Journal of Engineering Physics and Thermophysics, Vol. 75, No. 3, 2002

ANALYSIS OF THE EFFICIENCY OF CONTROL OF FLOW ABOUT BODIES USING VORTEX CELLS WITH ALLOWANCE FOR ENERGY EXPENDITURE

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UDC 532.517.4

Control of the flow about bodies of different geometry using vortex cells built into the contours is analyzed; the contribution of the expenditure of energy on intensifying the flow within the cells to the drag of the bodies is taken into account.

1. A method of control of flow about bodies using built-in vortex cells was proposed owing to the concept of an ÉKIP aircraft [1]. The shape of a vortex cell in the form of an ellipse which is submerged in the contour of a two-dimensional body analogous to the outline of the indicated aircraft in configuration has been considered in [2] for the first time. The central body of the same elliptical geometry was located within the vortex cell. The performed numerical analysis of laminar flow about a body of integral arrangement with several vortex cells has revealed that it is necessary to intensify the flow in vortex cells since the separating flow about bodies with passive cells is virtually no different from the flow about bodies without cells.

In [3], it has been shown with the example of flow about a circular cylinder with two vortex cells that intensification of the flow within them is capable of substantially changing the pattern of flow about the cylinder and of decreasing its resistance. The methodology of calculation of the laminar flow about bodies with vortex cells on the basis of the employment of intersecting different-scale O-shaped grids was illustrated for the first time.

In analyzing the turbulent steady-state flow about a circular cylinder with two cells in the presence of a separating plate in a near wake [4], one has detected its capacity to substantially influence the pattern of flow about the cylinder by changing the rate of suction from the surface of the central body of a cell. The decrease in the dimension of the separation zone is accompanied by a significant reduction in the drag. Thus, progressive suction in a small-size cell was tested for the first time as a means of intensifying the flow within it; it was also shown that a small-scale action exerts an influence on the large-scale external flow near the object.

As has been demonstrated in [5], the introduction of a momentum on the walls of vortex cells built into the contour of the ÉKIP aircraft model enables one to ensure the nonseparating laminar flow about a thick profile. For the turbulent regime [6], the analogous result is attained using low-flow-rate suction on the central bodies of vortex cells.

Finally, in [7, 8], in addition to a brief analysis of flow about the ÉKIP aircraft model at nonzero angles of attack, the emphasis is on the physical mechanism of initiation of vortex cells as the controlling action increases. It has been shown that this mechanism is related to the so-called explosive turbulization and is accompanied by an abrupt change in the loads on objects and to a decrease in the length of the near wake.

It is noteworthy that the two considered means of intensifying circulation flow in vortex cells, i.e., suction from the surface of the central body and its rotation, have revealed superior capacities for controlling the large-scale flow about a thick profile and a circular cylinder. However there is no question that this approach is energy-consuming and it is necessary to evaluate the expenditure of energy on implementing this approach so as to draw a conclusion on its efficiency.

We note that certain versions of evaluations of the energy expenditure in the analogous means of controlling the separation of a flow have been described by P. Chang in [9]. However, we should note the fundamental difference between the mentioned means of controlling the separation of a flow and of controlling flow about bodies using vortex

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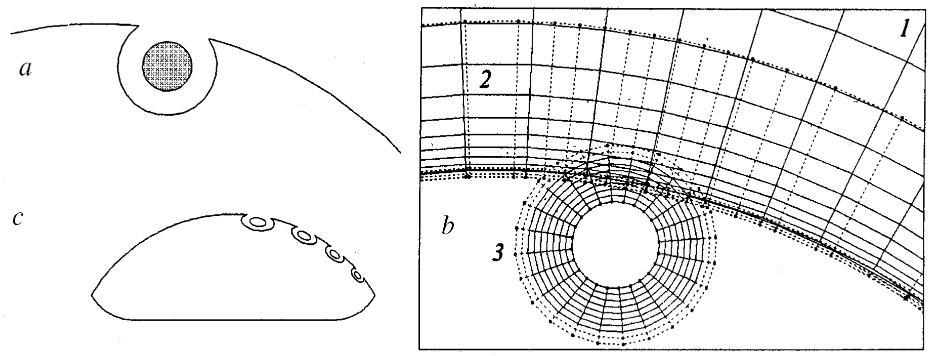


Fig. 1. Fragment of the contour of a cylinder with a vortex cell (a), the fragment of a composite grid (b) consisting of a two-stage (1, 2) grid near the cylinder and a grid in the vortex cell (3), and the contour of a thick profile with the layout of cells on the profile (c).

cells. In [10], it has been shown that a significant circulation is generated in vortex cells; therefore, the means proposed can be classified as the means of controlling the circulation of bodies.

