Journal of Engineering Physics and Thermophysics, Vol. 73, No. 3, 2000

NUMERICAL ANALYSIS OF THE INFLUENCE OF ROTARY REAR CYLINDERS ON A NONSTATIONARY WAKE BEHIND AN ELONGATED BODY

P. A. Baranov, S. A. Isaev, and A. E. Usachev

UDC 532:517.2

The influence of rotary rear cylinders on a nonstationary wake behind a rounded-off plate is analyzed numerically based on the solution of nonstationary Navier–Stokes equations on multiblock computational grids by the finite-volume method. It is shown that the von Kármán vortex trail, which develops behind the body to the point of formation of a virtually steady jet flow, substantially weakens as the rotational velocity of the cylinders increases.

1. One of the topical trends in modern aerohydromechanics is associated with the organization and control of flows, including flows past bodies of different geometry. Passive and active (with energy losses) means of affecting flows are distinguished (a brief classification of them can be found in [1]). The formation of cavities and mounting of obstacles of different scales on bodies and in their vicinity should be referred to passive means. As a result, large-scale vortex structures, which are capable of radically changing flow past a body and considerably improving its aerohydrodynamic characteristics, are formed. Thus, for example, coaxial mounting of a thin disk in front of a cylinder with a flat end allows one, with a proper choice of geometric dimensions of the arrangement, to reduce the profile drag of this body at small subsonic velocities of an oncoming flow by about two orders of magnitude and to obtain a flow pattern typical of streamlined bodies [1].

A new impetus to the studies of flows past passively affected bodies is connected with recently studied caught vortices and vortex cells (see, e.g., [2]).

Generators of small-scale vortices are able to substantially change the character of flow in a wall layer of a streamlined body and, first of all, to reduce its friction drag [3]. Traditionally, longitudinal and transverse grooves on the surface of a body and wavy contours of a small amplitude are considered as these elements. Recently, great interest has been shown in compact generators of vortices that are periodically mounted on streamlined surfaces. These are, for example, delta notches (wind vanes) [4] and concavities (holes) of different depth and shape [5]. As a rule, their use enhances heat- and mass-transfer processes with a relatively smaller increase in the resistance to refrigerant motion.

Active means of affecting the flow are divided into two groups: without mass supply (or mass removal) and with mass supply. Most advanced are the studies in the second group of means of flow control [6]. Injection or suction of a gas through porous parts of a streamlined body are the acknowledged means of controlling the boundary layer. At the same time, blowing out of jets on the side surface or at the bottom of the body, which serves for creating control efforts to the object and decreases bottom drag, became widely known. It is also important to note the use of pulsating wall jets for producing periodic wave structures propagating along the body surface and leading to a decrease in friction on the wall [7].

A means of vortex organization which is close to those mentioned is connected with caught vortices generated in cells and cavities within the contours of bodies. However, the efficiency of the influence of passive vortex cells on the character of flow past a body is small; this is demonstrated, in particular, for a thick profile in [8].

Academy of Civil Aviation, St.Petersburg, Russia. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 73, No. 3, pp. 606-613, May–June, 2000. Original article submitted July 30, 1999.

Intensification of a circulating flow in cells made it possible to solve the problem of control of flows past bodies until a nonseparating flow mode is formed. In [9], a reduction in the body drag due to the generation of a pulse within vortex cells is shown using numerical simulation of laminar flow past a transverse cylinder as an example.

In a turbulent mode of flow past a transverse cylinder with vortex cells, for enhancement of circulating flow, use is made of liquid suction through central bodies of the cells [10]. The mechanism of enhancement and the influence of the position of the cell on the body contour and the intensity of suction on a change in the drag of the cylinder and its components are analyzed in detail [11]. A considerable reduction in the drag and a decrease in the dimensions of the near wake behind the cylinder are revealed.

The concept of controlling the flow by active vortex cells lying within the contour of the body is successfully used for realization of nonseparating flow past a thick profile [12], which is the model of a promising aircraft of a "flying wing" type.

