relaxation fluctuations [8], flow-rate fluctuations of the fluid in the stagnation zone, large-scale disturbances and turbulence in the free viscous layer, instability of the return jet, displacements of the points of separation and attachment of the flow, and acoustic fluctuations in the resonance volume.

In the spectra of the base pressure fluctuations, the relatively low-frequency fluctuations (Sh < 0.1) are explained by the flow dynamics in the base region as a whole and are associated with the change in the amount of fluid circulating in the stagnation zone. Random fluctuations of the body due to external disturbances lead to changes in the flow parameters in the layer of influence and in the intensity of the tail shock waves and the pressure on the dividing streamline. These factors govern the amount of gas that is turned into the stagnation zone, and thereby the base pressure. The change in the ratio of the pressure on the cone to the base pressure changes the angle through which the flow is turned in the rarefaction wave, and the process is repeated. Fluctuations of the boundaries of the stagnation zone, the throat diameter, and the position of the tail shock waves have the consequence that the amount of fluid turned into the stagnation zone and the amount of fluid passing through the throat downstream is changed. When flow-rate fluctuations occur behind the throat, a wake with large-scale eddy structure must be formed. In this connection, it should be noted that the existence of regular periodic disturbances in the hypersonic wake behind a cone was established by interferometric measurements in a ballistic range [24].

One of the main sources of fluctuations are waves emitted by supersonic eddies in the free viscous layer. The strong fluctuations over a wide range of the spectrum contain not only acoustic frequencies emitted by the eddies passing near the sonic line but also frequencies corresponding to the Fourier spectrum of the interface intermittency (large vortices in the shear layer that do not pass close to the boundary M = 1). The coefficent of the space-time correlation of the velocity fluctuations in the turbulent boundary layer has a maximum corresponding to transport of eddies with velocities equal to 0.6-0.8 of the flow velocity. Using the cine frames to determine the velocity and eddy sizes, it is possible to find the frequency interval, which corresponds to Sh ≈ 0.4-0.8.

The pressure sensor fixed at the center of the base part essentially records the fluctuations of the stagnation pressure in the incoming jet. All the perturbations of the jet parameter arise in the region in which it is formed, i.e., in the region of the wake throat. These perturbations are due to fluctuations of the tail shocks and also the nature of the mixing in the region of the wake throat. For cones and cylinders placed parallel to the flow, two sensors were set up in each case at different distances from the base section. In a number of experiments a difference was noted in the pressure distribution over the base section: at low supersonic velocities (M < 0.4) the fluctuations were higher near the trailing edge (by 3-5 decibel), though at large subsonic and supersonic velocities (0.4 < M < 3) the fluctuations were greater at the center (by 2-3 decibel). At low velocities, the growth of the pulsations near the rim of the trailing edge is due to separating large-scale eddies. With increasing velocity of the oncoming flow, the main part in the distribution of the fluctuations is played by the transport of disturbances by the return jet.

The fluctuations of the base pressure at frequency Sh ≈ 0.1-0.5 are due to the nonstationary nature of the flow in the region of separation and attachment of the flow, the fluctuations of the return jet, and the resonance fluctuations in the stagnation zone. An estimate of the frequencies of the resonance acoustic fluctuations in the base region shows that for the tested models the range of Strouhal numbers is 0.3-0.5.

The intensity of noise emission by the viscous layer depends on the degree of turbulence in the layer, the maximal turbulence being attained in the region of the tangential discontinuity of the axial velocity between the external flow as it turns past the trailing edge and the stagnation flow. A reduction of the velocity gradients in the free layer helps to stabilize the flow and reduce the fluctuations. This is confirmed by experiments in which gas is blown into the base region [25], where a blowing of order 2-3% lowers the fluctuations by 2-3 times for the subsonic velocity range. In a first approximation, the wavelength of the acoustic wave emitted by the free viscous layer is determined by the thickness of the layer and the mean velocity in this region. For bodies of large diameter, the thickness of the layer and the size of the vortices increase, and there is a corresponding increase in the linear scales associated with the mixing process and the frequency of the emitted sound varies in inverse proportion to the diameter of the bodies. For the turbulent boundary layer, the thickness estimate $\delta\approx 0.37L\times\mathrm{Re}^{1/5}$ shows that with increasing Re one must expect a slight decrease in the thickness of the layer and, therefore, an increase in the frequency of the emitted sound. In the case of supersonic flow, the rarefaction of the flow in the Prandtl—Meyer wave at the trailing edge lowers the spectral density at high frequencies in the same manner as boundary layers with negative longitudinal gradient of the mean pressure [26].

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