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NUMERICAL INVESTIGATION OF THE MECHANISM OF DRAG REDUCTION OF A BODY WITH A LEADING SEPARATION ZONE

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Analysis of the mechanism of drag reduction of bodies with leading separation zones is given by the example of numerical modeling of axisymmetric turbulent flow past a set of two disks.

1. In a number of works (see, for example, [1-3]) it has been shown that the organization of large-scale vortex structures by placing a coaxial circular disk in front of a blunt axisymmetric body contributes to pronounced reduction in the profile drag and the head resistance of the body when the diameter of the front disk and the gap between the disk and the body are appropriately chosen (by approximately up to a factor of 50 in the case of a semi-infinite cylinder-disk arrangement for diameter $R = 0.75$ and $l = 0.75$ [3]). Numerical analysis of the mechanism of drag reduction of bodies with a leading separation zone (LSZ) [1, 2] has shown a strong dependence of the quality of the calculated results on the order of approximation of the convective terms in the transfer equations, on the method of statement of the boundary conditions on solid surfaces, and to a certain degree on the allowance for the influence of the curvature of current lines on turbulence characteristics. In the present work, we pursue a methodological investigation of the combined influence of the enumerated factors on numerical modeling of a set of two different disks in incompressible viscous flow. Based on the application of a refined computational model we analyze systematically the evolution of the vortex pattern of axisymmetric flow past the disk when it is located in a near wake behind the other disk. Comparison of the calculated results obtained with the available experimental data enables us to more closely investigate the special features of the controlling physical mechanism of profile-drag and head-resistance reduction for the set of disks.

2. The mathematical model of separated flow past thin disks is based on a system of Reynolds stationary equations written for natural variables in cylindrical coordinates. The intricacy of the realized vortex pattern motivates the use of a high-Reynolds-number version of two-parameter dissipative turbulence model to close the system of initial equations. Methodological investigations of separated flows performed in [4] showed the appropriateness of a modified $k-\varepsilon$-turbulence model that takes account of the influence of the current line curvature on the turbulence characteristics. According to the Rodi-Leschziner approach, a correction function f_c that depends on the Richardson turbulent number Ri_t is introduced in the expression for the turbulent viscosity factor: $f_c = 1/(1 + C_c \mathrm{Ri}_t)$. The additional semi-empirical constant C_c is determined during methodological experiments from the condition of the best agreement between the calculated results and the available experimental data [5] and is taken to be 0.1.

As is well known the adoption of the method of wall functions as boundary conditions on solid surfaces in calculating turbulent flows is governed by the incorrectness of the high-Reynolds $k-\varepsilon$-model in the immediate vicinity of a wall. However, admittedly, for separated and preseparated flows, the efficiency of this method, which is based on postulating the existence of a logarithmic velocity profile near the wall, is rightly questioned. The search for alternative boundary conditions led to an attempt to adopt the so-called "zero diffusion method" [4], which is tested in this work interchangeably with the standard method of wall functions for describing the type of flow in question.

The initial differential equations are discretized by the finite-volume method. The convective terms in the momentum equations are approximated using both a one-dimensional variant of the QUICK quadratic interpolation

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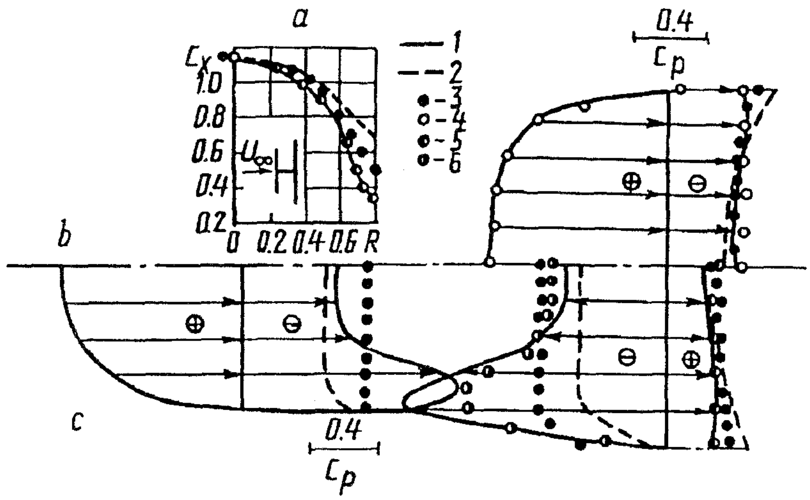

