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MECHANICS

Stabilization of the Wake behind a Circular Cylinder that Performs High-Frequency Angular Oscillations

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The effect of stabilization of the wake behind a circular cylinder in a laminar flow of viscous incompressible fluid at a high frequency of angular oscillations of the cylinder, which was observed in experiments by Taneda, is reproduced numerically. Mechanisms of holding the stabilized flow mode are considered. A new gridless numerical method of viscous vortex domains (VVD) is used.

It is known that, upon placing an immobile circular cylinder in a uniform flow of a viscous incompressible fluid in the range of Reynolds numbers $\mathrm{Re} = DV_\infty/\nu$, the wake has a regular form of the Karman track with oscillation frequency $f_0 = \mathrm{Sh}V_\infty/D$, where $D = 2a$ is the cylinder diameter and Sh is the Re-dependent Struchal number. In experiments [1], the effect of frequency f and amplitude θ_0 of forced angular oscillations of the cylinder on the flow structure was investigated at Re = 30–300; in this case, the amplitude of angular deviations $\theta(t) = \theta_0\sin(2\pi ft)$ varied in the range $0 < \theta_0 < 90°$, while the relative frequency of forced oscillations f/f_0 reached 20 and more. Precisely at such a high oscillation frequency, the track vibrations stopped in experiments [1], while the flow pattern acquired the form of flow around the cylinder by an ideal fluid without separation. In other experimental [2–4] and numerous computational studies, for example, [5–8], parameter $n = f/f_0$ was not larger than five. In these studies, primary attention was paid to another interesting effect, which is associated with the so-called frequency capture, when in vicinity $f \sim f_0$, track oscillations synchronize with forced oscillations with the accompanying abrupt increase in the medium resistance of the cylinder. In the theoretical study [9], the effect of the high frequency of angular oscillations of the cylinder on the structure of an unsteady boundary layer was considered. However, in this case, the steady-state distributions of velocity and pressure corresponding to the ideal flow around the cylinder without separation were postulated a priori out of the boundary layer on the cylinder. Therefore, the effect of stabilization of the track behind the cylinder under high-frequency oscillations found in experiments [1] was not reproduced or investigated numerically for a long time (comments for this item are given in [10]).

The absence of published data on the numerical modulation of experiment [1] can be associated with difficulties in calculation of the flows requiring high resolution of the spatial and time structure of the boundary layer. In particular, the cause can be the instability of numerical schemes, which is inherent to many methods in the solution of the problems with a sufficiently high value of the local Reynolds number as well as the notions on the insufficient practical significance of the stabilization effect at the frequency of forced oscillations of the cylinder so high as in experiments [1]. However, the numerical reproduction of this effect is of interest both for understanding of the physical cause of the phenomenon and for verification of possibilities of numerical methods.

STATEMENT OF THE PROBLEM

Before the initial point of time $t = 0$, the circular cylinder rests in an infinite space of an immobile incompressible viscous fluid. At $t > 0$, the cylinder moves so that its symmetry axis moves with a constant velocity in the direction perpendicular to the axis, while its surface executes harmonic angular oscillations with respect to the symmetry axis with a specified frequency and amplitude. The Reynolds number calculated by the motion velocity of the cylinder axis and its diameter Re = 111. This value was selected as the

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basis one for comparison with the results of study [1]. The fluid flow perturbed by the cylinder is described by unsteady two-dimensional Navier–Stokes equations, the boundary conditions on the cylinder surface are the adherence conditions by essence, and the conditions of degeneracy of perturbations are stated for infinity.

COMPUTATION PROCEDURE

Computations are performed by a gridless VVD method [11–14]. This method is characterized by the following common positive properties of vortex Lagrangian methods such as the absence of problems associated with the statement of boundary conditions for infinity, stability of a numerical scheme, and conservation of exactness of solutions for the features of the flow field and geometry of flown bodies arbitrarily varying in time. The latter circumstance is provided by the fact that mobile computational vortex elements self-organize and concentrate in high-gradient regions thereby automatically providing a high degree of resolution. The method possesses a low schematic viscosity [13], which makes it possible to carry out the calculations for large values of the Reynolds number.

In computations by the VVD method, the primary desired value is the vorticity field, evolution of which is governed by the Navier–Stokes equations. By this field, using the corresponding rigorous integral procedures, the velocity and pressure fields are determined [11]. The vortex particles are generated in the nodes of the body contour and further move in space retaining their circulation invariable with the velocity provided satisfying the laws of convective transfer and diffusion of the vorticity field according to the Navier–Stokes equations. An effective modification of the high-productivity algorithm of a rapid method for computation of the vector field of the fluid flow velocity is developed for the presence of a large number of discrete vortex elements in space [14].

