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NUMERICAL SIMULATION OF THE INFLUENCE OF VISCOSITY ON TURBULENT FLOW AROUND A THICK AIRFOIL WITH VORTEX CELLS

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A numerical investigation of the influence of viscosity on flow around a thick airflow with vortex cells has been carried out within the framework of the multiblock approach to the solution of steady-state Reynolds equations closed using Menter's zonal model of shear-stress transfer.

1. In [1, 2], a numerical substantiation has been given to a new method of controlling a flow, which involves the transformation of the external large-scale vortex structure and passage from the separated regime of flow around a thick airfoil (close to the longitudinal section of the frame of an "Ékip" aircraft) to an unseparated regime. Transformation of the flow is accompanied by a decrease in the drag and a significant increase in the lift–drag ratio due to the small-scale action in small vortex cells given an acceptable expenditure of energy and a relative simplicity of practical implementation. The reasons for the jump-like dependence of the integral aerodynamic characteristics of the body in flow on the degree of turbulization and intensification of flow in a vortex cell built into the contour of a circular cylinder have been investigated in detail.

In the turbulent regime of flow around an airfoil (Re = 10^4), it has been possible to intensify flow in the vortex cells and eliminate the separation in the wake of the airfoil almost completely by drawing the liquid off the surface of the central bodies; in this case, the drag was significantly decreased and the lift coefficient was increased. As the coefficient of flow through the central bodies of the vortex cell increases and the separation zone decreases, the stream angle relative to the airfoil changes and the point of separation of the flow is displaced, which points to a change in the velocity of circulation around the airfoil. A preliminary investigation of the influence of the Reynolds number on flow around a thick airfoil with vortex cells has been carried out in [1] within the framework of the two-parameter dissipation model of turbulence. Such analysis has been carried out in [3] for flow around an automobile profile near a mobile screen; in this case, quite an acceptable agreement with the available experimental data on the local and integral force characteristics has been obtained. Unfortunately, only a limited range of Reynolds numbers (10^4, 10^5, and 10^6) has been considered in [1], which gives no way of determining the asymptotic character of the dependences of the lift–drag ratios on Re. Moreover, it is of interest to refine the mechanism of vortex intensification in vortex cells with allowance for the significant difference in the scales of motion of the medium inside the cells and around the airfoil.

In recent numerical investigations [4–6], extensive methodological calculations have been carried out to evaluate the applicability of Menter's zonal model of shear-stress transfer [7] to analysis of the turbulent motion of a liquid in channels with passive and active vortex cells and of separated flow around a circular cylinder with a separating plate in the near wake. It has been shown that this low-Reynolds model representing a combination of the known Launder–Spalding k–ε model and Saffman–Wilcocks k–ω model has definite advantages over each of these models taken separately as applied to the prediction of the characteristics of flows with separation zones. In the present work, a more correct semiempirical model of turbulence — Menter's zonal model — is used in combination with fairly narrow grids for refinement of the results of numerical calculations of the influence of the Reynolds number on steady-state flow around a thick airfoil with vortex cells.

2. The problem is formulated in a two-dimensional steady-state definition with allowance for the separation of the flow within the framework of the concept of decomposition of the computational region and construction of mul-

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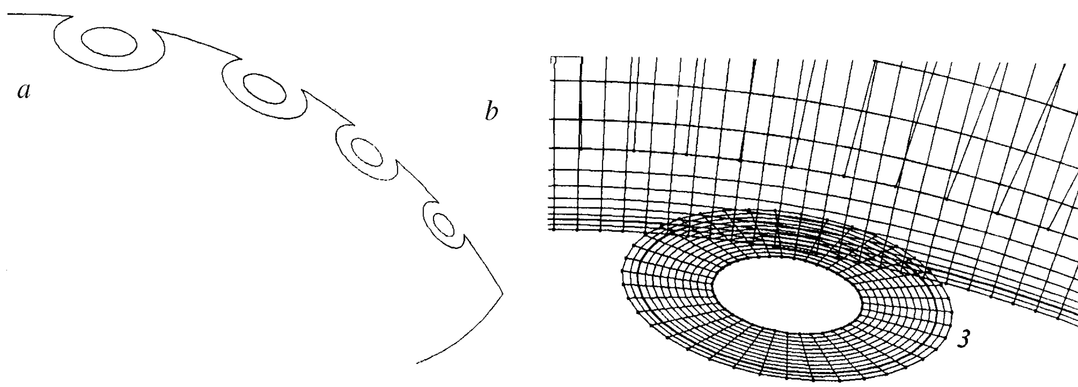