Fig. 1. Influence of numerical diffusion on drag coefficient C_x of two disks for a fixed gap $l = 0.5$ and a variable radius R of the front disk (a) on the profiles of the pressure coefficient C_p over the surfaces of the disk (b) and the two disks (c) in the case of $R = 0.8$ and $l = 0.5$. The calculated curves: 1) using QUICK and wall functions; 2) QUICK and the zero diffusion method; HDS and the zero diffusion method. The experimental data: 4) for a disk [7]; 5) for two disks [8]; 6) for the disk-cylinder arrangement [3].

scheme proposed by Leonard and the HDS hybrid scheme used in the widely employed TEACH codes [4]. In order to realize a computational procedure developed for counterflow schemes of the first-order approximation and based on a standard picture that is three-point in each coordinate direction, we modify the original Leonard scheme, which involves the provision of a diagonal predominance for the matrix of coefficients of the resultant algebraic equation by rearranging terms in expressions for convective flows through the sides of the mesh. This representation contributes to the convergence of the computational procedure with no bounds on the value of the grid Reynolds number. We note that diffusion flows are represented using central difference expressions. As in [6] difference analogs of differential equations for k and ε are written based on a hydrid scheme.

When constructing a computational algorithm for solving a problem that is based on the concept of splitting by physical processes, we adopt the SIMPLE method of pressure correction. The algebraic equations at each iteration step are solved by the method of linear scanning. The convergence of the iteration process is governed by the smallness of changes in the integral and local characteristics of flow past the bodies. Boundary conditions are laid down in the regular way: the conditions of an undisturbed flow are prescribed at the inlet boundary, those of symmetry are assigned on the symmetry axis, and "mild" boundary conditions are prescribed at the outlet boundaries. The location of the boundaries is chosen in a numerical experiment (for example, the distance from the cylindrical surface of the body to the upper boundary is taken to be 17). As in [1, 2] the calculations of turbulent flow past two disks for the Reynolds number $\mathrm{Re} = 10^5$ are performed on a highly nonuniform staggered grid with 60×30 and 50×36 nodes. The nodes of the grid are located with thickening in the region of location of the points of flow separation and reattachment as well as in that of the shear layers at the boundaries of the circulation zones and boundary layers near the surface of the disks; the minimum steps of the grid were 0.02 in the axial and radial directions. In the region of development of the shear layer, the grid in the radial direction is nearly uniform with a step of 0.03. The front disk had eight or nine nodes, while the rear disk had –14 to 19. A solution of the problem for fixed R and l is obtained, on the average, in 1500 iteration steps, the smallness of the increments in the turbulence characteristics on an iteration step serving as a convergence criterion. It is noted that convergence of the pressure distributions and, consequently, of the resistances of the disks is attained much more rapidly (approximately in 500 iteration steps) than in case of the turbulence characteristics. The relaxation coefficients used did not exceed 0.20–0.25. We note that the radius of the rear disk and the velocity and density of the incoming flow are chosen as parameters of dedimensionalizing.

TABLE 1. Calculated and Experimental Integral Characteristics of Flow Past Two Disks (Re = 10^5)

Algorithm		Geometry		Calculation				Experiment [8]	
Difference scheme	Boundary conditions	R	l	C_{x1}	C_{xp2}	C_{xd}	C_x	C_x	C_{xd}
Hybrid scheme	Method of zero diffusion	0.25	0.5	0.01	0.67	−0.42	1.12	1.09	–
		0.40	0.5	0.05	0.58	−0.41	1.04	1.00	–
		0.25	1.0	0.02	0.56	−0.42	1.00	0.98	–
		0.40	1.0	0.09	0.39	−0.40	0.88	0.90	–
	Method of wall functions	0.8	0.5	0.79	−0.42	−0.33	0.70		
				0.92	−0.57	−0.28	0.63	0.33	−0.28
Leonard scheme	Method of wall functions	0.8	0.5	1.02	−0.96	−0.27	0.33	0.33	−0.28

