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NUMERICAL INVESTIGATION OF THE EFFECT OF VISCOSITY ON SEPARATED FLOW PAST AN AUTOMOBILE PROFILE IN THE PRESENCE OF A MOBILE SCREEN

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The numerical simulation of laminar and turbulent separated flows of an incompressible viscous fluid past a two-dimensional complex-shaped body has been made on the basis of a factorized computational algorithm and H-like orthogonal grids in the presence of a mobile screen within a wide range of viscosity variation.

1. In the last few decades, the dynamics of large-scale vortex structures in variation of the viscosity of liquid media has invariably provoked interest among aerohydromechanical engineers. To a large extent this is associated with the progress in numerical simulation of separation flows, the development of admissible computational algorithms, and the growth in the computational resources of computers. It should be noted that only at the end of 1970s–beginning of 1980s (see, e.g., [1]) were the requirements imposed on selecting the schemes of an elevated (not less than second) order of approximation substantiated to achieve appropriate accuracy of the solution of the Navier–Stokes equations in predicting the characteristics of complex flows with circulation zones.

It is of interest to trace the basic tendencies in numerical studies of the evolution of the structure of stationary separated flows as the Reynolds number increases. The problems considered are certainly of a fundamental character and are reflected, in particular, in L. G. Loitsyanskii's well-known monograph [2].

It is historically established that two types of flows with circulation zones – closed flow in a square cavity with a moving boundary and flow of a homogeneous incompressible fluid past a transverse cylinder – has been subject to an extremely detailed analysis (see reviews in [3, 4]). However, as has been noted in [3], it is expedient to classify the conducted studies by the types of separation. Thus, it becomes possible to distinguish and unite into one group the works dealing with the consideration of flow past a disk [5], a cylinder, their combination [6], a stepped cylinder [7], and flow in a channel with a backward step [8]. The mentioned problems of a cavity and a cylinder should be referred to another group, and the problems of flow past a sphere and a profile should be added to them [see, e.g., [9]).

The effect of physical viscosity on the structure of the separated flow in the indicated problems manifests itself, as a rule, in a typical manner. As the Reynolds number increases, reciprocal-circulation flow becomes enhanced, and an increase in the sizes of primary large-scale vortices and the origination and evolution of the system of secondary vortices are observed. The presence of the walls bounding the flow exerts a substantial effect on the vortex dynamics.

This work is devoted to analysis of a little-studied flow near a profile of complex geometry near a mobile plane screen. Certain features of a turbulent mode of flow past such a profile were considered in [10-13]; however, the effect of viscosity was not studied in detail. The present work makes up for this deficiency.

2. The used methodology of numerical simulation of two-dimensional uniform flow of an incompressible viscous fluid past a body of arbitrary geometry is based on solution, within the framework of splitting by physical processes, of the initial system of Navier–Stokes equations for a laminar flow mode and the system of Reynolds equations for a turbulent flow mode, which is closed by a two-parameter dissipation model of

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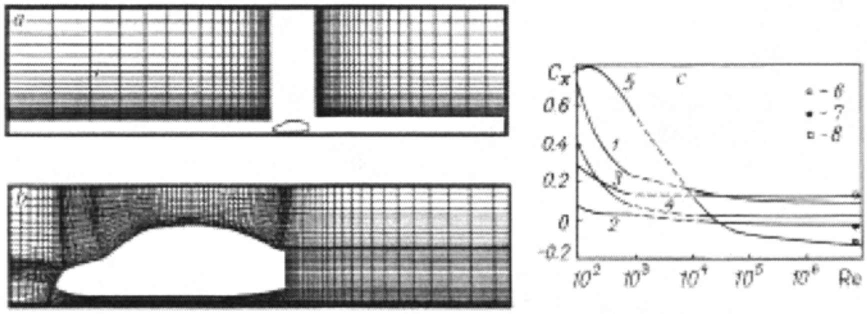

Fig. 1. Fragments of the H-type orthogonal computational grid around the profile of complex geometry near the mobile screen (the entire calculation region (a) and its central part (b)) and the dependences of the coefficients $C_x(1)$, C_{xp} (2), C_{xd} (3), C_{xf} (4), and C_{xn} (5) of the profile on the Reynolds number (c); experimental data 6-8 are taken from [12, 13].