Fig. 1. Arrangement of vortex cells (a) and fragments of computational grids inside a vortex cell (b); 1) outer grid around the airfoil, 2) grid adjacent to the airfoil, 3) grid inside the cell.

tistage intersecting scalene grids of the ○ type in the separated significantly different-scale subregions. The system of initial equations is written in divergent form for increments of dependent variables: velocity and pressure components. The momentum equations are supplemented with the continuity equation. The use of the multistage intersecting scalene computational grids of the ○ type makes it possible to substantially decrease the number of computational points and thus to save the computational resources and "tune" each grid to the scale of flow in the corresponding computational region by selecting the dimensions of the computational cells. Information on the values of the variables is transferred from grid to grid by the method of intergrid nonconservative interpolation. On each of them, the problem is solved within the framework of the SIMPLEC procedure of pressure correction. The discrete analogs of the equations are solved by the Buleev method of incomplete matrix factorization in the Stone version. The velocity of the incoming flow and the length of the airfoil chord are selected as the dimensionless parameters.

3. An algebraic nonorthogonal grid of the ○ type is constructed around the airfoil (Fig. 1); the first stage adjacent to the contour contains 41×520 points arranged with bunching toward the surface in a band of thickness 0.1. The step near the surface is taken to be equal to 0.0005. The second stage containing 80×250 cells covers the space around the airfoil at a distance of 40 chords. The vortex cells are divided by a grid of the ○ type, in the radial direction of which 51–41 points are arranged with bunching toward the central bodies. The grid is assumed to be uniform in the circumferential direction; in the region of the airfoil section, there are from 23 to 17 points (the number of points decreases with decrease in the dimensions of the cell).

Analysis of the evolution of the vortex structures formed in the case of flow around an airfoil with vortex cells as a result of intensification of the flow circulating in them due to the drawoff (U_n is assumed to be equal to 0.05 in all the cells) confirms on the whole the results obtained earlier with increase in Re. It is significant that, unlike the single calculations at three Reynolds numbers differing by an order of magnitude [1], the initial phase of their change in the range from 10^4 to $2.5 \cdot 10^4$ and the intermediate phase of their change in the range from $5 \cdot 10^4$ to $2.5 \cdot 10^5$ are considered in detail. The initial phase is exceptionally important (Fig. 2), since it is precisely in the limits of this phase that the flow around the airfoil becomes unseparated. It is worth noting that at Re = 10^4–$1.25 \cdot 10^4$ not all the vortex cells operate in the system of control of flow around the airfoil. Thus, the third cell begins to operate only at $\mathrm{Re} > 1.25 \cdot 10^4$, and the fourth vortex cell begins to operate at Re = $2 \cdot 10^4$. In the intermediate phase, which virtually lasts to the end of the Re range considered, the pattern of flow around the airfoil and the pattern of vortex structures inside the cells change insignificantly.

Flows circulating inside the cells are noteworthy. Virtually in all the cells on the leeward side there arise fairly large separation zones with attachment of the flow in the neighborhood of the sharp-pointed leading edge. This points to the fact that the shape of the selected elliptical cell is not optimum. The shape of a thick airfoil is also imperfect. Even at high Reynolds numbers, there is a separation zone in the near wake in the afterbody of the airfoil. The separation points, as usual, are located at the sites of jump-like change in the curvature of the contour.

