PRESSURE FLUCTUATIONS INDUCED IN A GROOVE BY A SUBSONIC OR SUPERSONIC GAS FLOW

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An experimental study has been made of pressure fluctuations induced by a subsonic or supersonic flow over a groove (open groove [1]). The spectrum of the pressure fluctuations in the groove has a continuous component and a discrete component. The discrete component was studied in [2-8], where the mechanism of the formation of the discrete component and its characteristic frequencies were considered. Some data on the continuous component of the spectrum are given in [9].

In this paper we study the effect of the flow parameters on the level of the continuous and discrete components in the pressure-fluctuation spectrum of a groove.

1. The experiments were carried out in subsonic and supersonic wind tunnels. The models studied fell into two groups. Group I comprised cylinders (or a composite model: cone + cylinder), with axisymmetric circular grooves on the side wall with depth h and relative length $\ell^0 = \ell/h$; the axis of the model coincided with the direction of flow velocity vector. Group II comprised flat plates which constituted the side wall of the working part of the wind tunnel, measuring 70 × 50 mm. Grooves with depth h, relative length $\ell^0 = \ell/h$, and width b = 70 mm were made in these plates.

All the experiments were done with rectangular grooves (Fig. 1, $\alpha_1 = \alpha_2 = 90°$, where α_1 and α_2 are the angles between the front or back wall of the groove and its bottom). The parameters of the flow in front of the groove and the sizes of the models used in the experiments are given in Table 1, where M_1 is the Mach number of the mainstream in front of the groove, T_0/T_W is the ratio of the stagnation temperature in the external flow to the wall temperature, Re is the Reynolds number, calculated from the parameters of the external flow and the length of the model from the critical point to the front edge of the groove; d is the diameter of the midsection of the model; A and B are the groups of experiments performed in a subsonic wind tunnel and a supersonic wind tunnel, respectively. The rectangular xy coordinate system was chosen with the x axis along the bottom and the y axis along the front wall.

Special measures were undertaken to reduce the acoustic background in the working part of the subsonic wind tunnel [longitudinal-slit perforation, fine-mesh screen stretched over the perforation, and working part encompassed by a damping chamber fitted with wedge-shaped noise absorbers (anechoic chamber)], which made it possible to completely eliminate the forma-

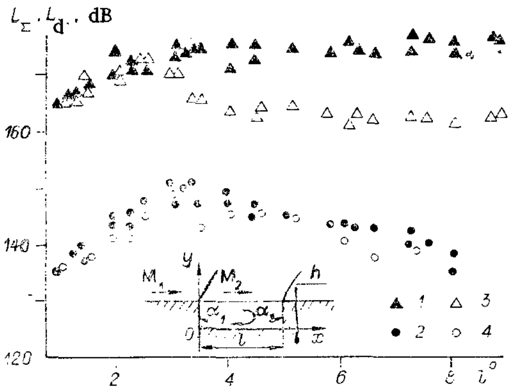

Fig. 1

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TABLE 1

Group of models	M_1	Re	$\frac{T_0}{T_w}$	h, mm	l^0	d, mm
I (A)	0,3—1,0	$6\cdot10^6$—10^7	1	10—65	1—6	230
I (B)	2,0—3,75	$4\cdot10^6$—$2\cdot10^7$	1	10—28	1—6	96
II (B)	2,0—4,0	$8\cdot10^5$—$6\cdot10^7$	1—1,6	10—25	1—8	—

tion of parasitic discrete components, which appear in subsonic wind tunnels, and also to reduce the continuous component of the acoustic background spectrum by 6-15 dB).

We placed No. 4136 pressure-fluctuation sensors (diameter 6.25 mm), manufactured by Brühl and Kjehr (Denmark), on the walls and bottom of the groove flush with its surface. A number of experiments on large models were carried out with capacitance-type sensors (diameter 18 mm). The sensor signal was recorded on an M-168 or Schlumberger (France) tape recorder and was then analyzed and processed with a Brühl and Kjehr analyzer. The spectral characteristics were determined for frequency bands of width Δf = 10 Hz and the total levels in the band were Δf = 20 kHz. The correlation characteristics were taken with an MMD70 correlator manufactured by Diz (GDR) in a 1/3-octave frequency band, using TDA-111 bandpass filters (GDR). The pressure fluctuations were measured to within 2-3 dB.

