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ELECTRONIC COMPUTER STUDY OF SEPARATION FLOW FEATURES AROUND A VIBRATING CYLINDER

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The nonstationary separation flow around a circular cylinder performing harmonic vibrations across the stream by an incompressible viscous fluid is investigated in a numerical experiment.

Three qualitatively distinct regimes of separated flow around a circular cylinder performing harmonic vibrations perpendicuarly to the free stream have been established by experimental means [1]. Regime I is neutral, for small dimensionless vibrations frequencies ($0 \leqslant Sh_1 \leqslant 0.04$), when their influence is not felt in the period of free vortex shedding from the cylinder, Regime II is transition ($0.04 \leqslant Sh_1 \leqslant 0.1$), and Regime III is "capture" ($Sh_1 > 0.1$) at which the frequency of free vortex shedding agrees with the frequency of cylinder vibration.

Among the theoretical papers in this area is [2] in which results of numerical experiments to compute the nonstationary separated flow of an ideal fluid around a vibrating cylinder are presented. However, this investigation is performed under the essential assumption about the site of stream separation on the cylinder surface since the separation points were not determined by a computation of the viscous flow in the boundary layer but were given in conformity with the experimental data for a selected Re number.

A method of modeling the nonstationary separation flow around bodies is proposed in [3, 4] on the basis of the synthesis of a scheme of an ideal medium and a boundary layer. Without any additional hypotheses not encompassed by these schemes, it permitted construction of the separation flow pattern around a fixed cylinder for both laminary and turbulent separation [4].

The present paper is devoted to modeling all the above-mentioned separation flow regimes around a vibrating cylinder on the basis of the same theoretical scheme. In addition to a phenomenological confirmation of the theoretical scheme, the authors tried to use a numerical experiment to set up the physical features of the phenomenon. It should be emphasized that the approach being developed possesses great generality and can be used not only for any profiles [3] but also for the study of spatial flows [5].

As in [3, 4], the flow as a whole around a cylinder is divided into a potential domain and a viscous flow domain in the boundary layer. The potential flow is computed by the method of discrete vortices [5]. Cumulative discrete vortices that replace the attached and free vortex layers are here arranged on the cylinder surface. The boundary conditions of nonpenetration of the cylinder surface were satisfied at the control points between the vortices.

In the presence of boundary layer separation from the cylinder surface, it is considered displaced completely at certain points in the potential flow domain in the form of free vortex sheets with intensity equal to the total boundary layer vorticity at its point of separation. Moreover, it is assumed that the discrete vortices by which the free vortex sheets are modeled move during the first step in time after boundary layer separation, at the average velocity of the center of vorticity of the boundary layer located at a distance of the displacement thickness from the streamline surface. At subsequent times they move together with the fluid and their circulations are conserved unchanged.

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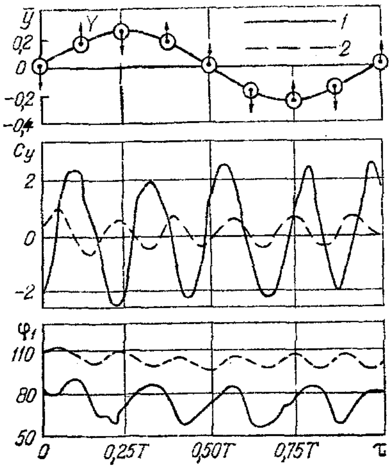

Fig. 1

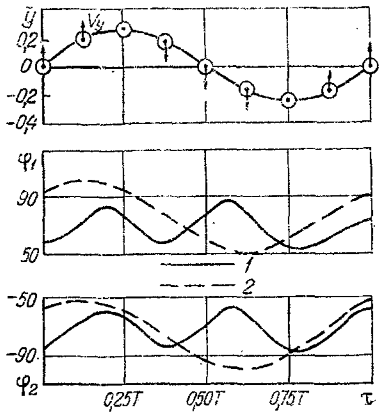

Fig. 2

Fig. 1. Features of the change in the lift coefficient Cy (dimensionless) and the location of the separation points φ_1 (deg) per period of cylinder vibration T for laminar ($1 - Re = 10^5$) and turbulent ($2 - 10^6$) separation (Regime I, $Sh_1 = 0.04$).

