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NUMERICAL MODELING OF THE EFFECT OF IMPROVING THE AERODYNAMIC EFFICIENCY OF PROFILES DUE TO THE SUCTION IN VORTEX CELLS

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Based on numerical solution of Reynolds equations that are closed using a two-parameter dissipative model of turbulence by the finite-volume method the authors substantiated a technique for decreasing the drag and achieving high efficiency of thick profiles by means of intensification of the flow in vortex cells built into the contour.

One of the topical directions in the development of aviation is associated with creating aircraft that are based on the use of systems for controlling the flow by means of vortex cells with their intensification by blowing-suction. The promising aircraft ÉKIP, which has the shape of a thick wing and uses a propulsion unit for the functioning of a system of suction from vortex cells along the contour of the aircraft can serve as an example of implementation of this concept [1]. Therefore an important role is played by the development of methods for solving conjugate problems of the aerodynamics of objects with different-scale structural elements of the flow and by the evaluation of the efficiency of flow control in numerical modeling of the flow along thick profiles with built-in vortex cells. It should be noted that the direction associated with solution of conjugate problems is one of the high-priority directions in the development of computational hydrodynamics.

Based on the development of the methodology of [2], we were the first to formulate and solve the conjugate problem of the effect of trapped large-scale vortex structures on the turbulent flow of an incompressible viscous fluid along a thick profile and on its aerodynamic resistance in intensification of the flow in vortex cells using suction through central bodies.

The algorithm used is based on the finite-volume method of solution of Reynolds-averaged Navier–Stokes equations, closed using a high-Reynolds two-parameter dissipative model of turbulence, within the framework of the concept of decomposition of the computational region and generation of O-type oblique-angled multistage grids with overlapping in separate substantially different-scale subregions. It is important to emphasize that the initial equations are written in divergent form for increments in the dependent variables: covariant components of velocity, pressure, turbulence energy, and its dissipation rate. The choice of the indicated dependent variables instead of the Cartesian velocity components that are commonly used enables us to improve the accuracy of calculations on very economical computational grids. Convective flows in momentum equations are calculated using a one-dimensional counterflow scheme of quadratic interpolation proposed by Leonard. In discretization of convective terms of the equations of transfer of turbulence characteristics use is made of both the indicated Leonard scheme and the UMIST scheme, which is a variation of the TVD scheme.

The computational model proposed is based on the concept of splitting by physical processes, realized in the SIMPLEC procedure for correcting pressure. Characteristic features of this iteration algorithm are determination of preliminary velocity components on a "predictor" step for "frozen" pressure and turbulent-viscosity fields and subsequent correction of the pressure on the basis of solution of a continuity equation with velocity-field corrections. In the computational procedure, we employ the method of global iterations by subregions with interpolation of the dependent variables in zones of subregion overlap.

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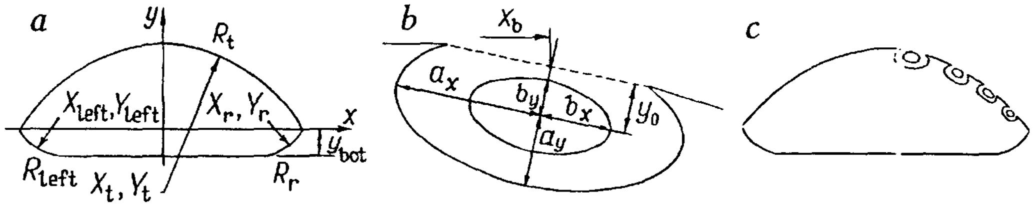

Fig. 1. Contour of a thick profile (a) and a vortex cell (b) with applied notation; diagram of the layout of the cells on the profile (c).

TABLE 1. Composition of the Thick Profile

X_t	Y_t	R_t	X_r	Y_r	R_r	X_{left}	Y_{left}	R_{left}	y_{bot}
0.0	−0.228	0.557	0.348	0.088	0.175	−0.348	0.088	0.175	−0.086

TABLE 2. Parameters of the Vortex Cells on the Profile with Enumeration of the Variants of Suction in the Central Bodies of the Cells

No. of cell	Geometric parameters of the cell						Variants of U_n		
	x_b	y_0/a_x	a_x	a_y/a_x	b_x/a_x	b_y/b_x	1	2	3
1	0.0876	−0.7	0.0584	0.5	0.5	0.05	0.02	0.05	0.05
2	0.2555	−0.7	0.0487	0.5	0.5	0.05	0.02	0.05	0.05
3	0.3649	−0.7	0.0389	0.5	0.5	0.05	0.02	0.05	0.075
4	0.4452	−0.7	0.0292	0.5	0.5	0.05	0.02	0.0.5	0.10