3. Calculated and experimental investigations of turbulent flow past a disk and two disks for a fixed gap l and varying radius R of the front disk are generalized in Fig. 1 and in Table 1. Most of the attention is given to the assessment of the combined influence of different important factors, i.e., scheme diffusion and boundary conditions on solid surfaces, on the reproduction of separated flow characteristics. As shown in [1, 2] flow past two disks is characterized by a rather intricate vortex structure in which the leading separation zone in the region between the disks and the large-scale vortex in the zone of a near wake behind the disks merge. The most important element of the structure seems to be the shear layer that develops at the boundary of the leading separation zone. For small radii of the front disk (R no larger than 0.4) when the leading separation zone is isolated from flow in the wake behind the disks, the influence of approximation viscosity on the coefficient of resistance C_x for the arrangement is small (Fig. 1a). However, as R grows to a value of 0.8 the errors of modeling the shear layer according to the hydrid scheme result in a considerable (up to 75%) disagreement between the calculated and experimental values of C_x. In calculations using the Leonard scheme, owing to better reproduction of the shear layer and decreased approximation viscosity we are able to obtain a much higher (by a factor of 1.5) rarefaction level in the leading separation zone and, consequently, a much smaller coefficient of resistance for the disks. Note that an increase in the order of approximation for the scheme has practically no effect on the bottom resistance of the two disks (Fig. 1c). We stress that the calculations of flow past disks in [1, 2] were performed with the zero-diffusion boundary conditions on the disk walls, and for this reason a substantial disagreement was observed between the calculated and experimental results on the coefficient of head resistance of two disks arranged for minimal resistance.

Application of difference schemes with decreased scheme diffusion enables us to more definitely and with smaller distortions assess the effect the statement of the boundary conditions on solid surfaces on the quality of a numerical solution. As is evident, allowance for diffusion flow from a wall in the method of wall functions provides better agreement between the results of the calculation and the available experimental data for the two disks [7] and qualitative similarity of the pressure distributions on the end surface of the rear disk of the arrangement in question (R = 0.8; l = 0.5) and the cylinder's end in the presence of a protruding disk of exactly the same configuration in front of it [3]. The zero-diffusion method smooths the pressure distribution in the leading separation zone between the disks and leads to overpressure in the vicinity of the sharp edge on the side of the bottom portion of the disk or two disks in flow. This results in overestimation of the head resistance for the arrangement of two disks of minimum resistance by approximately 60%. On the whole the methodological experiments performed pointed to the importance of allowance for the diffusion from the wall and to the suitability of the standard method of wall functions to predict developed circulation flows with a fixed separation point.

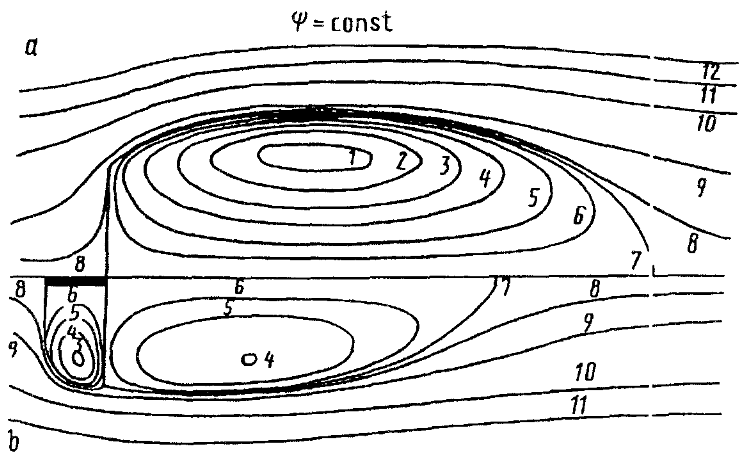

Fig. 2. Pattern of the current lines for a disk (a) and two disks (b) in turbulent uniform flow at $R = 0.8$; $l = 0.5$ and $\mathrm{Re} = 3.5 \cdot 10^4$: 1) $\Phi = -0.15$; 2) -0.12; 3) -0.09; 4) -0.06; 5) -0.03; 6) -0.01; 7) -0.0; 8) 0.01; 9) 0.1; 10) 0.5; 11) 0.9; 12) 1.3.