Fig. 2. Features of the change in location of the separation points φ_1, φ_2 (deg) during the cylinder vibrations period for laminar separation ($Re = 10^5$), in the transition regime II ($1 - Sh_1 = 0.07$), and the "capture" regime III ($2 - Sh_1 = 0.15$).

Nonstationary aerodynamic loads acting on a cylinder were found by integrating the pressure coefficient, determined by the Cauchy—Lagrange integral, over its outline. When determining the perturbed velocity potential in this integral, its discontinuity at points of free vortex sheet detachment from the cylinder because of boundary layer separation was taken into account on the cylinder surface. The magnitude of this discontinuity equals the velocity circulation over the closed contour enclosing the vortex shell under consideration.

The viscous flow in the boundary layer was computed by numerical integral of the system of nonstationary boundary layer differential equations by the method developed in the Moscow University Computation Center which is extended in [3, 4] to the analysis of the turbulent flow in a boundary layer in the presence of a longitudinal pressure gradient. The system of boundary layer differential equations was closed by using the turbulence model utilized in [3].

According to the mathematical model elucidated, the continuous process of the change in the boundary conditions of the problem and of all the flow parameters was replaced by discrete processes than occur at different times. The potential flow parameters which were used as boundary conditions to analyze the viscous flow in the boundary layer were computed successively at each time. The process of flow formation as a whole was studied in both domains during the transition from one computation time to another.

The method described above permits analysis of the viscous flow in the boundary layer from both the forward stagnation point of the cylinder, and from the rear in the case of reversible flow at the cylinder surface in its base domain. Use of this scheme permits computation of the aerodynamic and frequency characteristics of the flow with satisfactory agreement with experimental results for different Reynolds numbers [4].

The separation flow around a vibrating cylinder was computed by a simplified method that does not take account of the boundary layer in the base domain of the cylinder. As is shown in [4], in this case the frequency characteristics of the flow are in satisfactory agreement with experimental results but the aerodynamic drag is exaggerated.

Computations of the separation flow around a fixed cylinder ($Sh_1 = 0$) showed [4] that symmetric separation is developed on the cylinder at the initial instant after the origination of motion. Then the nonsymmetry of the flow around the upper and lower cylinder surfaces is manifest, which increases with the lapse of time. As the transient expires, that flow re-

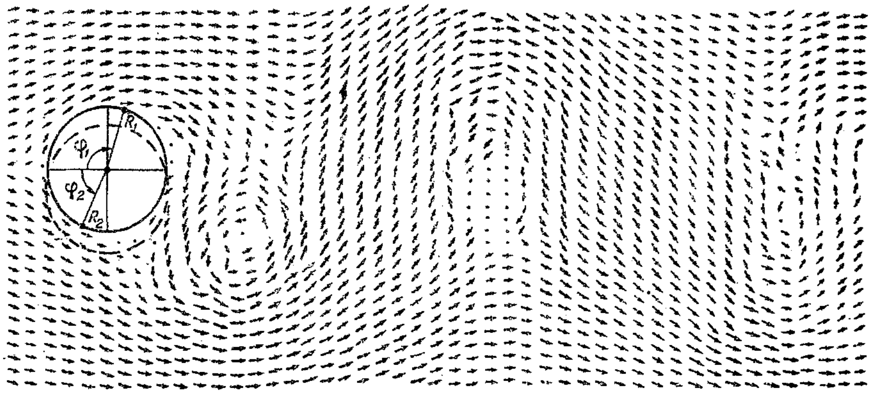

Fig. 3. Velocity field of a vibrating cylinder (upon approaching the upper position) in the "capture" regime III (Sh_1 = 0.15).

gime is built up for which the vortex clusters, formed because of boundary layer separation from the cylinder surface, are separated periodically at a frequency corresponding (as in experiment) to the number Sh = 0.19-0.2, and are entrained in the stream. This results in vibrations of the boundary layer separation points at a frequency equal to the frequency of vortex cluster separation. All the flow parameters, including the pressure, acquire the same periodic variation. An aerodynamic wake in the form of Karman streets is formed behind the cylinder.

