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NUMERICAL ANALYSIS OF THE MECHANISM OF DECREASING THE FRONTAL RESISTANCE OF THE ROLLING WHEEL BY GENERATING A CIRCULAR VORTEX IN FRONT OF IT

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In solving nonstationary Navier–Stokes equations by the factorized finite-volume method, we analyze the vortex mechanism of decreasing the drag of a rolling circular cylinder by generating a vortex in front of it due to the rotation of a small-diameter cylinder.

The problem of decreasing the drag of a wheel rolling on a plane is topical, in the first place, for sports cars, in particular, bolides, participating in the "Formula 1" rallies. The frame of such apparatuses is perfect from the point of view of aerodynamics, and the dominating contribution to their drag is made by the wide tires of the wheels. The present paper analyzes, on the basis of the solution of the model problem on the laminar flow along two equal rotating circular cylinders in the vicinity of a movable flat screen, the vortex method of decreasing the rolling resistance of a large-diameter cylinder representing a simplified model of a wheel. The front cylinder with a small diameter (Fig. 1a) is considered as a vortex generator or as a model of a blown swirling jet, and the system in general is analogous to blunt bodies arranged in tandem. As it has been shown, e.g., in [1–3], the organization of a large-scale vortex in the clearance between disks or between a disk and the coaxial cylinder makes it possible to considerably decrease the traction resistance of bodies and also leads to the appearance of a significant restoring moment (front stabilization effect).

In the last decade, a number of methods for controlling the flow past bodies by means of jet and vortex generators, whose application promotes an improvement of the aerodynamic characteristics of objects, have been investigated. For instance, placing vortex cells in the outline of the thick airfoil section provides its flow without separation and makes it possible to decrease the drag, increase the lifting force, and upgrade the aerodynamic quality [4–6]. Blowing on the side surface of an aerodynamic cylinder in the generation of jets, in particular, due to the throttling effect when the medium is transferred from the high-pressure zones to the near-wake region, considerably decreases the alternating loads on the body [7–9]. And, finally, the creation of a vortex layer in the vicinity of the dimpled relief can decrease the drag of a curvilinear wall [10]. Thus, the use of the vortex mechanism for decreasing the rolling resistance of the wheel appears to be fairly promising.

The methodological basis for solving the problems, both the stated one and those considered in [4–10], is the multiblock computational technologies of solving Navier–Stokes and Reynolds equations developed in the last decade [11, 12]. Their advantage is the application of block structured meshes of simple topology with partial overlap, which makes it possible to not only simulate the medium flow in multiply connected regions of complex curvilinear geometry without introducing wash errors, but also correctly resolve structural flow elements of different scales on specially introduced meshes of an adequate scale. The developed approach is analogous in accuracy to the application of nonstructured meshes adapted to the solution of a problem, but is much more economical than the latter. The nonstationary Navier–Stokes equations written in increments for natural variables on each mesh introduced are solved by the factorized finite-volume method in terms of the concept of splitting into physical processes realized in the procedure

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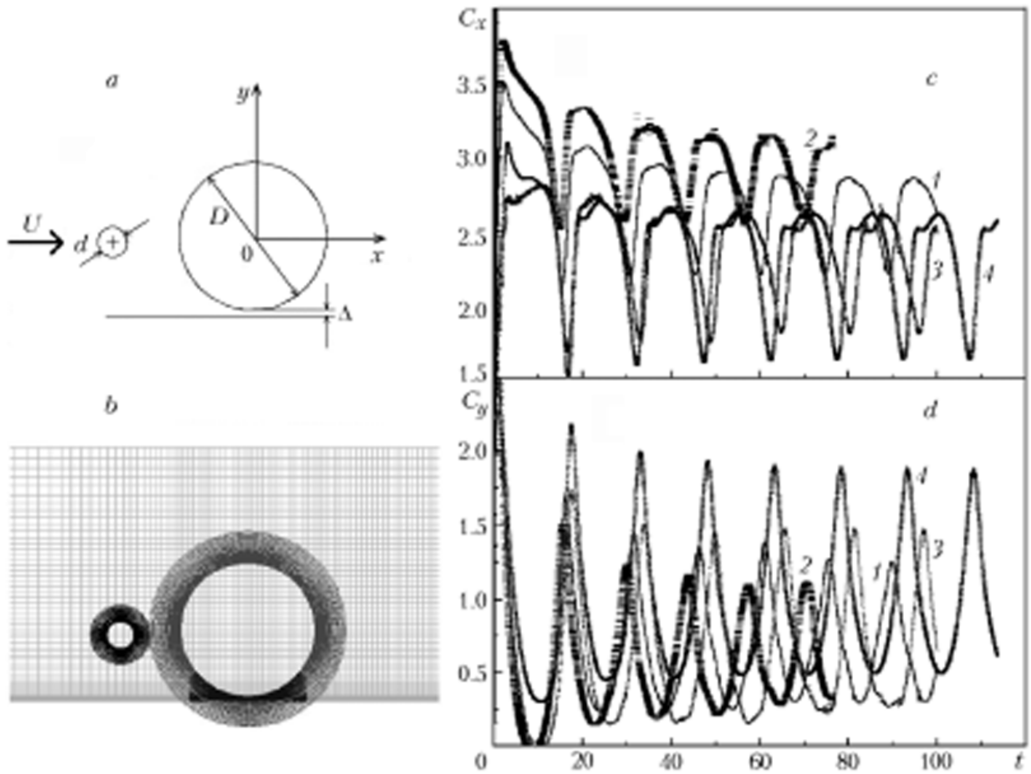