turbulence [10]. The flow past a body in the presence of a mobile screen is considered in a stationary statement with allowance for flow separation within a wide range of variation of Reynolds numbers. The turbulent character of the flow with developed circulation zones at high Reynolds numbers is simulated within the framework of a modified phenomenological approach which is related to the introduction of eddy viscosity and allows for the effect of the curvature of streamlines on the characteristics of turbulence after the idea of Leschziner and Rody. The use of a high-Reynolds version of the modified model is combined with the use of the method of wall functions developed by Launder and Spalding.

A system of governing equations in divergent form is written in curvilinear coordinates, matched with the contour of a streamlined body, for increments in the dependent variables: Cartesian components of velocity, pressure, and characteristics of turbulence (kinetic energy of turbulent fluctuations and dissipation rate of turbulent energy). Discretization of the governing differential equations is made by the finite-volume method on a curvilinear orthogonal grid of the H-type generated on the basis of an original elliptical procedure [11].

The computational model, which is based on the adoption of the idea of splitting by physical processes and realized in the SIMPLEC procedure for a pressure correction, is subdivided into a number of computational blocks. At the "predictor" stage, preliminary components of the velocity for "frozen" pressure fields and characteristics of turbulence are determined, and at the "corrector" stage, pressure is corrected on the basis of the solution of the continuity equation with subsequent corrections of the velocity field and calculation of the characteristics of turbulence and eddy viscosity.

The selection of a centered pattern with fixation of dependent variables to the center of the computational cell allows one to substantially simplify the computational algorithm and reduce the number of computational operations. The monotonization of the pressure field, which is necessary in this approach, is made within the framework of the Rhee–Chou approach [3, 10].

A high stability of the computational procedure is ensured by using, for discretization purposes, convective terms of the equations in the implicit side of one-side counter-flow differences, damping nonphysical oscillations through the introduction of artificial diffusion, and using pseudo-time stabilizing terms. The calculating efficiency of the computational algorithm increases when use is made of the method of incomplete matrix factorization for solving systems of nonlinear algebraic equations. Rather high accuracy of calculation is determined by discretization of the explicit side of the equations by the scheme of the second-order approximation, including discretization of the convective terms of the equations by Leonard's quadratic counter-flow scheme. This methodology allows minimization of the effects of "numerical" diffusion, which are especially substantial in calculations of separated flows.

3. Figures 1-4 sum up some results of calculation of laminar and turbulent stationary flows past a profile of complex geometry, representing a two-dimensional model of a Volkswagen automobile, in the vicinity of a mobile screen with variation in the Reynolds number within the range from 10^2 to 10^7. To solve the