The solution of the problem of separation flow around a vibrating cylinder is of special interest. As already mentioned above, Fedyaevskii and Blyumina [1] performed detailed experimental investigations of this regime of separation flow around a cylinder.

Results of numerical experiments by the method elucidated in [3, 4] for computing the nonstationary separation flow around a circular cylinder suddenly set into motion and, as in [1], performing harmonic vibrations across the flow according to the law $\bar{y} = \bar{y}_0 \sin(2\pi Sh_1 \tau)$, where $\bar{y}_0 = 0.25$, are presented below.

As for the flow around a fixed cylinder vibrating at low frequencies (Regime I, $0 \leqslant Sh_1 \leqslant 0.04$), the change in the lift coefficient C_y and the angle of stream separation φ_1 at upper (or φ_2 at the lower) surface of the cylinder occurs according to a periodic law (Fig. 1). The frequency of these vibrations is independent of the frequency of cylinder vibrations for both the laminar flow regime in the boundary layer (solid line, Re = 10^5) and the turbulent regime (dashes, Re = 10^6). However, since turbulent boundary layer separation occurs behind the cylinder middle section, the magnitude of the separation zone is considerably less in this case than for the laminar boundary layer. This results in a diminution in the amplitude of the cylinder lift coefficient fluctuations. Moreover, the frequency of vortex shedding from the cylinder surface increases from Sh = 0.19-0.2 for the laminar to Sh = 0.2-0.21 for the turbulent flow regime in the boundary layer.

Let us analyze the change in the law of the derivative $\partial Cy/\partial y$: its positive value indicates that the transverse aerodynamic force Y contributes to magnification of the cylinder vibrations (aerodynamics excitation is observed), while the negative value results in aerodynamic damping. At the midpoint of the period T of cylinder vibrations, the total time during which $\partial Cy/\partial y > 0$ and the time where $\partial Cy/\partial y < 0$ are identical, while the work of the force Y is almost zero. Therefore, there are not conditions for the origination of self-oscillations in the considered range of cylinder vibration frequencies ($0 \leqslant Sh_1 \leqslant 0.04$), hence Regime I is called neutral).

A reduction in the frequency of vortex shedding from the cylinder as compared with the first regime occurs for cylinder vibrations frequencies in the Strouhal number range $0.04 \leq Sh_1 \leq 0.1$ (Regime II). The fluctuations of all parameters are unstable in nature. Computations showed that the vortex shedding frequency at the end of this band is compared with the frequency of cylinder vibration, i.e., total "capture" of the vortex shedding frequency by the cylinder vibrations frequency occurs. The change in the angular position of the boundary layer separation points from the upper (φ_1) and lower (φ_2) surfaces of the frontal part of the cylinder is shown in Fig. 2 for one period of cylinder vibrations for a dimensionless vibration frequency of Sh_1 = 0.07. Shown in this same figure is the change in the parameters un-

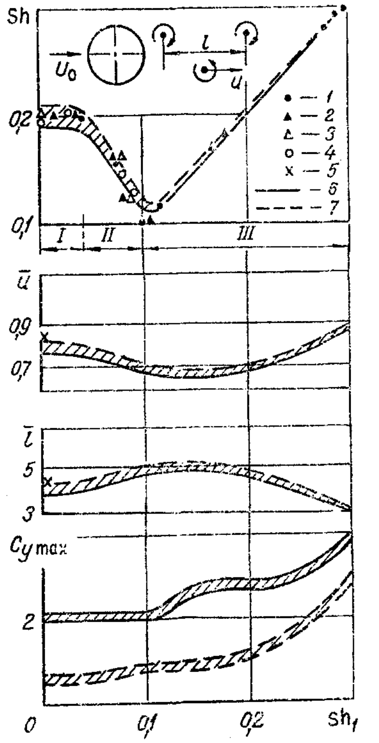

Fig. 4. Influence of the cylinder vibration frequency Sh_1 on the vortex shedding frequency Sh, their motion velocity $\bar{u}$, the spacing between them $\bar{l}$, and the amplitude of the lift coefficient C_y: 1-4) experimental data from [1] (1 — Re = $3.46 \cdot 10^5$; 2) $7.95 \cdot 10^5$; 3) $8.62 \cdot 10^5$; 4) $1.55 \cdot 10^6$); 5) experimental data from [6]; 6) computation (Re = 10^5); 7) computation (Re = 10^6).

der consideration for the value $Sh_1 = 0.15$ corresponding to Regime III. It is seen that the change in φ_1 and φ_2 is of stable periodic nature with a frequency equal to the frequency of cylinder vibration.