2. Let us consider the results of an experimental study of pressure fluctuations in a groove. The level of the pressure fluctuations will be written as

$$L = 20\log\left(\frac{\sigma}{\sigma_0}\frac{p_{at}}{p_1}\right),\quad L_1 = 20\log\left(\frac{\sigma_1}{\sigma_0}\frac{p_{at}}{p_1}\right),\quad L_\Sigma = 20\log\left(\frac{\sigma_\Sigma}{\sigma_0}\frac{p_{at}}{p_1}\right).$$

Here σ, σ_1, and σ_Σ are the rms values of the pressure fluctuations in the frequency band Δf = 10 Hz, 1 Hz, and 20 kHz, $\sigma_0 = 2\cdot10^{-5}$ Pa, p_{at} is the standard atmospheric pressure, and p_1 is the static pressure in the flow in front of the groove.

The experiments show that for plane flows when the groove width is $b^0 = b/h \geq 2$ a flow regime that is self-modeling in regard to the Reynolds number arises at Re $\geq 4\cdot10^6$ (with turbulent flow in the boundary layer in front of the groove). At Re $< 4\cdot10^6$ a decrease in Re does not cause the total levels L_Σ to rise. Below we consider a groove for $b^0 \geq 2$ and Re $\geq 4\cdot10^6$. From the experiments we see that the pressure fluctuations at the back wall are larger than at the front wall and the bottom of the groove. The maximum pressure fluctuations occur in the region of the back edge of the groove. Figure 1 shows the values of L_Σ at the front and back walls of the groove as its length varies for M_1 = 2.1, δ_1/h = 0.1-0.5, T_0/T_w = 1-1.6, $y^0 = y/h$ = 0.5 [1, 3) L_Σ; 2, 4) level of the primary tone of the discrete component L_d; 1, 2) back wall; 3, 4) front wall]. We see that as ℓ^0 of the groove increases the level L_Σ increases at the back wall. At $\ell^0 \leq 2.5$, the pressure fluctuations at the front wall are equal to those at the back wall. At $\ell^0 \geq 4$, the levels L_Σ at the front wall are roughly constant. Variation of T_0/T_w in the range from 1 to 1.6 have virtually no effect on L_Σ. The relative thickness of the boundary layer before it breaks away, δ_1/h = 0.1-0.5, also has no appreciable effect on the pressure fluctuations. The effect of M_1 in front of the groove on L_Σ is shown in Fig. 2, where points 1 are L_Σ (ℓ^0 = 2, δ_1/h = 0.3, T_0/T_w = 1), points 2 and 3 are the maximum levels L_d* at different values of ℓ^0, the dashed line represents L (ℓ^0 = 2, δ_1/h = 0.3, T_0/T_w = 1), the black points are for the back wall of the groove (y^0 = 0.5), the white points are for the front wall (y^0 = 0.5), and 3 are experimental data [7].

High levels L_Σ of the pressure fluctuations at the back wall are determined by the interaction of the turbulent mixing layer with the wall. The pressure fluctuations at the front wall are recorded by two processes: by noise emission from the site of interaction of the mixing layer with the back wall and by the interaction of the jet of return currents, which are formed in the groove, with the front wall. At short lengths ℓ^0 the velocity of the return currents is insignificant and the pressure fluctuations at the front wall are determined by the emission from the back wall (at $\ell^0 < 2.5$ the level of pressure fluctuations at the front wall is approximately equal to that at the back wall). At $\ell^0 > 4$ the jet of return currents has the main effect on the pressure fluctuations at the front wall.