4. Below, we present the results of a comparative analysis of flow past a disk and two disks. Particular attention is given to the mechanism of drag reduction of bodies with LSZ, the assessment of the role of viscous effects in this mechanism being emphasized.

Figures 2a and 3a show a typical pattern of flow in the wake behind the disk for $\mathrm{Re} = 3.5 \cdot 10^4$ and the picture of lines of constant values of the turbulent pulsation energy k. The thickening of the current lines and the lines of k = const in the shear layer demonstrate the presence of significant velocity gradients in it and a predominant generation of turbulence in its vicinity. It is of interest to note that the contours of the constant values of turbulent pulsation energy, which are shaped like stretched "tongues", are concentrated in the vicinity of the center of the large-scale toroidal vortex behind the disk. This points to the correct depiction of the experimentally observed tendency for an increase in the maximum-over-the cross section value of k with an increase in the distance along the axis, measured from the disk, up to the section in which the radial size of the circulation zone is maximum. This tendency corresponds to a build-up of the generation of turbulent energy as the shear layer develops. As the distance along the axis increases further a decrease in velocity gradients in the cross sections leads to reduced levels of turbulent energy. We should note the presence of two local maxima of k in the axis region, which correspond to the largest derivatives of the axial velocity component along the axial coordinate, i.e., to the zones of acceleration behind the point of attachment and stagnation in front of the disk of the axis flow in the vortex. Large maximum values of turbulent pulsations of the velocity components in the circulation zone behind the disk, which reach a level of 25–30%, correlate with similar values in the near wake behind the disk in a tube determined experimentally using a Doppler laser velocity meter [9]. The high level of turbulent characteristics in the near wake is largely due to convective-diffusion transfer of these values, i.e., to a peculiar kind of turbulence "pumping" in the circulation zone; the more intense the flow in the zone and larger the sizes of the zone, the higher, apparently, the level. Therefore, the circulation zone behind the disk acts as a powerful generator of turbulence that is next transferred downstream.

Organizing the forward separation zone in front of the disk when a disk of small diameter is installed leads to a reduction in pressure in the region between the disks and deformation of the pressure profile on the front of the rear disk with the formation of a peripherical pressure maximum displaced about the symmetry axis. An increase in the radius R of the front disk of from 0 to 0.4 for fixed l is accompanied by growth of the forward separation zone, travel of the point of attachment of the current line that separates circulation flow and the external flow; and of the peripherical pressure maximum toward the sharp edge of the disk as well as by the decrease in the pressure maximum and, consequently, the integral load on the front of the disk C_{xp_2} (see Table 1).

Therefore, we observe a growing screening influence of the front disk on the rear disk even for comparatively small values of R. At the same time, the bottom resistance of the two disks C_{xd}, which isgoverned