The work seeks to evaluate the efficiency of control of flow about bodies with vortex cells on the basis of taking into account the expenditure of energy on intensifying the flow in the cells, just as has already been done in the case of turbulent flow about a cylinder with cylinders rotating in circular cavities.

2. The conjugate problem on the influence of trapped large-scale vortex structures on the turbulent flow of an incompressible viscous fluid about a body of classical geometry, i.e., a circular cylinder for the case of the position of a circularly shaped cell relative to the center of the cylinder (Fig. 1a) has been solved in [4] on the basis of numerical modeling. The vortex cell has the central body of the same geometry with organization of suction of the flow over the entire contour.

The computational algorithm is based on the finite-volume method of solution of the Reynolds-averaged Navier–Stokes equations which are closed using the high-Reynolds two-parameter dissipative model of turbulence within the framework of the concept of decomposition of the computational region and generation of multistage skew grids of the same type (O-type) with overlap in the singled-out substantially different-scale subregions.

The computational model is based on the concept of splitting by physical processes implemented in the SIMPLEC procedure of pressure correction. The characteristic features of such an iteration algorithm are determination, at the "predictor" step, of the preliminary velocity components for "frozen" pressure and turbulent-viscosity fields and subsequent correction of the pressure on the basis of the solution of the continuity equation with velocity-field corrections. The computational process is constructed in such a manner that one "predictor" step accounts for several local iteration steps in the block of pressure correction. Next, in solving the equation of transfer of turbulence characteristics, the field of turbulent vortex viscosity is redistributed. In the computational procedure, we use the method of global iterations in subregions with subsequent interpolation of dependent variables in the zones of overlapping of the subregions.

This approach has been verified in solving the test problem on the turbulent flow of an incompressible viscous fluid in a channel with a circular vortex cell [11]. The velocity of the incoming flow is taken as the dimensionless scale. The Reynolds number is prescribed to be 10^4.

3. To solve the problem of turbulent flow about a transversely oriented cylinder and to more accurately resolve the different-scale structural elements we have singled out the wall region with a thickness of about 0.1 diameter of the cylinder (it is selected as the characteristic dimension), the intermediate circular region covering the separation zone in the near wake behind the cylinder, and the peripheral annular zone whose external boundary is located at a rather large distance (of about 50–100) from the body. Introduction of several annular zones (Fig. 1b), which is equivalent to the construction of multistage grids, is related not only to the acceleration of the convergence of the solution of the problem by decreasing the number of computational grids but, which is more important, also to the setting of the local grid to the characteristics of the represented structural element of the flow: the boundary layer on the cylinder surface, return flow in the wake, and the flow field at a large distance from the body. It should be noted that

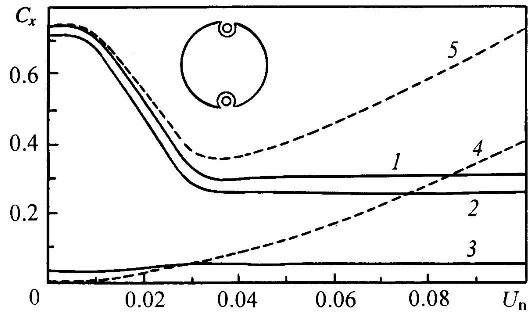


Fig. 2. Dependences of the drag coefficient C_x (curve 1) and its components C_{xp} (curve 2) and C_{xf} (curve 3) and of the coefficient of additional resistance C_x^{add} (dashed curve 4) and the drag coefficient corrected with allowance for energy expenditure C_x^{cor} (dashed curve 5) on U_n.

the calculated results have been obtained under the assumption of implementation of a symmetric regime of flow about the cylinder which corresponds to the turbulent regime of flow about a circular cylinder with a dividing plate in the near wake. The number of nodes was 15×40 in the external zone, 60×80 in the intermediate zone, and 21×80 in the wall zone. The step near the wall was 0.0005.

