PRESSURE PULSATIONS ON A RIGID WALL CAUSED BY A VORTEX STREET

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A topic of obvious interest is the interaction between the vortex wake behind bluff bodies and nearby objects, in particular plane surfaces. At present the most detailed studies in flows such as these have been on the characteristics of the velocity field of the vortices [1, 2]. The main topic of attention in what follows is pressure pulsations on a wall caused by separation of vortices from an adjacent cylinder. This problem is especially important for the determination of vibrations and noises due to bodies located on the rigid boundary of the flow.

Experiments were conducted in a low-turbulence wind tunnel with a closed working part of cross section $30 \times 30\ cm^2$ and length 120 cm. A diagram of the apparatus is given in Fig. 1. Cylinders 1 of length 20 cm were placed next to the side wall 2 of the tunnel at a distance of 60 cm from the convergent channel. The maximum blocking in the working part of the tunnel during the experiment was 10%. The coordinate system made it possible to change the position of the cylinder relative to the microphone 3, which is built in flush with the wall. The pressure p_c on the wall was measured by means of capacitor mircophones measuring 1 by $\frac{1}{2}$ in. and made by the firm RFT.

A SK-4-72 analyzer was used in order to analyze the signals. Measurements showed that the thickness of the boundary layer on the wall in these experiments was only one half to one fifth of the gap between the wall and the cylinder, and so the cylinder encountered a flow without any velocity shear.

Figure 2 gives the energy spectra A(f) of the pressure pulsations (f is the frequency) at Reynolds number $Re = 10^5$ ($Re = U_0 d/\nu$, U_0 is the velocity of the flow, d is the diameter of the cylinder, and ν is the kinematic viscosity) for various distances l between the cylinder and the wall. In the upper diagram in Fig. 2 the broken line indicates the spectrum of the pressure pulsations on the wall in the absence of the cylinder. As the dimensionless distance l/d decreases, the maximum of the spectrum obtained by averaging over 64 realizations is displaced towards large frequencies, a fact which indicates an increase in the mean frequency f_1 of vortex shedding. The corresponding changes in the Strouhal numbers for various Reynolds numbers are shown in Fig. 3 (1) $Re = 10^5$, 2) $Re = 6 \cdot 10^4$, 3) $Re = 2.5 \cdot 10^4$). In Fig. 3 $S = f_1 d/U_0$, and $S_0 = f_0 d/U_0$, while f_0 is the frequency of the separation of the vortices when the cylinder is removed from the wall to a distance considerably greater than its diameter. We note that in the experiments in question the removal of the cylinder from the wall to a distance of $l = 0.5d$ was accompanied by an increase in the pressure pulsation frequency which attained 20%, and the width Δf of the energy spectrum A(f) at the $0.7A_{max}(f_1)$ level amounted to $\Delta f = 0.3f_1$. The form of the pressure pulsation spectra differs from the velocity pulsation spectra given in [1, 2]. Thus in [2] the displacement of the spectral peak when the cylinder approached the wall was only 10%, while the width of the spectrum was an order of magnitude less: $\Delta f \simeq 0.03f_1$. These differences are due to the fact that it is the pressure on the wall which is being measured in this experiment, while in the boundary region the important factor is the interaction between the vortices and the boundary layer. The velocity field of the vortices outside the boundary layer is analyzed in [2].

We shall briefly discuss one of the possible mechanisms by which the repetition frequency of the vortices varies when the cylinder approaches the wall. We approximate the shear flow behind the cylinder by the velocity profile U(y) with tangential discontinuities of the form: $U(y) = U_0$ when $y > d/2$; $U(y) = 0$ when $-d/2 < y < d/2$; $U(y) = U_0$ when $-l - d/2 < y < -d/2$. The result may be obtained that the phase velocity c for a mode whose increase leads to the formation of a vortex street with a checkerboard arrangement

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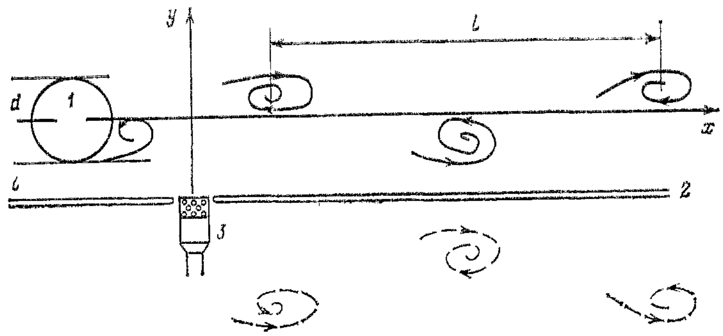