Fig. 1. Scheme of the flow along a rotating circular cylinder in the presence before it of a vortex generated by the rotation of a small cylinder (a); multiblock calculation mesh (b); time dependences of the drag coefficient (c) and the lift coefficient (d): 1) without the front body; 2) clockwise rotation of the front cylinder; 3) same, counterclockwise rotation at $x_f = -1.2$; 4) same, counterclockwise rotation at $x_f = -0.95$.

with global iterations, whose kernel is the SIMPLEC pressure correction [1–15]. To decrease the influence of numerical diffusion in calculating flows with large-scale vortex structures, the convective terms in the implicit part of the transfer equations are given in the counterflow scheme with quadratic interpolation. Test calculations of the nonstationary flow past a circular cylinder [11–15] point to the acceptability of the implicit Euler scheme, for approximating the nonstationary term, and of linear interpolation for determining the parameters in the near-boundary cells of block meshes. Global iterations at each time step terminate as soon as convergence of the fields of dependent variables with a given acceptable accuracy is reached.

The laminar nonstationary flow of an incompressible viscous liquid along rotating equal circular cylinders in the presence of a movable screen is considered at Reynolds number Re = 150 in a two-dimensional statement. The Reynolds number is determined by the characteristic scales of the problem — the rate of steady flow at the inlet to the calculation region U and the diameter of the larger cylinder D. The value of the Reynolds number is chosen from the condition of acceptability of using the two-dimensional model of [13]. All geometrical parameters pertain to D and velocity components pertain to U. The rate of motion of the screen is equal to 1, and the relative clearance $\Delta = 0.04$. The relative diameter of the front circular cylinder is taken to be equal to $d = 0.2D$, its center coordinates are $x_f = 1.2$ and 0.95, $y_f = 0.5$, and the clockwise and counterclockwise rotation velocity is 25 (and the tangent velocity component on the airfoil outline is given to be equal to 2.5). The circular cylinder in the presence or absence of a front cylinder is located in rectangular calculation regions with sizes 56.2×16.2 and 31.2×11.1 at a distance from the input boundary equal to 10.6 and 5.6, respectively. At the input to the region the uniform flow parameters were registered, and at the output and the upper boundary "soft" boundary conditions corresponding to quadratic extrapolation of the parameters to the boundaries were given. The relative velocity components on the rotating cylinder and the movable screen are equal to 1.

TABLE 1. Integral Aerodynamic Characteristics of the Circular Cylinder Averaged over the Oscillation Period of C_y

Aerodynamic characteristic	Configuration of bodies		
	without front body	$x_f = -1.2$	$x_f = -0.95$
C_x	2.64	2.32	2.31
C_y	0.7	0.68	0.98