Inside the vortex cells, the grid is constructed uniformly in the circumferential direction and in the radial (21 nodes are selected) direction. We prescribe the number of points on the cavity section (15 nodes). Thereafter the total number of points in the circumferential direction is calculated from the condition of equality of the angular step. The diameter of the vortex cell is taken to be 0.2, while the diameter of the central body is taken to be 0.1. All the linear dimensions are referred to the diameter of the cylinder.

The efficiency of vortex cells as a tool for reducing the resistance of the cylinder is analyzed on the basis of evaluation of the additional (equivalent) resistance caused by the suction of the fluid through the surface of the central body.

The additional resistance in the case of suction from the central-body surface is determined in terms of the power required to maintain the flow rate of the fluid through the central body. Taking into account that two cells are located on the cylinder, we obtain

$$C_x^{\text{add}} = 2N_q \Big/ \left(\frac{1}{2}\rho U^3 d\right) = 4p_{\text{av}}q \, . \qquad (1)$$

The coefficients of resistance versus the suction velocity U_n on the central bodies $C_x^{\text{add}}(U_n)$ and $C_x^{\text{cor}}(U_n)$, where $C_x^{\text{cor}} = C_x + C_x^{\text{add}}$ is the drag coefficient of the cylinder with vortex cells which is corrected with allowance for the energy expenditure, are plotted in Fig. 2 as dashed lines.

The additional resistance of the cylinder increases approximately in proportion to the quadratic dependence on the velocity of suction of the fluid from the surface of the central body in a vortex cell. Clearly, the optimum of U_n for which the corrected coefficient of drag takes on a minimum value exists. In the case in question $U_n^{\text{opt}} \approx 0.034$; C_x^{cor} turns out to be equal to 0.35, which is 53% lower than the drag coefficient of a smooth circular cylinder.

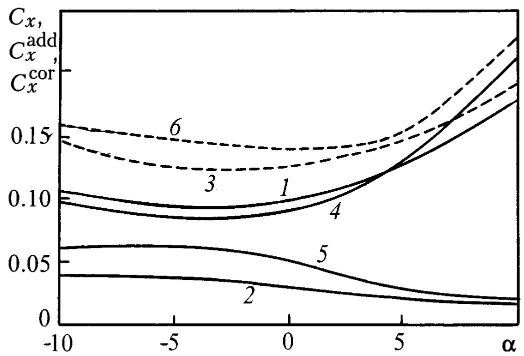
4. The subject of investigation of this work is also a thick profile whose upper part represents an arc of a circle and whose lower part is formed by the segments of the arcs of the right-hand and left-hand circles of small radius and a plane [6] (Fig. 1c). In this case we select the dimension of the chord of the thick profile as the linear scale. A series of four elliptically shaped vortex cells with central bodies of the same geometry is built into the profile.

Let us consider two versions of activation of vortex cells with variation of the angle of attack from –10 to 10°:

1) $U_n = 0.05$ in all the cells;

2) $U_n = 0.05$ in the first two cells, 0.075 in the third cell, and 0.1 in the fourth cell.

The total coefficient of flow rate is estimated at 0.021 in the first case and at 0.027 in the second case.



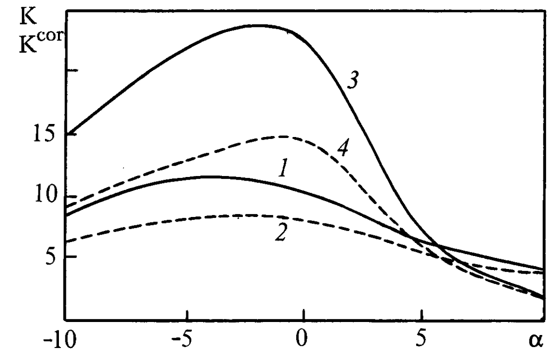


Fig. 3. Dependences of the drag coefficient C_x (curves 1 and 4), the coefficient of additional resistance C_x^{add} (curves 2 and 5), and the drag coefficient corrected with allowance for energy expenditure C_x^{cor} (dashed curves 3 and 6) on α for the versions of intensification 1, 2, and 3 ($U_n = 0.05$ in all the cells) and 4, 5, and 6 (0.05 in the first two cells, 0.075 in the third cell, and 0.1 in the fourth cell).