The flow in a vortex cell can be intensified without mass supply in rotation of a cylinder in the cell. It is of interest to note that attention to rotary cylinders partially submerged in the body arose regardless of the vortex cells. Thus, for example, a rotary cylinder with a cut was used to generate nonstationary vortex structures drifting along the body surface and causing alternating local loads on it. In [13], this motion of large-scale vortices was calculated in a test version for longitudinal flow past a cylinder. An experimental study of flow past bodies of different geometry with mounted rotary cylinders [14] showed the possibility of eliminating the nonstationary character of this process and reaching a stationary mode with a rather high angular velocity.

This study is an extension of [15], where an efficient computational method was developed and a numerical experiment on the effect of the vorticity, produced by the passive and active vortex cells of various scales mounted in the body, on a nonstationary wake behind a circular cylinder was conducted. Here, elongated two-dimensional bodies and, in particular, a plate with a rounded-off nose part and with rear vortex cells are considered.

2. The computational algorithm used is based on a generalized procedure of global iterations which is intended for solving the Navier–Stokes equations by the finite-volume method [15] on multiblock crossing O-type grids. The system of initial equations is written in divergent form for increments in covariant velocity and pressure components in curvilinear nonorthogonal coordinates. This approach, as has already been mentioned in [10], is characterized by more rigorous representation of flows through the edges of computational cells. In approximation of the source term which involves, for the case of a nonstationary problem, a time derivative of the dependent variable, the convective flows were calculated by a one-dimensional countercurrent scheme of square interpolation suggested by Leonard [1]. It should be noted that the Leonard scheme must be applied to the Cartesian velocity components rather than to covariant ones; otherwise the violation of the test of a "uniform flow" is possible.

At each time step the computational procedure is based on the concept of splitting by physical processes, which is realized in the SIMPLEC procedure of pressure correction. Typical features of the considered iterative algorithm are the determination of preliminary velocity components for "frozen" pressure fields at the "predictor" step and subsequent correction of pressure on the basis of the solution of the continuity equation with velocity-field corrections. The process of calculation is constructed so that several local iteration steps in the block of pressure correction fall at one "predictor" step. The computational procedure also involves the interpolation block of the determination of dependent variables in the zones of overlapping of the subregions. The details of the procedure are given in [15].

3. A purposeful effect of artificially generated vorticity on the nonstationary flow in the wake behind an elongated two-dimensional body was exerted on a plate with a rounded-off nose part and two rear circular cells with a diameter of 0.4 (Fig. 1a). The rotary cylinders with a diameter of 0.32, the rotation direction of which agrees with the direction of flow past the plate, are placed in the cells. In this problem, the thickness of the plate and the velocity of the oncoming flow are taken to be the scales in nondimensionalization.

To solve the problem of laminar nonstationary flow of a homogeneous incompressible viscous fluid past the considered body for a more accurate resolution of different-scale structural elements, it is appropriate

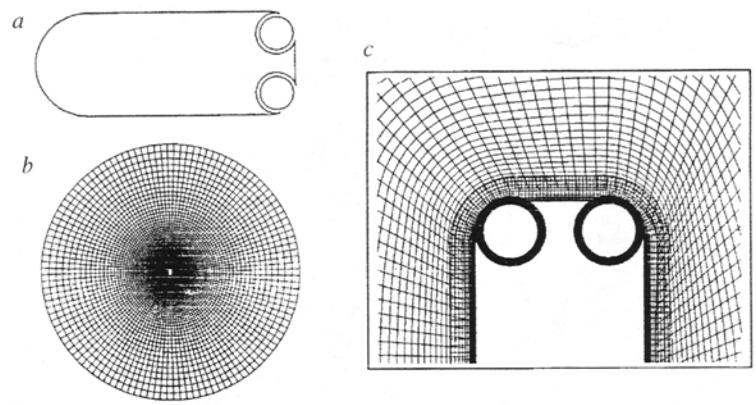

Fig. 1. Schematic of the object (a), computational grid (b), and its fragment (c) for numerical simulation.