A centered gauge with joining of the dependent variables to the center of the computational grid enables us to simplify the computational algorithm and to decrease the number of computational operations. Possible pressure oscillations are suppressed on the basis of the Rhee–Chou approach. High stability of the computational procedure is ensured by the use of one-sided counterflow differences for discretization of convective terms in the implicit part of the equations for increments in the sought variables, by the damping of nonphysical oscillations by means of introduction of artificial diffusion in the implicit part of the equations, and by the use of pseudotemporal stabilizing terms. The efficiency of the computational algorithm is also improved by solving the systems of nonlinear algebraic equations by the method of incomplete matrix factorization in the Stone version (SIP). In the calculations, we employed the standard method of wall functions [3].

The object of investigation of this work is a thick profile whose upper part is an arc of a circle of radius R_t with center at the point X_t, Y_t while the lower part is formed by segments of arcs of right-hand and left-hand circles of small radius (with coordinates of the centers X_r, Y_r and X_{left}, Y_{left} and radii R_r and R_{left}, respectively) and a plane ($y = y_{bot}$). The contour of the profile together with the notation is shown in Fig. 1a, while the characteristic dimensions are listed in Table 1. The size of the chord of the thick profile is selected as the linear scale.

A series of four vortex cells of elliptical shape with central bodies of the same geometry is mounted in the profile in question. The topology of a cell is shown in Fig. 1b, while the linear dimensions of the cells with their position relative to the center of the profile (Fig. 1c) are listed in Table 2. The possibility of prescribing velocity components that correspond to blowing-suction conditions on the walls of the vortex cells and the central bodies is realized in the computational complex developed. The velocity of the incoming flow is taken as the scale of nondimensionalization. The Reynolds number is set equal to 10^4.

This investigation is confined to a comparative analysis of three variants with different velocities of suction U_n through the surfaces of the central bodies (see Table 2). The considered model for intensification of the vortex flow in a cell reflects to a certain degree the process of intake of air through a porous insert on the basis of its ejection using a propulsion unit. As a result of such action within the cells, a pulse that alters substantially the flow along the profile is introduced in the external flow through cuts in the thick profile.

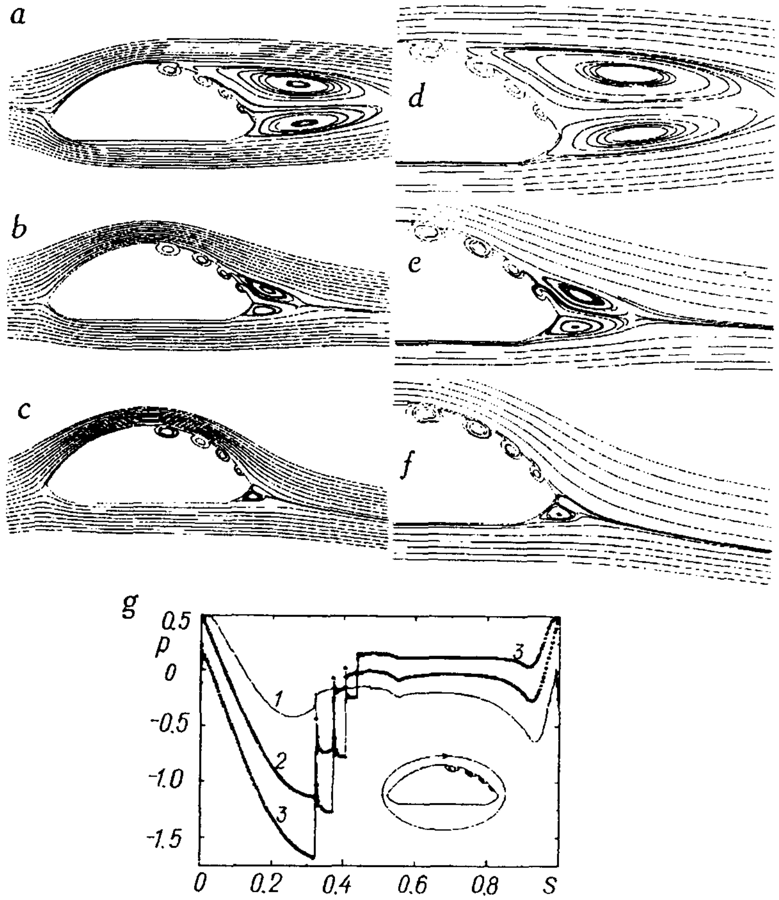

Fig. 2. Comparison of the patterns of turbulent flow along a profile with vortex cells (a, b, and c) and its tail (d, e, and f) and of the pressure distributions along the profile (g) for, respectively, the three variants considered for suction though the central bodies of the cells: a, d) 1; b, e) 2; c, f) 3.