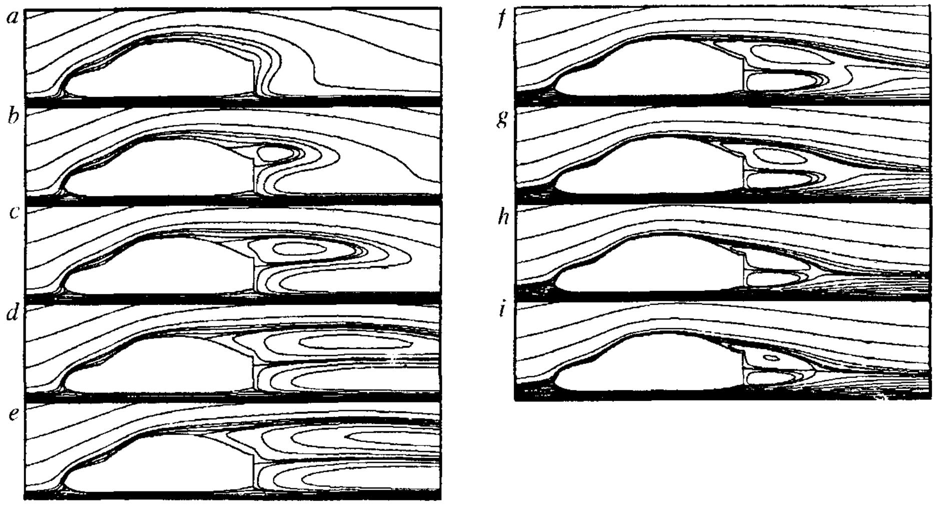

Fig. 2. Influence of the Reynolds number on the vortex pattern of flow past a profile: a) Re = 10^2; b) $2 \cdot 10^2$; c) $4 \cdot 10^2$; d) $7 \cdot 10^2$; e) 10^3; f) 10^4; g) $2 \cdot 10^4$; h) 10^5; i) 10^7. The streamlines correspond to the values of the stream function in the range from –0.03 to 0.3.

problem of two-dimensional flow past an automobile contour, the H-type grid, which is close to orthogonal, is selected (the grid has a rectangular cut at the center of the curvilinear computation region). Figure 1a, b shows the fragments of the grid near the automobile. The computation region is divided into 150 × 60 nonuniformly distributed cells. The automobile contour accounts for 15 cells in the transverse direction and 81 cells in the longitudinal direction. The inlet boundary is set at a distance of 7.5 of the automobile profile chord, which is taken as the characteristic dimension in this problem. The outlet boundary lies at a distance of 5.6 from the profile; the vertical size of the computation region is 3.39, clearance 0.06, and thickness of the automobile profile 0.3.

A uniform flow, which simulates the flow in the working part of a subsonic wind tunnel, is set at the inlet boundary. At the upper and outlet boundaries, "mild" boundary conditions are specified. The conditions which correspond to a mobile screen are set at the lower boundary, i.e., a solid wall moves at the velocity of an oncoming flow, which is taken as the characteristic one.

Stationary flow past the profile in the laminar mode is calculated within the range of Reynolds number variation from 10^2 to 10^3, and in the turbulent mode from 10^4 to 10^7. Thus, the transient mode characterized by a nonstationary cyclic vortex pattern is not considered here; however, the dashed portions of the curves in the dependences of the integral characteristics of the profile on the number Re correspond to this mode.

As is seen from the dependences of the integral force characteristics of the profile on the Reynolds number (Fig. 1c), their behavior is, on the whole, similar to the curves C_x(Re) for bodies of various shapes (cylinders, spheres, disks, disk-cylinders) [4-6] in their motion in an infinite space. The drag coefficient of the profile undergoes the most substantial changes on the portion of transition from low to moderate Reynolds numbers, when the effect of physical diffusion weakens and the processes of convective transfer becomes prevailing. In the mode of developed turbulent flow, the rate of change in the integral force characteristics decreases greatly, especially at Re exceeding 10^5.

Since the considered body is substatially extended in geometry and has a streamlined shape, it is characterized, just as in the absence of the screen by the predominance of the coefficient of friction resistance over the profile component this predominance is especially pronounced in the laminar mode. Owing to the cut in the rear part, the bottom drag plays a predominant part in the drag. It should be noted that the profile drag in the turbulent mode of flow past a body is negative, i.e., the pulling force caused by the distribution of static pressure around the contour affects the curvilinear profile.