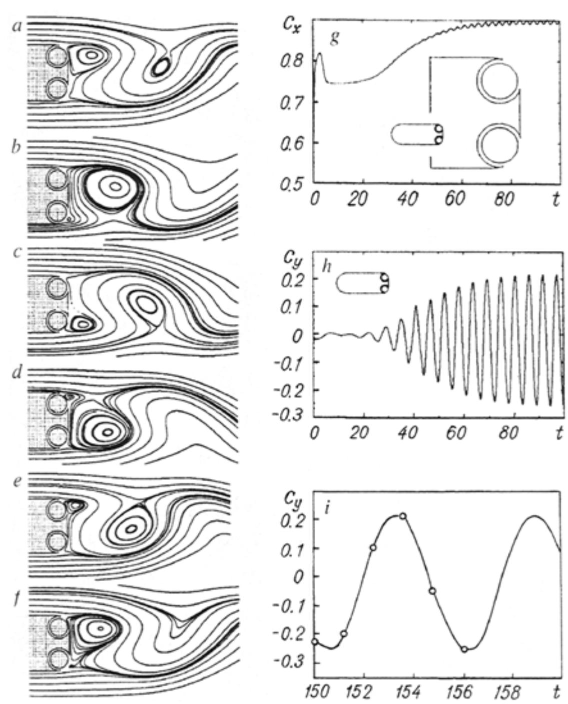

Fig. 2. Patterns of vortex flow in the near wake of a plate with passive cells in a self-oscillating mode (a-f) which correspond to the instants t = 150, 151.2, 152.4, 153.6, 154.8, 156; C_x (g) and C_y (h) as functions of time and the behavior of C_y (i) in a self-oscillating mode at the specified instants.

to separate a near-wall region of a thickness of 0.15 of the cylinder diameter and a peripheral annular zone whose external boundary lies at a distance of 40 diameters from the body (Fig. 1b). The introduction of several annular zones is connected not only with acceleration of the convergence of problem solution due to the reduction in the required number of computational cells, but also, and what is more important, with adjustment of the local grid to the characteristics of the represented structural element of the flow: a boundary layer in the cylinder surface, return flow in the wake, and flow past the body at a large distance from it. The number of nodes in the external zone is taken equal to 80 × 120 and in the near-wall zone 17 × 200. The pitch at the wall is 0.002. The Reynolds number is 250. The system of equations is integrated with the dimensionless-time step Δt = 0.02.