Characteristic pressure-fluctuation spectra, measured in the groove, are shown in Fig. 3. Depending on M_1, Re, and ℓ^0, discrete components which may exceed the continuous spectrum

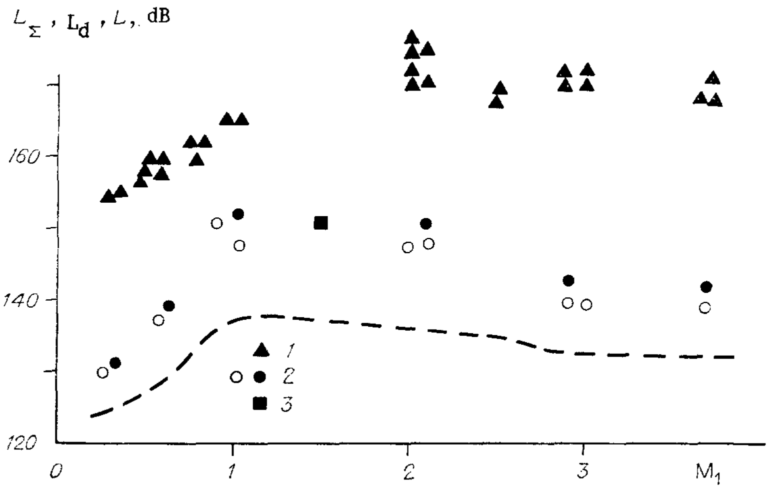

Fig. 2

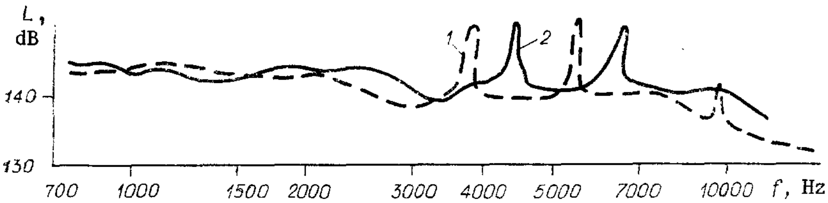

Fig. 3

by 6-15 dB can appear in the pressure-fluctuation spectra. For example, the level of the discrete component in spectra obtained at the back wall of the groove at $M_1 = 2.1$, $\ell^0 = 3.3$, $Re = 4.5 \cdot 10^6$, and $T_0/T_W = 1$-1.6 (lines 1 and 2 represent $T_0/T_W = 1$ and 1.6) is $L_d = 150$-151 dB and exceeds the level of continuous noise by 10-12 dB. This pressure-fluctuation spectrum without the groove does not contain discrete components, since the intensity of the continuous noise in the frequency range f = 500-5000 Hz is at the level L = 115-120 dB. Thus, the rms amplitudes of the resonant pressure fluctuations in the groove exceed the rms amplitude of the continuous noise at the surface without the groove by a factor of 30-40 and in the groove by a factor of 4. At the frequencies f = 700-5000 Hz the level L = 140-145 dB, i.e., the rms values of the continuous noise in the groove exceeds the rms values of the continuous noise at the surface of the model without the groove by a factor of 10-30.

Below we give data from experiments on the discrete-component levels obtained for the front and back walls of the groove at $Re > 4 \cdot 10^6$. The results of the experiments can be approximated for the front wall for $M_1 = 0.3$-1.0, $\ell^0 = 0.7$-6.6, $\delta_1/h = 0.2$-0.5 by the relation $L_d = b_0 + b_1 M_1$, where $b_0 = 123.6$ and $b_1 = 21.4$. It is useful to break up the experimental results for the back wall. The first group consists of data obtained at $0.7 \le \ell^0 \le 1.5$. They form a single relation $L_d = L_d(M_1)$ for the primary and first tones of the discrete component with respect to M_1 of the mainstream, which is universal in the range $M_1 = 0.4$-1.0 and is given by the formula $L_d = \bar{b}_0 + \bar{b}_1 M_1$ ($\bar{b}_0 = 120$, $\bar{b}_1 = 25$). A similar relation $L_d = б_0 + б_1 M_1$ ($б_0 = 130$, $б_1 = 20$) can be constructed for the second group of experimental data found for $1.5 \le \ell^0 \le 6.6$.