Analysis of the velocity fields in the neighborhood of the vibrating cylinder showed that the frequency of fluctuation of all the flow parameters is determined by the frequency of vortex cluster separation. Hence, the agreement between the vibrations frequencies φ_1, φ_2 and the transverse aerodynamic forces indicates the total "capture" of the frequency of vortex shedding by the frequency of cylinder vibration. However, because of the amplification of the nonstationarity of the flow as a whole as the cylinder vibration frequency increases, the amplitudes of the vibrations φ_1, φ_2 as well as C_y increase. Moreover, because of the major appearance of inertia of the potential flow and the flow in the boundary layer, a negative phase shift appears between the cylinder vibrations and the angles of stream separation φ_1 and φ_2, which increases as Sh_1 grows.

Therefore, the characteristic feature of the third regime of the separation flow around a vibrating cylinder is the presence of the total "capture" of the frequency of vortex cluster separation from the cylinder by the frequency of cylinder vibrations.

It must be noted that the angular location of the stream separation points at the upper (φ_1) and lower (φ_2) surfaces of the cylinder changes in synchronization in all three regimes examined.

The vector velocity field behind a vibrating cylinder in the "capture" regime (Sh_1 = 0.15) is displayed in Fig. 3 at the dimensionless time $\tau = 21$ when the cylinder moves from down to up at a velocity of $V_y = 0.17U_0$ during vibration while the boundary layer flow is laminar. The vortex cluster being formed in the lower part of the cylinder base region is seen. As time passes, this vortex cluster increases in size during cylinder upward motion, and its upward motion lags behind the cylinder motion. At the next instant, when the cylinder is in the extreme upper position, this vortex cluster separates and is entrained by the stream.

As is seen from Fig. 3, the presence of the vortex in the lower part of the base region and the increase in its total circulation in time during upward cylinder motion causes more and more intense deceleration of the stream at its lower surface. This nature of the velocity change on both the cylinder contour and in time is the reason for the nonsymmetric location of the points of boundary layer separation on the cylinder upper (R_1) and lower (R_2) surfaces (Fig. 3).

All the parameters considered change analogously during downward motion, but in the reverse direction.

Two vortices of different signs separate from the cylinder during one period of vibrations in the "capture" regime, and an aerodynamic wake is the form of a vortex with regular location of the vortex clusters is formed behind the cylinder.

The mean position of the cylinder is shown by dashed lines in Fig. 3.

Analysis of the results of computations (Fig. 4) showed that, as in experiment, three regimes of separation flow around a cylinder are observed. Regime I includes the range of variation of the kinematic Strouhal numbers (Sh_1) from 0 to 0.04 for cylinder vibrations. Vortex shedding in this frequency regime is independent of the cylinder vibration frequency and equals the vortex shedding frequency from a fixed cylinder. Partial "capture" of the vortex shedding frequency by the cylinder vibration frequency is observed for the values $0.04 \leqslant Sh_1 \leqslant 0.1$ (Regime II). Regime III ($Sh_1 > 0.1$) is characterized by total "capture" of the vortex shedding frequency by the cylinder vibrations frequency.

For a turbulent flow regime in the boundary layer ($Re = 10^6$) the vortex shedding frequency in Regimes I and II ($0 \leqslant Sh_1 \leqslant 0.1$) is somewhat higher than for laminar flow ($Re = 10^5$). The lines corresponding to these regimes (Fig. 4) limits the range of parameter variation for different cylinder vibrations frequencies.