The influence of the physical viscosity on the flow around an airfoil with vortex cells manifests itself as a sharp increase in the lift coefficient C_y in the range of Reynolds numbers from 10^4 to $2 \cdot 10^4$; C_x changes not so mark-

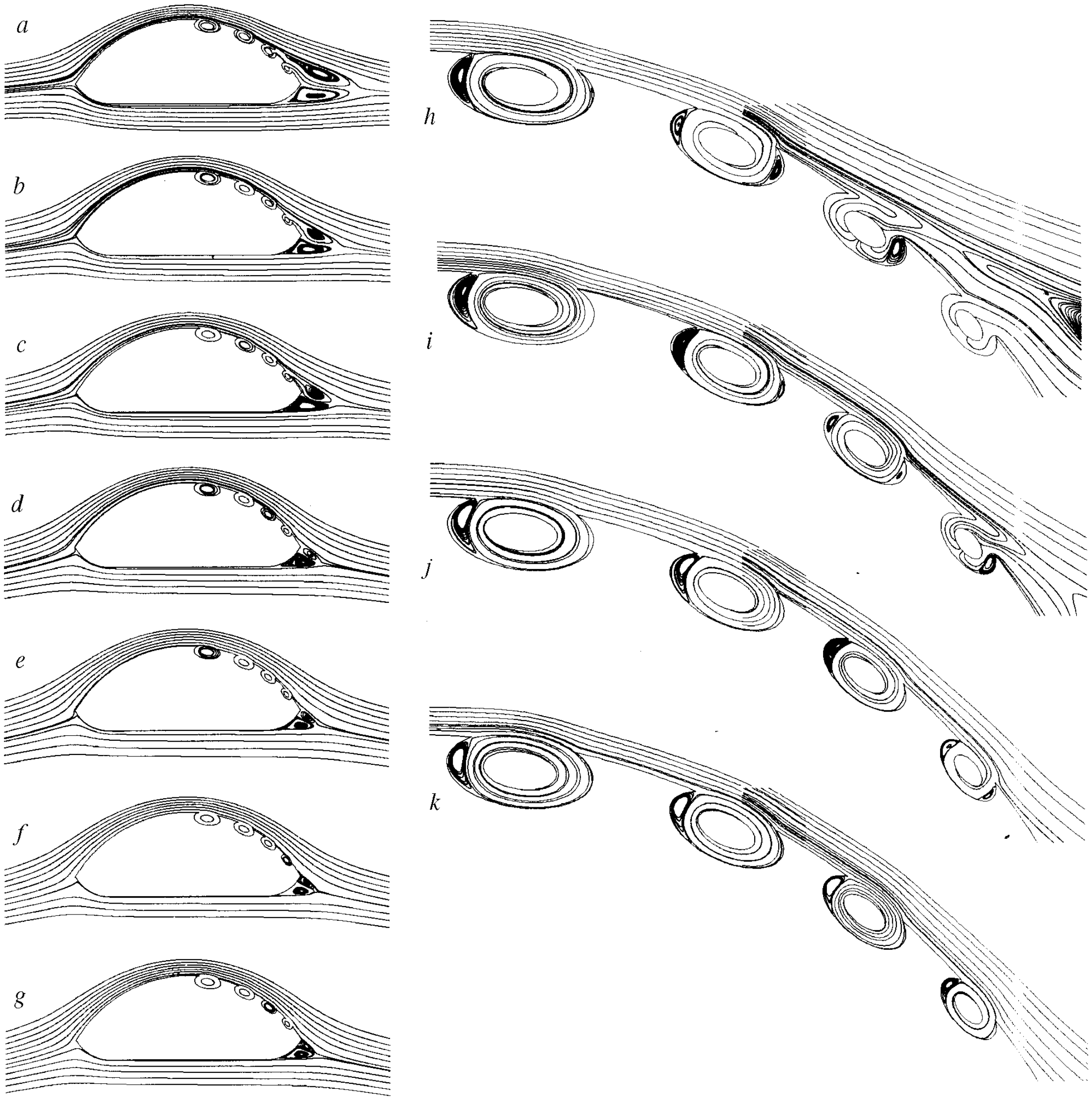

Fig. 2. Patterns of flow around a thick airfoil with active vortex cells (a–g) and around its afterbody (h–k) at different Reynolds numbers: a) Re = 10^4; b) $1.25{\cdot}10^4$; c) $1.5{\cdot}10^4$; d) $2{\cdot}10^4$; e) $5{\cdot}10^4$; f) $1.5{\cdot}10^5$; g) $2.5{\cdot}10^5$; h) 10^4; i) $1.5{\cdot}10^4$; j) $2.5{\cdot}10^4$; k) $2.5{\cdot}10^5$.