RESULTS OF COMPUTATIONS FOR Re = 111, $\Theta_0 = 45°$

In the absence of forced oscillations ($f = 0$), a nonsteady wake with the Struchal characteristic number Sh ≈ 0.17 is formed behind the cylinder. As parameter $n = f/f_0$ increases from 0 to 10, the hydrodynamic wake behind the cylinder remains nonsteady. In this case, the average extension of the region of recircular flow behind the cylinder remains at the level of $4a$ until $n \approx 10$; however, the rate of the return motion substantially decreases. Thereby, at $n > 11$, the nearby wake behind the cylinder already does not contain the region of the return motion, and its stabilization takes place.

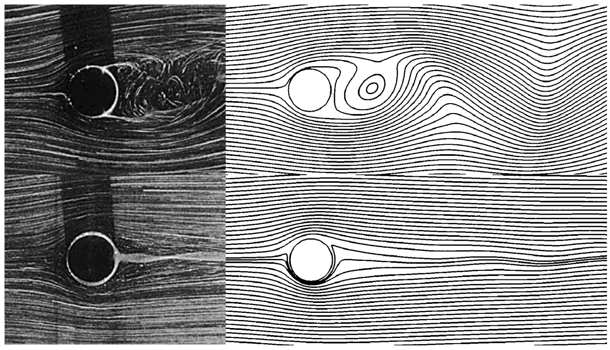

Fig. 1. Flow of the immobile cylinder (at the top) and the cylinder performing angular oscillations (at the bottom) at Re = 111, $\theta_0 = 45°$, and $n = 20$; the experiment [1] is to the left.

As parameter n increases, an abnormal mode of a substantial increase in the amplitude of vibration oscillations of the wake was observed in region $n \approx 1$. This increase is accompanied by complication of the vortex structure of the flow in the bottom region immediately behind the cylinder as well as by a considerable increase in the amplitude of vibrations and average value of the resistance coefficient of the cylinder. This phenomenon is associated with the above-mentioned capture effect of the frequency; it was investigated in detail in many experimental and computational works [2–8, etc.].

The patterns of instant current lines near the cylinder, which is immobile and oscillating with a high frequency, agree well with each other; see Fig. 1.[1] At $n = 20$, the wake appears stable; however, in a narrow layer near the cylinder surface, the particles of the fluid are entrained by the rotation of the surface; therefore, the flow is nonsteady. To understand the mechanism of stabilization of the wake, it is necessary to consider the processes in this layer.

Figure 2 represents the current lines and corresponding distributions of Lagrangian vortex particles at different phases for the same period of high-frequency oscillations of the cylinder for the stabilization mode. Black points imagine the vortex particles with a negative circulation (with the clockwise direction of rotation), and bright points, with positive circulation. It is evident that the near-wall layer on the cylinder has the structure of alternating rings of positive and negative vorticity.

The mechanism of stabilization of the wake under high-frequency oscillations of the cylinder can be represented as follows. At a half-period of the counterclockwise rotation of the cylinder, there are the stages

[1] Here and below, the flow patterns are represented in the coordinate system associated with the cylinder axis.