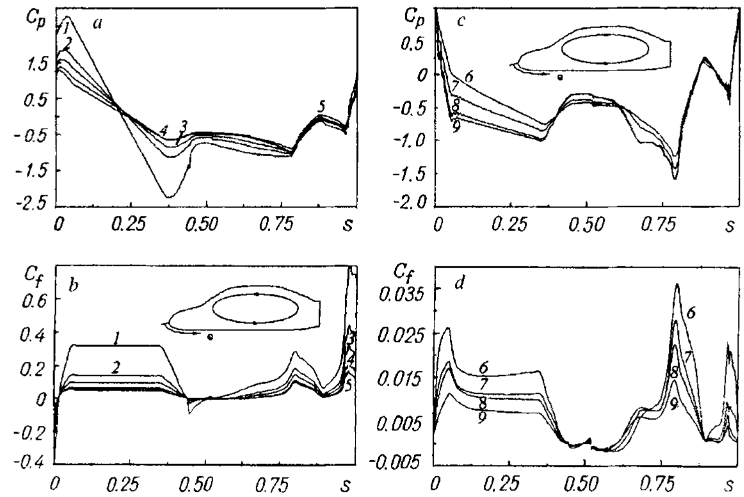

Fig. 3. Comparison of the distributions of the coefficient of pressure C_p (a, c) and friction drag C_f (b, d) over the surface of the profile in laminar (a, b) and turbulent (c, d) modes of flow: 1) Re = 10^2; 2) $2 \cdot 10^2$; 3) $4 \cdot 10^2$; 4) $7 \cdot 10^2$; 5) 10^3; 6) 10^4; 7) $2 \cdot 10^4$; 8) 10^5; 9) 10^7.

It is of particular interest to follow the dynamics of variation in the coefficient of normal force with increase in the Reynolds number. At Re = 200 the dependence C_{xn}(Re) has a local maximum, and within the range of Re variation from 10^4 to 10^5 it changes sign, thus becoming negative. Thus, as Re increases, the normal force is converted from the force separating the profile from the screen to a pressing one which facilitates better road grip of the tires. Figure 1c shows the comparison of the calculated integral force characteristics of the profile with the experimental data obtained on the basis of [12, 13]. The very close agreement of the presented results indicates the acceptability of the numerical predictions.

An analysis of the information about the local and integral characteristics of the flow and the dynamics of vortex structures (Figs. 2-4) with variation in Re allows a detailed consideration of the evolution of flow past a body and substantiation of the dynamics of the total force loads.

As is seen from the spectra of flow past a profile presented in Fig. 2, with an increase in the Reynolds number from 10^2 to 10^7 the character of the flow is transformed from nearly unseparated at Re = 10^2 to the formation of a structure of two large-scale vortices, which is virtually independent of the Reynolds number, in the developed turbulent mode in the near wake behind the body [10]. In a laminar mode of flow, a considerable growth of vortices in the wake with the movement of the separation point upstream is noted. It is of interest to emphasize that the point of separation of the two large-scale vortices on the rear part of the profile lies below the point of inflection of the contour and has a tendency to displacement to the center of the rear zone. The movement of the point of separation of an oncoming flow to the front point of inflection of the contour in a turbulent mode of flow past the profile is also noteworthy.

The deformation of the curves of the coefficients of pressure and friction, which occurs with increase in Re, shows great differences in the behavior of the curves for laminar and turbulent flows past a body (Fig. 3). The results for Re = 10^2 stand by themselves, whereas the curves for the Reynolds numbers lying within the range of from $2 \cdot 10^2$ to 10^3 do not noticeably differ from each other. A substantial scatter in the characteristics, which is caused by an increase in the gradients in the forepart of the profile, is typical of a turbulent mode of flow.

In the clearance between the automobile and the screen, acceleration flow of the channel type with a pressure drop along the channel length is realized. The wake region is, on the contrary, characterized by isobaricity, which is inherent in jet flows. In turbulization of the flow, the pressure field has a strong nonuniformity in the upper part of the contour with a distinct rarefaction in the convex part. The zone of increased

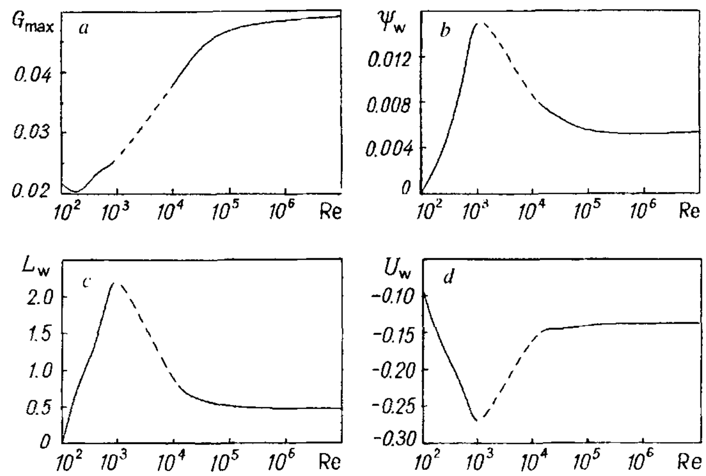

Fig. 4. Flow rate of a fluid through the gap between the profile and the screen (a), the maximum stream function in the separation zone behind the profile (b), the length of the separation zone (c), and the maximum velocity of the return flow in it (d) as functions of the Reynolds number; the dashed portions of the curves correspond to the assumed zone of the transient flow mode.

pressure is reproduced correctly in front of the concavity in the vicinity of the front glass. Here a very thin and short separation zone also appears.