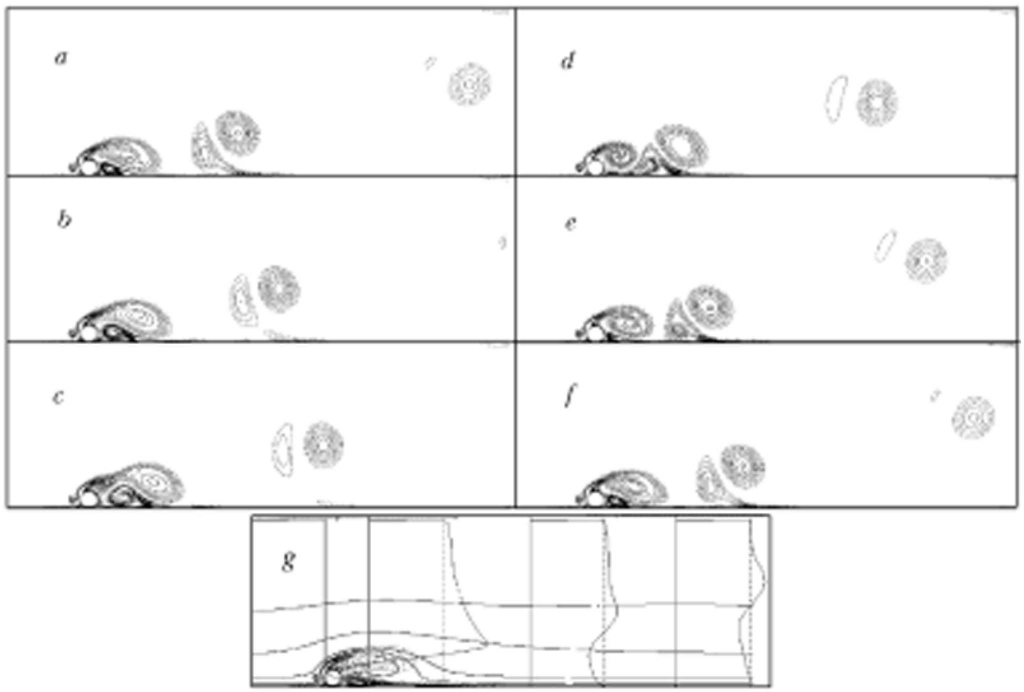

Fig. 2. Evolution of the pattern of constant vorticity values given with a 0.5 step from –5 to 5 on the oscillation period of C_y in flowing along a circular cylinder with a rotating small-diameter cylinder for $x_f = -0.95$; $y_f = 0.5$; a) $t = 130.8$; b) 133.8; c) 136.8; d) 139.8; e) 142.8; f) 145.6; g) pattern of the vorticity field averaged over the period $C_y(t)$ with streamlines and profiles of the longitudinal velocity components. Vertical dotted lines show the unit level of

The multiblock calculation meshes consist of intersecting rectangular and cylindrical meshes (Fig. 1b). The main rectangular meshes contain 150 × 80 and 190 × 100 cells, respectively, for regions with a smaller and a greater detailing of the flow vortex. The circular cylinder is surrounded by a circular zone of width 0.2, which was covered with a cylindrical mesh (40 × 120 cells). To describe the flow in the clearance between the circular cylinder and the wall, a special curvilinear mesh containing 1760 cells is introduced. The size of the near-wall width is given to be equal to 10^{-4} and 10^{-3} for the two considered multiblock meshes. The small-diameter cylinder is also surrounded by a circular mesh containing 2673 cells. The time step was chosen to be equal to 0.01. The solution of the problem was carried out from the moment of sudden onset of motion to the moment the self-oscillation mode of flow along the cylinder or the system of cylinders became steady.

Figures 1 and 2 and Table 1 present some of the numerical results obtained. Figure 1a, d compares the results of the numerical simulation of the flow along a circular cylinder in the absence (curves 1) and presence of the clockwise (curve 2) and counterclockwise (curves 3, 4) rotating small-diameter cylinder, and the latter therewith is located near the body (curves 4) and at a distance from it (curves 3). In all cases, a cyclic process of flow along the cylinder develops, as is shown in Fig. 2 for one of the considered cases. The initial instant of time $t = 130.8$ corresponds to the minimum value of C_y.

Particular consideration was given to the averaging of the periodic process, as was done in [13–15]. The procedure of determining the mean value of a parameter on the basis of its extreme values estimated by the superposition of instantaneous temporal distributions of values on the oscillation period of the lifting force is used. First the maximum and minimum values (g_{max} and g_{min}) of the oscillating characteristics are determined. The the mean values of these characteristics are calculated as $\bar{g} = \left(|g_{max}| + |g_{min}| \right)/2$. Figure 2g and Table 1 show the local and integral characteristics — the drag coefficient C_x and the lift coefficient C_y — averaged over the oscillation period of C_y.

As is seen from Figs. 1, 2 the self-oscillation regime of the flow along a rotating cylinder in the presence of a movable screen differs considerably from the analogous regime of flow along a circular cylinder in a space unbounded by walls [13]. A vortex train develops in the near-wall region representing a system of two vortices with opposite vorticity with gradual decay with time of their intensity. A pair of vortices arises from the aggregation of vorticity bunches differing in sign and value. The separating intensive primary vortex behind the rotating cylinder interacts with the nonstationary secondary near-wall vortex of lower intensity. As a result, the vortex pair formed separates from the wall and, following a path close to a linear one, is carried downstream over the wall. It should be noted that the rotation of the front small-diameter cylinder does not change qualitatively the pattern of the vortex dynamics but influences the intensity of the vortex system formed. Thus, the clockwise rotation of the front cylinder leads to an increase in the drag of the rear circular cylinder, and a change in the direction of the flow swirl, on the contrary, promotes its decrease. A decrease in the distance between the cylinders at a fixed position of the cylinder of diameter D produces a strong effect on the lift coefficient C_y, and the drag coefficient C_x therewith remains unaltered. As follows from Table 1, the generation of the first vortex may lead to a decrease in the drag coefficient by 12%. It should be noted that the Strouhal number equals 0.07 and is 2.5 times smaller than in the case of the flow along a circular cylinder in an unbounded space.

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NOTATION

C_x, drag coefficient (in fractions of dynamic pressure $\rho U^2/2$); C_y, lift coefficient (in fractions of dynamic pressure $\rho U^2/2$); D, cylinder diameter, m; d, diameter of the small cylinder (in fractions of D); g, dependent variable; Re, Reynolds number (Re = $\rho UD/\mu$); t, time (in fractions of D/U); U, uniform flow rate, m/sec; x and y, horizontal and vertical coordinates (in fractions of D); Δ, clearance between the cylinder and the plane (in fractions of D); μ, coefficient of dynamic viscosity, kg/(m·sec); ρ, density, kg/m^3. Subscripts: f, position of the center of the front cylinder; max, min, maximum and minimum values.

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