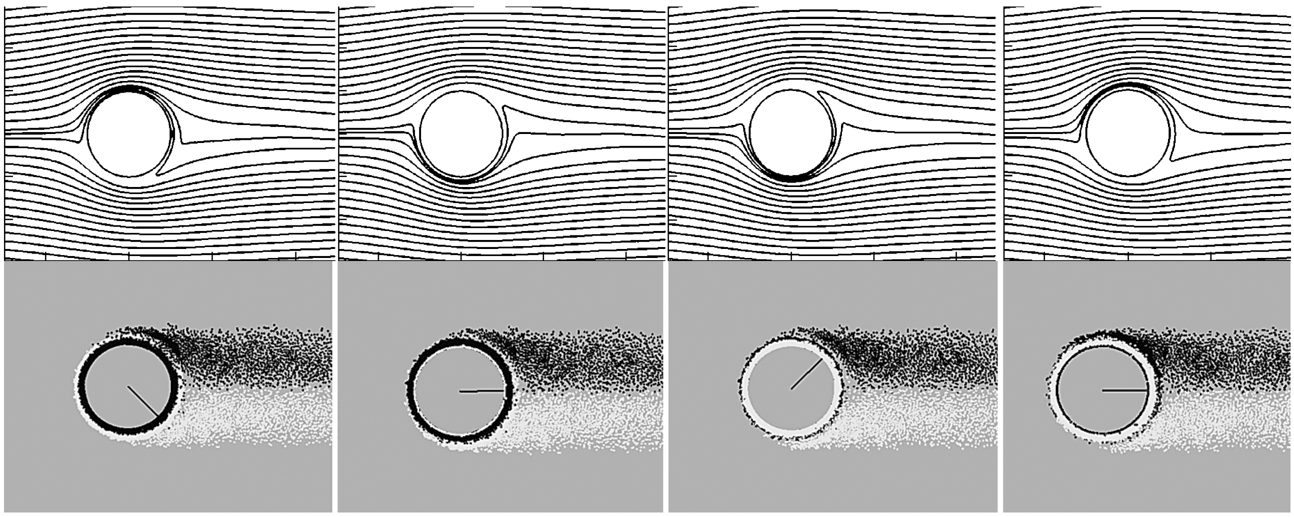

Fig. 2. Lines of the current and distribution of Largangian vortex particles near the cylinder at different stages during the period of forced angular oscillations of the cylinder.

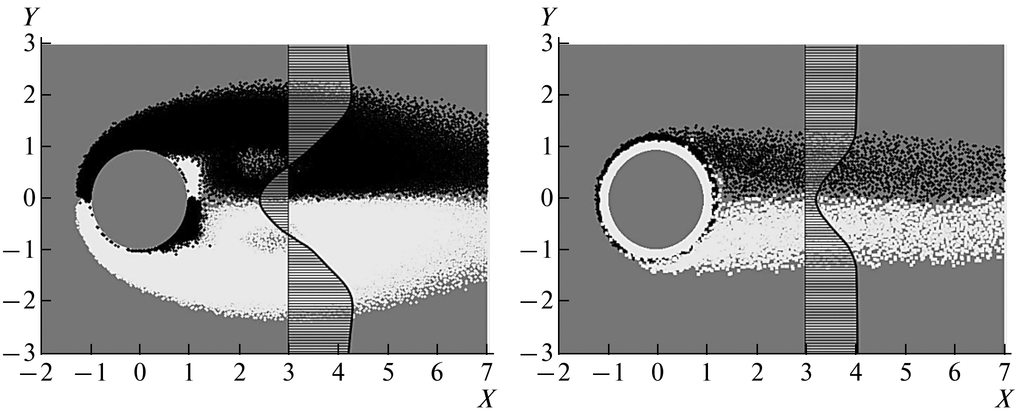

Fig. 3. Velocity profiles behind the immobile (to the left) and oscillating (to the right) cylinders during the initial period of formation of the wake.

of accelerating and retardating motion, respectively, and initially negative and then positive vorticity is generated over the cylinder surface. Similarly, generation of two rings of alternating-sign vorticity under the rotation of the cylinder to the opposite direction takes place. Diffusion and annihilation of opposite vortexes in the vicinity of the boundaries between the neighboring rings leads to their mutual weakening. As a result, from the boundary layer on the rapidly oscillating cylinder, the fluid, which is substantially less eddying than in the case of an immobile cylinder, is entrained into the outer flow.

The aforesaid is confirmed by the comparison of the flows at $n = 0$ and $n = 20$ at the point of time $t = 12a/V_\infty$ at the initial segment of the motion when the flow behind the nonoscillating cylinder still retains the initial symmetry. In Fig. 3, against the background of Lagrangian vortex particles, the corresponding profiles of the longitudinal velocity in the transverse section of the wake at a distance of one caliber behind the cylinder are constructed. In the case $n = 0$, the velocity on the symmetry axis is directed to the side opposite to the velocity of the incident flow, i.e., the reverse flow occurs, while at $n = 20$, no reverse flow is observed. The difference in velocities on the wake axis and out of it in the same section characterizes the linear density of circulation. It is considerably higher in the case of the nonoscillating cylinder.