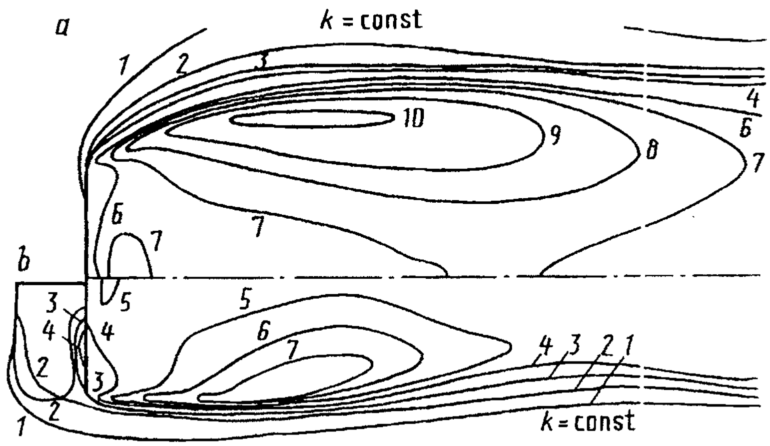

Fig. 3. Pattern of the isolines of turbulent pulsation energy for a disk (a) and two disks in uniform flow at $R = 0.8$; $l = 0.5$, and $Re = 3.5 \cdot 10^4$: 1) 0.0005; 2) 0.005; 3) 0.015; 4) 0.025; 5) 0.035; 6) 0.045; 7) 0.055; 8) 0.065; 9) 0.075; 10) 0.085.

by the bottom pressure behind the rear disk, the length of the circulation zone between the disks, and the flow intensity in it, remain practically constant, which points to the governing influence of separation of the flow from the sharp edge of the rear disk in the formation of the wake behind the disks and to the weak relationship between circulation zones in the wake behind the disk and in the region between the disks. It is noteworthy that the front disk experienced a strong action of the rear disk. In place of the region of reduced pressure that is usually realized in the wake behind an isolated disk and is characterized by negative values of excess pressure (with respect to the pressure in the incoming flow), in the case of flow past two disks, a region of increased pressure forms behind the front disk, which causes a significant decrease in the coefficient of resistance for the front disk C_{x_1} as compared with the case of isolated flow past it.

Therefore, an increase in the radius R of the front disk leads to a reduction in the overall resistance of the disks, on the one hand, at the expense of decreased contribution to the resistance of the integral load on the front of the rear disk C_{xp_2}, and, on the other, because of the very small resistance of the front disk. For large distances l between the disks, a more rapid increase in C_x occurs with increasing R (see Table 1). The good agreement, within 3–5%, between the calculated and experimental coefficients of resistance for the two disks in the range of R of from 0 to 0.4 shows the applicability of a rather rough computational model for assessing the resisance of the disks in the regime of developed turbulent flow when viscous effects in the flow are very substantial.

The evolution of the forward separation zone with increasing radius of the front disk leads to a growth in the ejection capabilities of the viscous shear layer that develops behind the sharp edge of the front disk, and, consequently, to a progressive pressure reduction in the zone down to a value that is much lower than that of the pressure behind an isolated disk (Fig. 1b and c). The displacement of the point of flow attachment in the vicinity of the sharp edge causes a transition to the regime of flow past the disks with the formation of a unified viscous shear layer that covers the circulation zones in the region between the disks (see Fig. 2b) and in the wake behind the disks. This flow regime is characterized by minimal resistance of an disks (Fig. 1a). As has been established in the numerical experiment the major contribution to the total resistance of the disks in this case is made by the front disk, its resistance, due to the strong decrease in pressure in the region between the disks, exceeding the resistance of an isolated disk (see Table 1). At the same time, the rear disk, which is all located in a region of reduced pressure (Fig. 1c), experiences a pulling action due to the pressure drop in the forward separation zone and in the wake behind the disks. Therefore, the overall resisance of the two disks turns out to be smaller than the resistance of the front disk and, with a rational choice of the radius R, can be much smaller (more than thrice for $l = 0.5$) than the resistance of an isolated disk.

Figures 1-4 compare the results of caclulating the local parameters of the flow and turbulence characteristics for a single disk and two disks ($R = 0.8$; $l = 0.5$) in uniform incompressible flow with a zero turbulence level Tu.