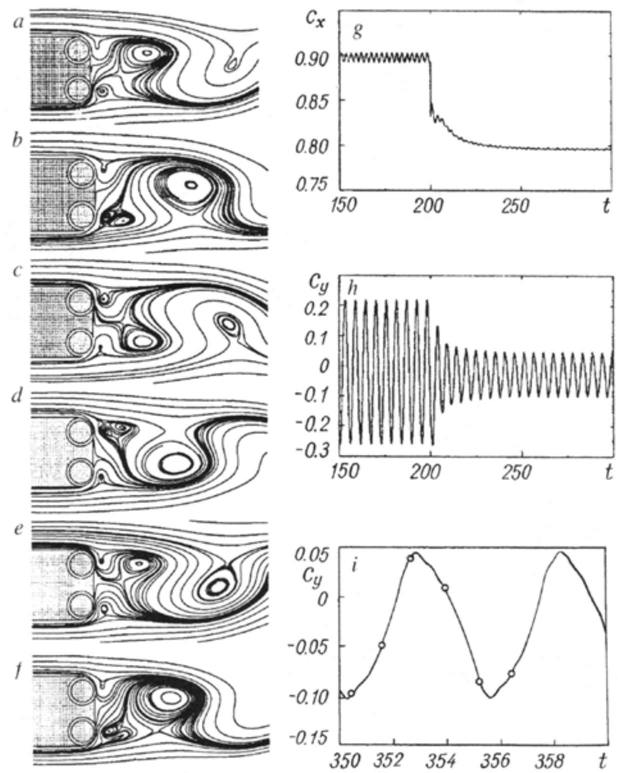

Fig. 3. Patterns of vortex flow in the near wake of a plate with active cells at U_t = 0.5 in a self-oscillating mode (a-f) which correspond to the instants t = 350.4, 351.6, 352.8, 354, 355.2, 356.4; the evolution of C_x (g) and C_y (h) in time and the behavior of C_y (i) for the plate with active cells at U_t = 0.5 in a self-oscillating mode at the specified instants.

The flow in the wake behind the cylinder is affected by vortex cells, the configuration of which with the grid structure used is shown in Fig. 1c. Inside the vortex cells, the grid is constructed uniformly in the circumferential and radial directions. Thirteen nodes are selected along the radius. The cut of the cavity has 21 nodes. The total number of points in the circumferential direction is taken from the condition of constancy of the angular step. The tangential velocity component U_t on the central body of the cell varies from 0 (a passive cell) to 5.

Figures 2-4 give some of the results obtained.

As is seen from Fig. 2, in flow of a viscous incompressible fluid past a rounded-off plate with passive rear cells (U_t = 0) at Re = 250, the self-oscillating mode of the flow in the wake reaches a steady state that is similar to laminar flow past a transverse cylinder (the Strouhal number Sh = 0.185), which was described earlier in [15]. This mode develops successively through the stages of formation of a symmetric vortical wake and loss of its stability.

The evolution of vortex structures in the near wake behind the body, including the case of the influence of vorticity generated by rotation of cylinders in vortex cells, is the central point of this study. Interest in it in analyzing flows past a body which have a cyclic character (at $U_t < 2$) should be particularly emphasized. Therefore, several vortex patterns within the recurrent cycle that correspond to the points plotted on the graphs $C_y(t)$ are presented for each mode of flow which differs in the degree of influence on the near wake.

For a body with passive vortex cells, the cyclic character of generation and descent of large-scale vortices comparable with the thickness of the plate is similar to that behind the circular cylinder. The interrelation between the evolution of vortex structures and the behavior of the coefficient of normal force $C_y(t)$ is of interest. Extrema of C_y appear at the instants when a large-scale vortex attached to the body completely covers its

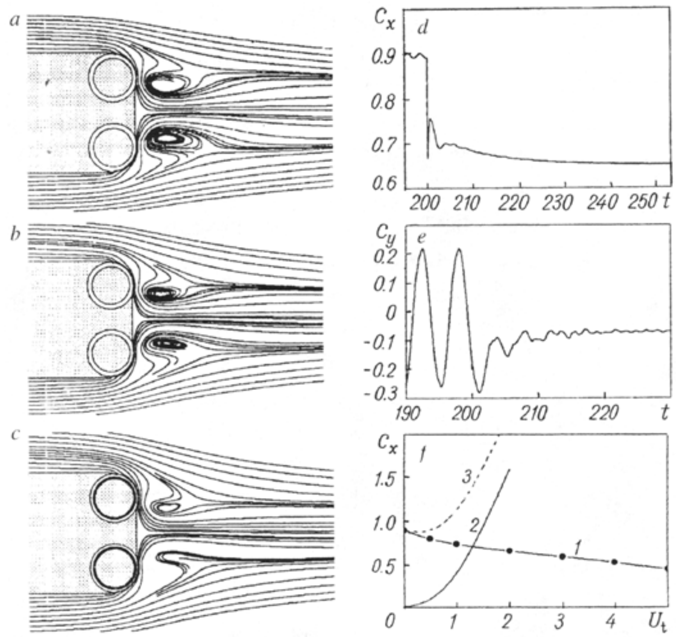

Fig. 4. Patterns of a steady-state vortex flow in the near wake of a plate with active cells at U_t = 3 (a); 4 (b); 5 (c); the evolution of C_x (d) and C_y (e) in time for the plate with active cells at U_t = 2 starting with the self-oscillating mode at U_t = 0; C_x of the plate with vortex cells (f) as a function of the rotational velocity of central bodies (1) with allowance for equivalent drag due to energy losses (2); dashed line 3 shows the total drag.