TABLE 3. Aerodynamic Characteristics of the Thick Profile with the Cells for Different Velocities of Suction through the Central Bodies

No. of variant	C_x	C_{xp}	C_{xf}	C_y	M_z	K
1	0.1607	0.1309	0.0298	−0.2390	0.0981	–
2	0.0982	0.0637	0.0345	1.0123	−0.0010	10.308
3	0.0853	0.0516	0.0337	2.2515	−0.0456	26.395

An algebraic nonorthogonal O-grid is constructed around the profile, and the first stage adjacent to the contour contains 21 × 200 cells that are arranged with bunching toward the wall in a 0.1-thick band. The wall step is chosen equal to 0.0005. The second stage of 80 × 120 cells covers the space around the profile at a distance of 80 chords. The vortex cells are divided by the O-grid, in the radial direction of which there are 21 cells. Multistage grids enable us to efficiently and faithfully represent the flow in the near wake behind the body, in the boundary-layer region, and within the cells.

Figure 2 and Table 3 present some numerical results obtained for the spectra of the flow along the thick profile at a zero angle of attack and for local and integral force loads on it for different intensities of the suction through the central bodies of the vortex cells.

It is noteworthy that with low suction velocities (of about 2% of the incoming-flow velocity) a developed separation zone is formed behind the profile (Fig. 2a). As shown in greater detail in Fig. 2d, in this case most of the vortex cells (starting with the second cell) are practically inactive (do not draw in air from the near-wake zone).

The negative lift coefficient is explained not so much by the low rarefaction at the top of the profile with practically isobaric flow in the vortex cells (Fig. 2g) as by the strong rarefaction below the profile caused by orientation of the incoming flow at a negative angle to the profile (the stagnation point is located at the top of the profile).

An increase in the suction velocity (to 5%) leads to a change in the pattern of the flow along the profile from separating to nonseparating (Fig. 2b) accompanied by a decrease in the drag and an increase in the lift. It should be noted that, for the Reynolds number in question, an insignificant and low-intensity separation region is retained and the last cell also turns out to be passive (Fig. 2d).

An increase in the suction velocity in the last cells intensifies the flow in them and contributes to the realization of totally nonseparating flow along the upper part of the profile (Fig. 2c and f). The insignificant separation zone in the tail is associated with the rounding-off of the profile at this site and causes practically no pronounced deterioration of the aerodynamic charactersitics. The high efficiency of the thick profile (about 25) is due not only to the strong rarefaction on the upper surface but also to the pressure increase at the bottom of the profile caused by a change in the angle of flow arrival at the profile (Fig. 2g).

Thus, we have substantiated a technique for controlling efficiently the flow along thick profiles with vortex cells in air suction through central bodies. This approach differs significantly from the classical approach to control of the turbulent boundary layer on wings that involves a large energy expenditure to realize it. In the technique proposed, the flow rates through the central bodies of the cells are comparatively low (because of the small surface area), and the main problem in air suction is not so much to remove the low-energy layer in the vicinity of the wall and thereby permit passage of high-pressure layers to the body surface as to impart an additional pulse to the surface layers of the profile by intensifying the large-scale vortex structures trapped in the cells. Air suction, in this case, works only in twisting of the vortex.

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NOTATION

x and y, longitudinal and transverse Cartesian coordinates; s, relative distance along the contour of the body measured counterclockwise; X, Y, and R, coordinates of the centers of circles whose arcs are generating lines of the contour of the profile; x_b, coordinate of the center of the cut in the profile at the site of the location of the vortex cell; y_0, distance from the center of the cell to the plane of the profile's cut (embedding of the cell in the contour of the profile); a_x and a_y, semimajor and semiminor axes of the elliptical contour of the vortex cell; b_x and b_y, semimajor and semiminor axes of the elliptical contour of the central body of the vortex cell; p, excess pressure referred to the doubled velocity head; C_x, C_{xp}, and C_{xf}, coefficients of drag, profile resistance, and frictional force; C_y, lift coefficient; M_z, pitching-moment coefficient; K, aerodynamic efficiency; U_n, velocity of suction on the central body. Subscripts: t, r, and left: upper, right-hand, and left-hand arcs of the contour; bot: bottom of the contour.

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