edly in this range (Fig. 3). Clearly, such behavior of the integral force loads is explained by the fact that the character of flow near the airfoil becomes similar to the unseparated one as the Re number increases. In this work, it has been revealed that the above process is due to the turbulization of flow in vortex cells when the velocity of the flow in them increases. It is significant that the dependence C_y(Re) is asymptotic in character when Re $\to \infty$.

Consideration of the aerodynamic coefficients of the airfoil and the cells individually shows that they have significant features. When the Reynolds number increases, the airfoil itself (not including cells) is acted upon by an increasing tractive force (pull) that is balanced to a large measure by the drag force in the vortex cells. In this case, the first cell having the largest dimensions does not make the largest contribution to the drag — the second vortex cell is responsible for this.

It should be noted that an analogous situation is observed in the case of flow around a cylinder with a coaxial leading disk (a cylinder with a leading separation zone) when the diameter of the disk and the gap between it and the end of the cylinder are properly selected: the drag force of the cylinder is virtually completely balanced by the tractive force acting on the cylinder [8].

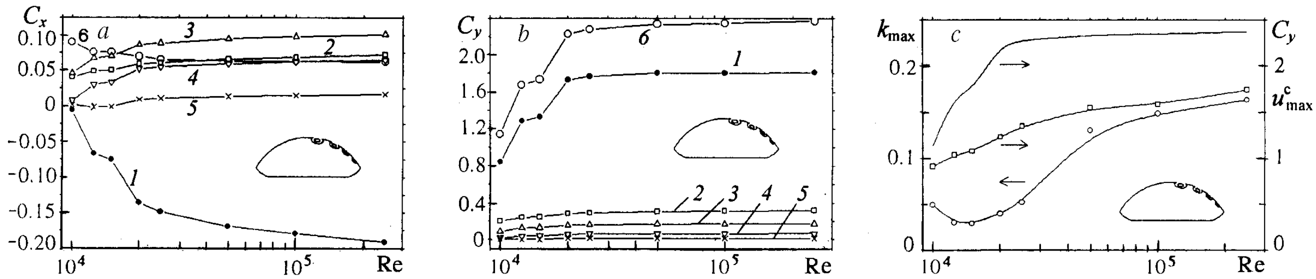

Fig. 3. Dependence of the drag coefficient (a) and the lift coefficient (b) on Re for a thick airfoil (curve 6) and its components: airfoil (1) and vortex cells (2–5); c) dependence of C_y, u^{c}_{max}, and k_{max} on Re.

In the region where Re = 10^4–$1.25 \cdot 10^4$, the behavior of the integral characteristics of the fourth cell is anomalous. Its drag and lift (lifting force) are negative. This is explained by the fact that the fourth cell does not operate in the indicated range. We note that the level of its drag is very low throughout the Re range considered.

Increase in Re leads to an increase in the maximum longitudinal velocity in vortex cells up to values about 1.8 times higher than the velocity of the incoming flow. At the same time, the maximum level of turbulent pulsations within the cells increases. We note that the portion of decrease in k_{max}(Re) (Fig. 3) corresponds to the position of the point with a maximum turbulent energy in the near wake of the airfoil.

The lifting force of the airfoil with cells is made up of the force acting on the airfoil itself and the force generated in the cells; the total contribution of the latter is very significant (more than 35%). This effect of supercirculation of an airfoil with cells has been analyzed in more detail in [9].

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NOTATION

x, y, Cartesian coordinates; u, longitudinal velocity component; k, energy of turbulent pulsations; ε, rate of dissipation of turbulent energy; ω, relative rate of dissipation of turbulent energy; C_x and C_y, drag and lift coefficients; Re, Reynolds number; U_n, rate of drawoff on central bodies. Subscripts: max, maximum value; c, parameters in a vortex cell; n, normal.

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