Analysis of the vector velocity fields at different times and for different values of Sh_1 showed that the relative velocity $\bar{u} = u/U_0$ of the vortex motion in the aerodynamic wake behind the cylinder and the relative distance $\bar{l} = l/d$ between the vortices of the same sign are practically unchanged in Regime I of the separation flow around a vibrating cylinder. Because of the reduction in the vortex shedding frequency and the elevation of their intensity and because of the increase in their time of formation in the second regime, the relative distance $\bar{l}$ between them increases while the velocity of their motion diminishes. But in the "capture" regime (Regime III), their circulations diminish because of the increase in the vortex shedding frequency, which is the reason for the rise in the relative velocity of their motion and the reduction of the distance between them.

As already mentioned above, the amplitude of the transverse aerodynamic force coefficient acting on the vibrating cylinder grows with the increase in the cylinder vibrations frequency in the "capture" regime. However, for a turbulent flow regime in the boundary layer when the points of stream separation are behind the midsection of the cylinder (see Fig. 1) and the separations zone is considerably smaller, the amplitude of the C_y fluctuations is lower than for laminar flow in the whole range of cylinder vibrations frequencies.

Therefore, the flow model proposed in [3, 4] permits observation of features, in a numerical experiment, for the nonstationary flow around a vibrating cylinder by a viscous fluid, and obtaining quantitative results that are in good agreement with experimental data.

NOTATION

d, y, y_0, diameter, transverse deflection, and amplitude of cylinder vibrations; l, spacing between vortices; φ_1, φ_2, angular location of the points of separation; U_0, unperturbed stream velocity; V_y, velocity of transverse cylinder motion; u, velocity of vortex motion; f_1, cylinder vibrations frequency; f, vortex shedding frequency; t, time; ν, kinematic velocity; $Sh_1 = f_1d/U_0$, dimensionless cylinder vibrations frequency, the kinematic Strouhal number; $Sh = fd/U_0$, Strouhal number of vortex shedding; $Re = dU_0/\nu$, Reynold number; $\tau = tU_0/d$, dimensionless time; $\bar{y} = y/d$; $\bar{y}_0 = y_0/d$; $\bar{l} = l/d$; $\bar{u}/U_0$; t_1, period of cylinder vibrations, and $T = t_1U_0/d$, dimensionless period of vibrations.

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DISTRIBUTION OF VELOCITY PULSATIONS IN A CHANNEL WITH MIXING OF OPPOSITELY SWIRLED STREAMS

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The influence of swirling and of the degree of concurrent flow on the magnitude and distribution of turbulent pulsations in the mixing of oppositely swirled streams is investigated. The correspondence between the pulsation characteristics of the mixing layers of swirled flows and concurrent jets is established.

Experimental data [1, 2] show that there is a generality in the mechanisms of mixing of oppositely swirled streams and concurrent jets, which is manifested most clearly in flows with significant transverse shear. For example, it was shown in [2] that the relative velocity profiles in a mixing layer of oppositely swirled streams with a degree of concurrent flow m = 1 are self-similar with respect to the channel length and they coincide in shape with the corresponding profiles in the mixing layers of concurrent unswirled jets. The analogy in the laws of expansion of these mixing layers is established.

The analysis carried out in [2] was based on hypotheses that the rate of growth of the mixing layer is proportional to the magnitude of the transverse pulsation velocity, which in turn is proportional to the transverse gradient of the averaged velocity [3]. Such an approach is evidently unsuitable for the analysis of flow of a more complicated form, and one must turn to the investigation of the pulsation characteristics of the flow, which characterize the processes of turbulent exchange directly, without the resort to additional hypotheses. The present article is devoted to the consideration of this question. The investigation carried out in it is a continuation of [2] and is directed toward the search for regularities in the development of the pulsation characteristics of flow arising during the mixing of coaxial, oppositely swirled streams in a channel and their comparison with the corresponding characteristics of unswirled flows with transverse shear.

The experiments were carried out on an installation, the working part of which consisted of an annular channel with an inside diameter of 0.22 m, an outside diameter of 0.34 m, and a length of 0.5 m. Swirled air streams entered the working section from two coaxial chan-

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