rear part and has, correspondingly, the highest rate (Fig. 2f and d). Naturally, the sign of C_y is defined by the direction of flow rotation in the generated vortex. The sign of $C_y(t)$ changes upon full detachment (separation) of the mentioned large-scale vortex (Fig. 2e). In this case, the vortex of opposite sign, which arises alternately from above and from below, picks up force.

The rotation of cylinders built into the circular cells leads to the enhancement of flow circulation in them and generation of vorticity within the wall jets in the rear part of the plate. As a result, at low rotational velocities there arises an ordinary cyclic self-oscillating process with a vortex trail displaced from the body because of the interaction of the indicated jets in the symmetry plane of the plate. It is significant that these jets are responsible for the formation, near the vortex cells, of the vortices of opposite signs which disagree with the direction of the main flow.

At U_t = 0.5, as can be seen from Fig. 3i, extremum values of $C_y(t)$ are also reached with the maximum sizes of large-scale vortices developing in the space behind the rear cut of the plate (Fig. 3a, c). However, in contrast to the situation with passive cells, these vortex structures have half as large a transverse size.

One more unusual feature is the evolution of vortex patterns, which manifests itself with increase and decrease in the coefficient of normal force and is associated with the formation of a "suspended" pair of vortices in certain periods of time (Fig. 3b, d, f). The reason for the formation of such a strange, at first glance, configuration is explained by the generation of vortices entering the von Kármán trail and the time connection of them with the above-mentioned vortices generated by the rotary cylinders. The complex character of the vortex pattern of flow in many respects depends on the fact that forming and then disappearing vortices are relatively weak.

Figure 3 shows the transient character of change in integral forces affecting the plate in enahncement of the flow in vortex cells. In this case, the amplitude of oscillations C_x nearly vanishes, and C_y decreases threefold with respect to the initial levels which are characteristic of flow past a body with passive vortex cells.

An increase in the rotational velocity of the cylinders U_t to unity noticeably stabilizes the pattern of the flow immediately behind the rear part of the plate, thus sharply enhancing large-scale vortices generated by the wall jets. They acquire a stable character, and the vortex trail moves aside still farther from the body. The extrema of $C_y(t)$, as before, are connected with the formation of vortices of the largest transverse sizes in the vicinity of the body; however, in this respect these vortices are noticeably inferior to similar vortex structures at smaller rotational velocities U_t. Although the flow behind the plate has a distinct periodic character, the behavior of $C_y(t)$ represents a dependence that is far from being sinusoidal, which is due to the considerable influence of the jet flow on the source side of the rear part of the plate on the development of the vortex wake.

At rotational velocities exceeding 2, the flow in the wake behind the plate becomes virtually stabilized (Fig. 4) and acquires a jet character; all integral characteristics of the body cease to change with time. However, rear vortices, caused by the rotary cylinders, remain. As the rotational velocity increases, their intensity and transverse size gradually decrease. The observed dynamics is undoubtedly connected with the influence of induced turbulence on the regime of flow past a plate. It is obvious that the removal of the von Kármán trail in the near wake behind the rear part of the plate is caused by the generation of vorticity of opposite sign with respect to that which arises in a naturally formed shear layer.

In Fig. 4f, a decrease in the drag of the plate (curve 1) caused by the rotation of the circular cylinders in vortex cells is compared to the energy expenditure on attaining this effect. The additional drag force (curve 2) is estimated by proceeding from the calculation of the power applied to overcome friction forces on the rotary cylinders. As a result of analysis, we can assume that with a laminar character of flow (in our case, at Re = 250) the expenditure on realizing the effect of drag reduction and eliminating the von Kármán trail turns out to be very substantial. However, the existence of the optimum of the so-called reduced drag (curve 3) at small U_t is revealed. Moreover, we can assume that the mentioned features of the evolution of vortex structures under the effect of the generated turbulence on a nonstationary wake behind a body will also remain within the range of variation of the Reynolds number that is of practical interest.