A decrease in physical viscosity leads, as follows from Fig. 4, to a monotonic increase in the flow rate of the fluid through the gap between the profile and the screen irrespective of the mode of flow. At the same time, as Re increases, the tendencies in the behavior of maximum values of stream functions and the velocity of return flow and the length of the separation zone in the near wake behind the body are opposite for the laminar and turbulent modes. The high-rate increase in the sizes and intensity of the flow separation region behind the body is similar to the evolution of the large-scale vortex structures in the wake behind the transverse cylinder [10] and in the channel with a backward step [8]. In turbulization of the flow, its character in the separation zones changes radically. The dimensions of the large-scale vortices in the near wake and their intensity decrease monotonically, thus tending to asymptotic values. It is of interest to note that maximum velocities of the return flow at Reynolds numbers of 10^3 and 10^7 differ twofold, being equal to 0.325 and 0.135, respectively.

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NOTATION

s, distance measured clockwise along the contour of the profile and related to its length; U, longitudinal velocity component; C_p, coefficient of pressure; C_f, coefficient of friction; Re, Reynolds number; ψ, stream function; C_x, C_{xp}, C_{xd}, C_{xf}, and C_{xn}, motion drag, bottom drag, base drag, friction drag, and coefficient of normal force; L_w, length of the separation region in the near wake behind the body; G, flow rate through the gap between the profile and the mobile screen. Subscripts: w, parameter in the near wake behind the body; max, maximum value.

REFERENCES

1. I. A. Belov and S. A. Isaev, *Prikl. Mekh. Tekh. Fiz.*, No. 1, 41-45 (1982).

2. L. G. Loitsyanskii, *Mechanics of Liquids and Gases* [in Russian], Moscow (1985).
3. I. A. Belov, S. A. Isaev, and V. A. Korobkov, *Problems and Methods of Calculation of Separated Incompressible Fluid Flows* [in Russian], Leningrad (1989).
4. I. A. Belov and N. A. Kudryavtsev, *Heat Transfer and Resistance of Tube Bundles* [in Russian], Leningrad (1987).
5. I. A. Belov, S. A. Isaev, M. I. Nisht, and A. G. Sudakov, *Inzh.-Fiz. Zh.*, **50**, No. 3, 390-396 (1986).
6. V. K. Bobyshev, S. A Isaev, and O. L. Lemko, *Inzh.-Fiz. Zh.*, **51**, No. 2, 224-232 (1986).
7. S. A. Isaev, V. M. Suprun, and O. L. Shul'zhenko, *Inzh.-Fiz. Zh.*, **60**, No. 3, 433-439 (1992).
8. S. A. Isaev and A. E. Usachev, in: *Industrial Aerodynamics* [in Russian], Moscow, 43-75 (1991).
9. P. A. Baranov, S. A. Isaev, Yu. S. Prigorodov, and A. G. Sudakov, *Aviats. Tekh.*, No. 3, 30-35 (1999).
10. S. A. Isaev, N. A. Kudryavtsev, and A. G. Sudakov, *Inzh.-Fiz. Zh.*, **71**, No. 4, 618-631 (1998).
11. S. Ya. Grabarnik and S. A. Isaev, *Inzh.-Fiz. Zh.*, **71**, No. 5, 872-879 (1998).
12. R. Buchheim, H. Röhe, and H. Wüsteberg, *Volkswagen. Forschung-neue Technologien. Sonderdruck aud ATZ Automobiltechnische Zeitschrift*, H. 11, 91 (1989).
13. K. Kitoh, T. Kobayashi, and H. Morooka, in: *Proc. Int. Conf. "Comput. Mech. 86: Theory and Appl.,"* Tokyo (1986), pp. 77-82.