Fig. 4. Dependences of the coefficient of aerodynamic quality K (curves 1 and 3) and its value corrected with allowance for energy expenditure K^{cor} (dashed curves 2 and 4) on α for the versions of intensification 1 and 2 ($U_n = 0.05$ in all the cells) and 3 and 4 (0.05 in the first two cells, 0.075 in the third cell, and 0.1 in the fourth cell).

This model of intensification of the vortex flow in a cell reflects to a certain degree the process of intake of the air through a porous insert on the basis of the ejection of air using a propulsion system. Such an action inside the cells results in the introduction of a momentum, which changes substantially the flow about the profile, into the external flow through the cuts in the thick profile.

We construct an algebraic nonorthogonal grid of O-type around the profile; the first stage adjacent to the contour contains 21×200 cells arranged with bunching toward the wall in a band of thickness 0.1. The wall step is taken to be 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 subdivided by the O-type grid in whose radial direction 21 cells are uniformly arranged. We also prescribe a uniform grid in the circumferential direction; 21 cells are located in the region of the cut of the profile. Multistage grids enable us to efficiently and accurately represent the flow in the near wake behind a body, in the region of the boundary layer, and inside the cells.

On the basis of (1), taking into account that four vortex cells are built into the contour of the profile, we obtain

$$C_x^{add} = 4N_q \Big/ \left(\frac{1}{2}\rho U^3 d\right) = \sum_{i=1}^{4} 2p_{avi} q_i \, .$$

The dependences $C_x^{cor}(\alpha)$, where $C_x^{cor} = C_x + C_x^{add}$, are plotted as dashed lines in Fig. 3.

We have the minimum of $C_x^{cor}(\alpha)$, which is 0.124 at $\alpha = -2.5^o$ for the first version of activation (which is 26% lower than in the case with passive cells) and 0.137 for the second version (which is 18% lower than in the case with passive cells); this minimum remains constant, in practice, in the range of α from −1 to 2.5^o.

It should be noted that the maximum of C_y in the first version is 1.05 at $\alpha = -2.5^o$ and 2.05 at $\alpha_{opt} = -1.2^o$, whereas it takes on a negative value (–0.37) when the vortex cells are not activated.

Figure 4 plots as the dashed lines the dependences $K^{cor}(\alpha)$, i.e., the dependences of the coefficient of aerodynamic quality of the profile with vortex cells which is corrected with allowance for the energy expenditure.

We have the maximum of $K^{cor}(\alpha)$, which is 8.5 at $\alpha = -2.5^o$ for the first version of activation and 14.8 at $\alpha = -1^o$ for the second version.

Evaluation of the energy contribution, attributed to the suction on the central bodies of vortex cells, to the resistance has enabled us to establish the existence of the optimum values of the angles of attack for which the drag of the profile and its aerodynamic quality corrected with allowance for energy expenditure are extremum. Under the above specific conditions, the efficiency of this means of controlling the drag amounts to 26% in the first version of intensification and to 18% in the second version. It has been noted that the lift coefficient takes on a positive value while the corrected aerodynamic quality for the profile of a relative thickness of 43.5% attains values of 8.5 and 14.8 respectively.

Thus, the evaluations made in this work enable one to substantiate the efficiency of the considered means of controlling the flow about bodies of different geometry with vortex cells built into the casing in the case of activation of the cells due to the suction on the central bodies.

The authors express their thanks to G. G. Chernyi and Yu. V. Lapin for useful discussions of the problem.

This work was carried out with support from the Russian Foundation for Basic Research under project Nos. 00-02-81045, 99-01-00722, 99-01-01115, 02-01-00670, 02-01-0116, and 02-02-81035.

NOTATION

ρ, density of the fluid; N_q, power required to maintain the flow rate of the fluid through the central body in the vortex cell; $p_{\rm av}$, average value of the static pressure (referred to the double velocity head) on the surface of the central body in the cell; q, flow rate through the surface of the central body; C_x, C_{xp}, and C_{xf}, coefficients of drag, profile resistance, and frictional force; C_y, lift coefficient; $C_x^{\rm add}$, coefficient of additional drag; $C_x^{\rm cor}$, drag coefficient of the object with vortex cells corrected with allowance for energy expenditure; K, aerodynamic quality; $\rm K^{cor}$, aerodynamic quality of the profile corrected with allowance for energy expenditure; $U_{\rm n}$, velocity of suction on the central body; α, angle of attack. Subscripts and superscripts: opt, optimum value; i, number of vortex cell; n, normal; av, average; add, additive; cor, corrected.

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