Fig. 1

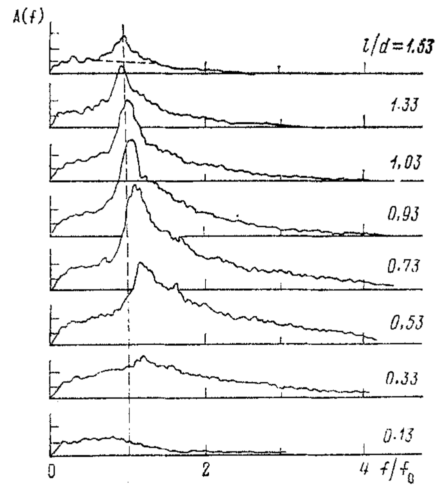

Fig. 2

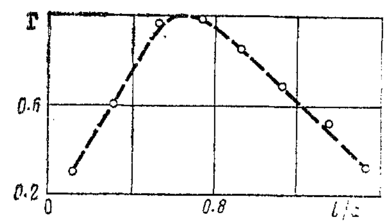

Fig. 4

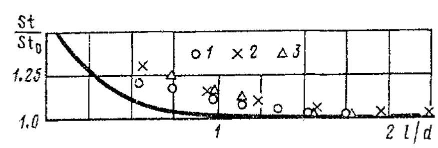

Fig. 3

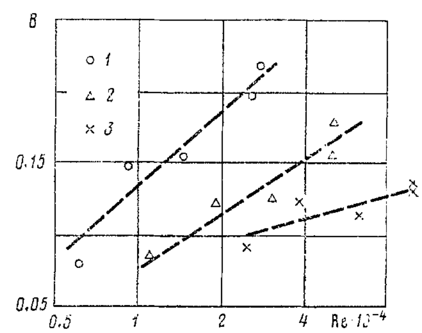

Fig. 5

of vortices has the form

$$\operatorname{Im} c = U_0 m/(1+m^2), \quad \operatorname{Re} c = U_0/(1+m^2), \quad m = \frac{\{\operatorname{ch} kd - [\operatorname{ch}^2 kd - \operatorname{sh}^2 kd\,(1-e^{-kl})]^{1/2}\}^{1/2}}{(1+e^{-kl})\operatorname{sh} kd}$$

where $k = 2\pi/L$, and L is the period of the wave.

We assume that the three-dimensional scale of the vortex street does not depend on the distance of the cylinder from the wall (this assumption requires direct experimental verification). We take $L = 4.5d$, in accordance with [3]. The phase velocity of a wave with such a period increases with diminishing distance l. The relative change in the frequency of the wave, which is equal to the relative change in the number St, is shown in Fig. 3 (continuous line). We shall discuss qualitatively the effect on the frequency of the wave produced by an increase in its amplitude, resulting in the localization of the vorticity, which is distributed originally along the tangential velocity discontinuities, into concentrated vortices. Obviously, when there is a rigid wall, the hydrodynamic field of the street is equivalent to the fields of two vortex streets which are mirror-symmetric relative to the plane $y = -l - d/2$ (see Fig. 1). Evidently the inner series of vortices accelerates the motion of the "mirror" street, but the outer series retards it. Because the inner series is nearer to the wall, the phase velocity and frequency of the wave increase with increasing amplitude.

An interesting question is the dependence of the strength of the pressure pulsation spectra on the position of the cylinder. For Reynolds numbers $Re \sim 10^5$ the dependence of $\Gamma = \langle p_c^2 \rangle^{1/2} / \langle p_c^2 \rangle^{1/2}_{max}$ on l/d is shown in Fig. 4. The microphone was located during the measurements at a distance of $x = 2.5d$ downstream from the axis of the cylinder. It can be seen that the root-mean-square pulsations have their maxima when the gap is given by $l/d = 0.75$. We note that for smaller Reynolds numbers, to $Re = 5 \cdot 10^3$, the greatest magnitude of the pulsations was observed at those same values of x/d and l/d.

Figure 5 shows the root-mean-square pressure pulsations divided by the kinetic energy head $B = \langle p_c^2 \rangle^{1/2} / (\frac{1}{2}\rho U_0^2)$. In view of the fact that the diameter of the measuring microphone was comparable with the period of the vortex street, the experiment recorded the pressure averaged over an area S equal in diameter to the microphone. If the pressure at the wall varies as $p = p_0 \cos(\omega t - kx)$, where $k = 2\pi/L$, the pressure averaged over an area S of radius R will be equal to

$$p_c = \frac{p_0}{\pi R^2} \iint\limits_S \cos(\omega t - kx)\, dS = \alpha p_0 \cos \omega t, \quad \alpha = J_0(kR) + J_2(kR)$$

where J_0 and J_2 are Bessel functions. Therefore in Fig. 5 the root-mean-square pressure pulsations are normalized by the coefficient α. It is characteristic that the magnitude of the pulsations depends on the Mach number $M = U_0/c$, c being the velocity of sound in air (see Fig. 5; 1) $M = 0.022$; 2) $M = 0.044$; 3) $M = 0.09$). Also dependent on the velocity of the flow is the magnitude p_b of the background fluctuations on the wall in the absence of the cylinder. However, their magnitude is shown by measurement to be small in comparison with the pulsations due to the vortex street. Thus the background root-mean-square pressure pulsations divided by the hydrodynamic pressure head $\beta = \langle p_b^2 \rangle^{1/2} / (\frac{1}{2}\rho U_0^2)$ are 0.035 when $M = 0.022$, 0.02 when $M = 0.44$, and 0.015 when $M = 0.09$.

In conclusion we note the most important experimental results. When the cylinder approaches the wall the frequency of the pressure pulsations increases. This effect is observed right to $Re = 10^5$. The maximum magnitude of the pulsations on the wall is observed when the cylinder is removed from it to a distance of one and half radii, and the maximum amplitude of the pressure pulsations on the wall can attain 20% of the dynamic pressure head.

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