The conducted numerical study of nonstationary flow past a plate with rear cylinders of a smaller diameter rotating within vortex cells showed that as the rotational velocity of the cylinders increases, the turbulence induced in the wake not only decreases the intensity of the vortices of the von Kármán trail but is virtually capable of eliminating the rear separation of the flow and stabilizing the flow in the wake, thus causing some reduction in the drag of the body.

The authors express their gratitude to G. Yu. Stepanov for assistance in the preparation of the paper.

This work was carried out with financial support from the Russian Fund for Fundamental Research (projects Nos. 99-01-01115 and 99-01-00772).

NOTATION

t, time; C_x, drag coefficient; C_y, lift (transverse) coefficient; U_t, tangential velocity on the rotary central body of the vortex cell; Re, Reynolds number; Sh, Strouhal number.

REFERENCES

1. I. A. Belov, S. A. Isaev, and V. A. Korobkov, *Problems and Methods of Calculation of Separated Incompressible Fluid Flows* [in Russian], Leningrad (1989).
2. A. V. Bunyakin, S. I. Chernyshenko, and G. Yu. Stepanov, *J. Fluid Mech.*, **358**, 283-287 (1998).
3. G. R. Hew (ed.), *Reduction in Viscous Friction* [Russian translation], Moscow (1984).
4. J. C. Han, J. J. Huang, and C. P. Lee, *Enhanced Heat Transfer*, **1**, No. 1, 37-52 (1993).
5. S. A. Isaev, A. I. Leont'ev, and A. E. Usachev, *Inzh.-Fiz. Zh.*, **71**, No. 3, 484-490 (1998).
6. P. Chang, *Control of Flow Separation*, Hemisphere (1976).
7. R. I. Soloukhin, B. A. Kolovandin, B. I. Puris, et al., in: *Processes of Turbulent Transfer* [in Russian], Minsk (1985), pp. 3-15.

8. S. A. Isaev, Yu. S. Prigorodov, and A. G. Sudakov, *Inzh.-Fiz. Zh.*, **71**, No. 6, 1116-1120 (1998).
9. P. A. Baranov, S. A. Isaev, Yu. S. Prigorodov, and A. G. Sudakov, *Pis'ma Zh. Tekh. Fiz.*, **24**, Issue 8, 33-41 (1998).
10. P. A. Baranov, S. A. Isaev, Yu. S. Prigorodov, and A. G. Sudakov, *Pis'ma Zh. Tekh. Fiz.*, **24**, Issue 17, 16-23 (1998).
11. S. A. Isaev, P. A. Baranov, A. E. Usachev, and D. P. Frolov, in: *Proc. 8th Int. Symp. on Flow Visualization*, Sorrento, September 1-4, 1998, pp. 217.1-217.8.
12. P. A. Baranov, S. A. Isaev, Yu. S. Prigorodov, and A. G. Sudakov, *Inzh.-Fiz. Zh.*, **72**, No. 3, 568-571 (1999).
13. I. A. Belov, B. A. Kolovandin, and N. A. Kudryavtsev, in: *Processes of Transfer in Turbulent Flows* [in Russian], Minsk (1988), pp. 22-38.
14. V. J. Modi, M. S. U. K. Fernando, and T. Yokomizo, *AIAA J.*, **29**, No. 9, 1400-1406 (1991).
15. P. A. Baranov, V. L. Zhdanov, and A. G. Sudakov, *Numerical Analysis of Nonstationary Flow Past a Cylinder with Introduction of Induced Vorticity into a Near Wake*, Preprint No. 5 of the Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute," National Academy of Sciences of Belarus, Minsk (1998).