Both profiles of the longitudinal velocity on the wake have inflection points (Fig. 3), which should lead to instability of the flow. However, instability of the wake behind the oscillating cylinder is developed more slowly because of its lower intensity; therefore, it appears stable for a considerable distance from the cyl-

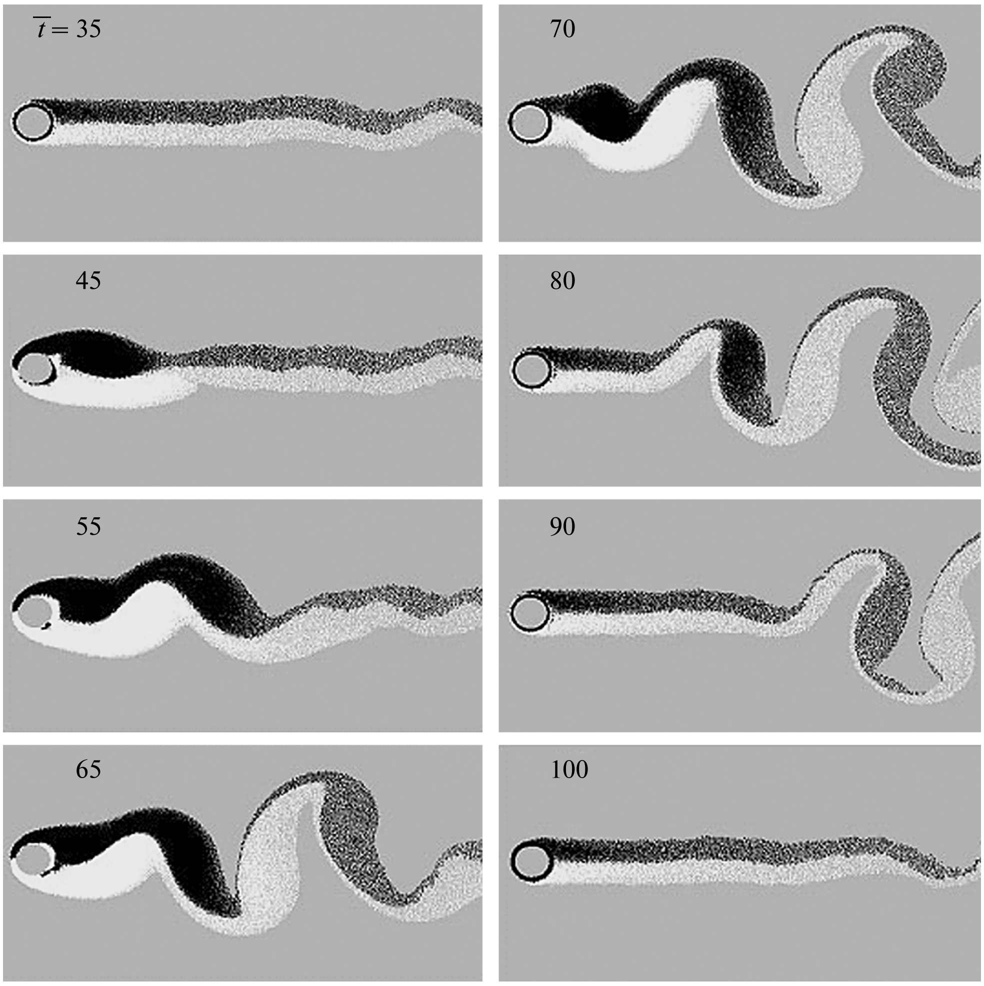

Fig. 4. Evolution of the wake after stopping (to the left) and after resumption (to the right) of forced oscillations of the cylinder.

inder although transverse long-wavelength oscillations of the wake nevertheless appear with time at large distances downstream (Fig. 1).

In conclusion, let us present the results of the computational experiment, in the course of which, the "switching off" and repeated "switching on" of forced high-frequency oscillations of the cylinder takes place:

$$n(t) = \begin{cases} 20, & 0 < \dfrac{t}{t_0} < 35; \\ 0, & 35 < \dfrac{t}{t_0} < 66; \\ 20, & \dfrac{t}{t_0} > 66; \end{cases}$$

$$t_0 = \frac{a}{V_\infty}.$$

Some of the obtained flow patterns at different points of time are presented in Fig. 4. After finishing the oscillations, intense vortical layers start to come out of the cylinder surface. Losing stability, they gradually acquire the form of a Karman vortex track. After renovation of high-frequency oscillations, the intensity of vortex layers coming out into the flow abruptly decreases and the vortex track formed previously gradually moves downstream.

Therefore, the experimentally found effect of stabilization of the wake after the rapidly oscillating cylinder [1] is explained by the effect of mechanisms of diffusion and annihilation of the vortexes in thin concentric layers of the alternating-sign near-wall vorticity. To reproduce these mechanisms in the computational experiment, it is necessary to provide high resolution of the vorticity field in the near-wall region and stability of the computational circuit with respect to abrupt gradients of the strength of this field. A new numerical method of viscous vortex domains [11–14] applied by us satisfied the listed requirements, and using it, we succeeded in reproducing the effect of stabilization of the wake behind the circular cylinder performing high-frequency rotational oscillations.

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