The variation of the levels of the discrete component with respect to the ℓ^0 and M_1 for the supersonic flows ($M_1 > 1$) is shown in Figs. 1 and 2. Figure 1 illustrates the effect of the relative groove length on L_d (points 2 and 4) at $M_1 = 2.1$. The maximum level L_d^* occurs at $\ell^0 \approx 3$. The level L_d at $\ell^0 < 1$ could not be obtained in the experiments since the amplitude—frequency characteristic of the microphones used in the experiments had an upper frequency limit ($f_u = 20$ kHz). In the range $\ell^0 > 9$ the discrete components are absent because of the reconstruction of the flow in the groove (the open groove becomes a closed groove). Similar results on L_d were also obtained for other values of $M_1 > 1$. The frequency fluctuations at the frequency of the discrete component at the surface of the back edge of the groove are of the hydrodynamic type, since they are caused by the periodic action of large-scale vortices of the mixing layer on that surface [8]. On the other surfaces of the

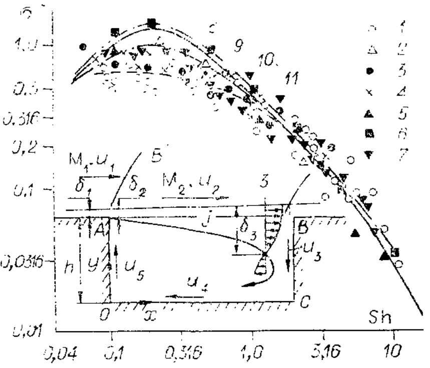

Fig. 4

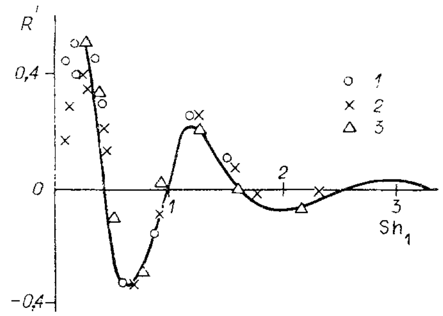

Fig. 5

groove (front wall, bottom, part of the surface of the back wall) the frequency fluctuations at the frequency of the discrete component are of the acoustic type. The physical nature of these pressure fluctuations were discussed in [8].

The maximum levels L_d^* in the groove for different values of ℓ^0 and the range M_1 = 0.3-3.7 are collected in Fig. 2. We can see that the largest pressure fluctuations occur at $M_1 \approx 1$. The levels L_d^* exceed the levels L by 6-15 dB.

Analysis of the experimental data on the continuous component of the pressure-fluctuation spectra reveals that it is hydrodynamic in nature. The shape of the pressure-fluctuation spectrum resembles that of the spectrum obtained when a turbulent jet flows onto a flat barrier. Figure 4 shows the dependence of the relative spectral density $\sigma^0 = \sqrt{f_0}\sigma_1/\sigma_\Sigma$ on the Strouhal number Sh = f/f_0 [points 1) M_1 = 2.1, ℓ^0 = 2.4-5.2, T_0/T_W = 1-1.6, $x^0 = x/h$ = 1.6-2.6, y^0 = 0; 2) M_1 = 2.9, ℓ^0 = 3.2, T_0/T_W = 1, x^0 = 1.6, y^0 = 0; 3) M_1 = 2.1, ℓ^0 = 2.4-3.2, T_0/T_W = 1, x/ℓ = 1, y^0 = 0.4-0.7; 4) M_1 = 3, ℓ^0 = 2.1-3.2, T_0/T_W = 1, x/ℓ = 1, y^0 = 0.4-0.7; 5) M_1 = 2.4, ℓ^0 = 2.3, T_0/T_W = 1, x/ℓ = 0, y^0 = 0.2-0.5; 6) M_1 = 1.5, ℓ^0 = 2.25, T_0/T_W = 1, x/ℓ = 1, y^0 = 0.5 [7]; 7) M_1 = 0.3-1, ℓ^0 = 1.5-2.0, T_0/T_W = 1, x/ℓ = 1, y^0 = 0.4-0.7; Re = $(4\text{-}20)\cdot 10^6$]. The results obtained by processing the experimental data measured at the back and front walls and the bottom of the groove form one relation.