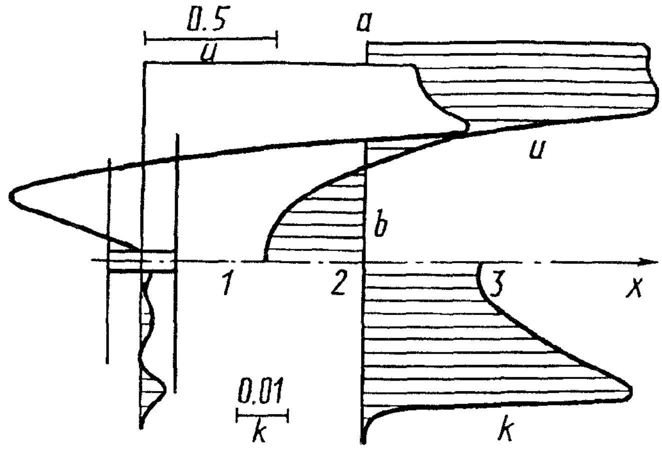

Fig. 4. Profiles of the axial velocity component (a) and the turbulent pulsation energy (b) in the middle section between disks and in a near wake behind the disks ($R = 0.8$; $l = 0.5$) in the regime of turbulent uniform flow for Re = 10^5.

Attention is drawn to the extremely nonuniform distribution in the leading separation zone of static pressure, which is a consequence of inhomogeneous flow in the large-scale vortex in the region between the disks. The center of the vortex turns out to be displaced to the separating current line, which causes the zone of flow-velocity maxima and hence maximum rarefaction to be located in the vicinity of the sharp edge of the front of the rear disk. The rather low resistance of the two disks is due to the high intensity of flow in the vortex (the velocity of return flow in the middle plane of the cavity between the disks is more than 50% of the velocity of the incoming flow) and the high level of rarefaction in the vicinity of the sharp edge ($C_{p\min} = -1.2$). It is noteworthy that the intensity of the large-scale vortex in the region between the disks, as determined by the largest value of the current function, turned out to be higher than the intensity of circulation flow in the near wake behind the disks. As follows from the vortex structures of flow past the bodies in Fig. 2 the occurrence of a LSZ in front of the disk alters substantially the flow in the wake behind it, leading to a decrease in the sizes of the circulation zone in the axial and radial directions as well as to an increase in the bottom pressure (see Table 1).

Therefore, though the zones of separated flow between the disks and behind the disks turn out to be divided we observe an indirect influence of the flow in the LSZ on the flow in the near wake, which is reflected primarily in the slope of the dividing current line to the symmetry axis in the sharp edge of the rear disk. The reduction in near wake sizes and the smoother character of flow past the two disks as compared with the flow past isolated disk are directly associated with the decrease in the head resistance for the system of disks. As Fig. 3b shows the structures for the lines of the constant values of turbulent pulsation energy in the near wake behind the disks have a tongue-like shape that is similar to the case of flow past the isolated disk. The maxima of k are also generated in the vicinity of the center of the large-scale vortex in the shear layer behind the disks. It is pertinent to note that the turbulence intensites in the near wake behind the disks turn out to be lower by approximately a factor of 1.5 than in the wake behind single disks. The extremely important circumstance that contributes to the insight into the mechanism of drag reduction of bodies with an LSZ is the drastic difference in the profiles of turbulence energy in two sections: in the middle section between the disks and in the cross section in the vicinity of the center of circulation flow in the near wake behind the disks. Flow in the large-scale vortex in the region between the disks is characterized by a turbulence energy level that is more than an order of magnitude smaller than the turbulence energy level in the near wake behind the disks. That is, in the case of low head resistance of the arrangement of two disks, flow in the LSZ is characterized by a insignificant level of turbulent vortex viscosity, i.e., is practically nonviscous.

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NOTATION

x, y, axial and radial coordinates; R, radius of front disk; l, gap between disks; u, v, Tu, axial and radial velocity components and turbulence level of the incoming flow; C_p, pressure coefficient; k, ε, energy of turbulent pulsations and its dissipation rate; C_c, additional semiempirical constant in the correction function that allows for the influence of the curvature of current lines on turbulence characteristics; Ri_t, Richardson turbulence number; Re, Reynolds number; Φ, function of current; C_x, C_{xd}, coefficients of drag and bottom resistance; C_{x_1}, C_{x_2}, coefficient of drag for the front disk and coefficient of normal force on the front of the rear disk.

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