For the back wall $f_0 = u_j/\delta_3$, for the bottom of the groove $f_0 = u_3/\ell$, and for the front wall $f_0 = u_4/h$. Here u_j is the velocity at the dividing line of the current of the turbulent mixing layer, u_3 is the velocity at the dividing line of the boundary layer at the back wall, and u_4 is the velocity at the outer boundary of the boundary layer at the bottom of the groove. According to [1], $u_j/u_2 = 0.548 + 0.018M_1$, $u_3 \approx 0.42\ u_2$, and $u_4 = 0.3\ u_2$ for $M_1 < 1$ and $u_4 = 0.25\ u_2$ for $M_1 \geq 1.5$; the thickness δ_3 of the turbulent mixing layer in front of the back wall was calculated by the method of [1]. The choice of the characteristic dimensions δ_3, ℓ, and h in the relation for f_0 is not random. The turbulent mixing layer carries vortices, whose characteristic scale is proportional to δ. After interacting with the back wall of the groove, the mixing layer forms a flow (directed along the wall toward the bottom), which can be considered as flow in the turbulent mixing layer of a jet of radius $\ell/2$ flowing onto a flat barrier, the bottom of the groove. When $\ell^0 > 4$, the pressure fluctuations at the front wall are determined by the interaction of the stream of return currents of radius h/2 with that wall.

Figure 4 shows the relative spectral densities, measured at the flat barrier when a turbulent jet flows onto it (plane jet – line 8, r/R_1 = 0; axisymmetric jet – lines 9-11, r/R_1 = 0, 0.8, and 1.2, respectively). The axis of the jet is perpendicular to the plane of the barrier, r is the distance of the observation point, and R_1 is the radius of the jet before the interaction with the barrier. The relative spectrum for distances r/R_1 = 0 was taken from [10] and the spectra at r/R_1 = 0.8 and 1.2 were supplied by V. M. Kuptsov. From Fig. 4 we see that the experimental data obtained in the groove are in satisfactory agreement with data on a jet flowing onto a barrier.

Let us consider the correlation characteristics of the continuous component of the pressure-fluctuation spectrum. Figure 5 shows the results of measurements of the real part of the longitudinally normalized reciprocal spectrum $R' = R'(\Delta x, 0, f)$, using two microphones set up on the bottom of the groove with a distance Δx between their centers [points 1-3 correspond to M_1 = 3.7, 3.7, 2.1; ℓ^0 = 3.3, 2.6, and 3; $\Delta x/\ell$ = 0.14, 0.2, and 0.24; T_0/T_W =

1.35, 1.42, and 1; and the line represents calculation from Eq. (2.2) at $Sh_1 > 0.25$]. Here $Sh_1 = k\Delta x$ ($k = 2\pi f/u_2$ is the wave number). The data from experiments at $Sh_1 > 0.25$ are described satisfactorily by $R' = \exp[-(a_x/b_x)Sh_1]\cos(a_x Sh_1)$ ($a_x = 1.57$, $b_x = 3.14$).

The nature of the relation $R' = R'(Sh_1)$ corresponds to hydrodynamic pressure fluctuations. Indeed, the velocity of sound is characteristic of acoustic pressure fluctuations as $Sh_1 \to 0$, $R' \to 1$. In our case, the determining velocity is the flow velocity u_2 and at $Sh_1 < 0.25$ a decrease in Sh_1 at $\Delta x/\ell$ = const causes a decrease in R' (see Fig. 5), which is inherent to hydrodynamic pressure fluctuations.

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INTERNAL WAVE FIELD IN THE NEIGHBORHOOD OF A FRONT EXCITED BY A SOURCE MOVING OVER A SMOOTHLY VARYING BOTTOM

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The problem of the propagation of surface waves harmonic in time and quasisinusoidal in space over a smoothly varying bottom is solved in [1] by using the geometric optics method. An analogous problem for internal waves with an arbitrary Brunt–Väisälä frequency distribution over the depth was examined in [2]. The case of internal waves locally sinusoidal in space and time in the presence of slowly varying shear flows was investigated in [3]. Airey wave transformation in a smoothly inhomogeneous layer along the horizontal is examined in [4]. Fronts and lines of equal phase are constructed in [5] for a source moving in a stratified fluid layer in the case of constant layer depth. The asymptotic of the solution for the moving source in the neighborhood of the front of a mode taken separately was written down in [6].

The problem of an internal wave field in the neighborhood of the front of a separate mode generated by a point mass source moving over a smoothly varying bottom is examined in this paper by the method of traveling waves [7], which is one modification of the geometric optics method.

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