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MODELING OF REDUCTION IN THE RESISTANCE OF A BODY OF REVOLUTION IN A VISCOUS FLUID

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The problem of flow past a body of revolution with modeling of a traveling wave on its surface has been solved. Parametric investigations of the qualitative and quantitative influence of the parameters of the traveling wave on control over the flow past the body of revolution have been carried out.

Introduction. The mechanism of reduction in the hydrodynamic resistance of bodies has been substantiated theoretically in [1, 2] and has been checked by numerical experiment in [3–5]; this mechanism involves a reorganization of flow in which the boundary layer is replaced by periodic flow. A positive answer to the question of whether periodic flow can be formed by the action of a wave traveling on the body's surface has been found and the qualitative and quantitative influence of the parameters on control over conical flow has been investigated. In this work, which is a continuation of [5], in which the velocity of external potential flow was prescribed in the form of a power function corresponding to flow past conical bodies (including a cylinder and a backward cone), the subject of numerical experiment has been the model of an axisymmetric body of 20% thickness. This work seeks to investigate the influence of the parameters of a traveling wave (amplitude, phase velocity, and frequency) on control over flow past a body of revolution for minimization of its hydrodynamic resistance.

Formulation of the Problem and Method of Its Solution. Numerical modeling is carried out by solution of the total Navier–Stokes equations in the domain of a "geometric boundary layer" introduced in [5] on a moving computational template which is shifted downstream in solving the entire problem and covers a subdomain as large as two adjacent surface waves. This approach substantially reduces the computation time with a guaranteed level of numerical dissipation of solution, since the characteristic Reynolds number is determined from the wavelengths at which the domain is decomposed. In the calculations carried out, the lower boundary of the domain was deformed according to the law of a traveling wave with a variable amplitude. The wavelength changed on each portion of the flow region, since it was determined by the value of the phase velocity, which was selected in proportion to the flow velocity and changed together with it.

The computational grid in the physical domain is geometrically adapted to the contour of the body of revolution and is clustered in its vicinity, whereas in the canonical domain it is rectangular.

The system of nonstationary Navier–Stokes equations is supplemented with boundary conditions at the boundaries of the templates. We have prescribed the velocity of potential flow at the external boundary, the coincidence of the velocity of motion of the fluid with the velocity of motion of the boundary on the surface of the frame, the flow parameters equal to their values either at the boundary with the adjacent wave or to the parameters of potential flow of the body for the first wave, and "soft" boundary conditions at the right boundary.

The Navier–Stokes equations written in the form of conservation laws have been solved by the large-particle method [6]. The length of the frame was taken as a unit length and the velocity of the incident flow was taken as a unit velocity. Potential axisymmetric flow past the frame was obtained by solution of the potential equation by the boundary-element method for the integral equation equivalent to it.

Calculation Results. We carried out a series of parametric calculations in which the varied parameters were phase velocity, amplitude, position of the amplitude maximum, and angular frequency of the surface wave. Variation of the phase velocity is determined by the values of the relative (referred to the velocity of potential flow at the run-

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TABLE 1. Parameters and Results of Numerical Experiments

Variant of calculation	Re	ω	x^*	A_0	A^*	U_{ph}/U_0	U_{ph}/U^*	U_{ph}/U_f	*SDe*
1	$1.0{\cdot}10^6$	$6.0{\cdot}10^4$	0.35	$5.0{\cdot}10^{-4}$	$1.0{\cdot}10^{-3}$	0.5	1.0	2.0	$-6.56{\cdot}10^{-3}$
2	$1.0{\cdot}10^6$	$6.0{\cdot}10^4$	0.35	$2.5{\cdot}10^{-4}$	$5.0{\cdot}10^{-4}$	0.5	1.0	2.0	$-6.87{\cdot}10^{-3}$
3	$1.0{\cdot}10^5$	$6.0{\cdot}10^4$	0.35	$5.0{\cdot}10^{-4}$	$1.0{\cdot}10^{-3}$	0.5	1.0	2.0	$-1.50{\cdot}10^{-2}$
4	$1.0{\cdot}10^6$	$3.0{\cdot}10^4$	0.35	$1.0{\cdot}10^{-3}$	$2.0{\cdot}10^{-3}$	0.5	1.0	2.0	$2.17{\cdot}10^{-2}$
5	$1.0{\cdot}10^6$	$1.2{\cdot}10^5$	0.35	$2.5{\cdot}10^{-4}$	$5.0{\cdot}10^{-4}$	0.5	1.0	2.0	$-3.57{\cdot}10^{-2}$
6	$1.0{\cdot}10^6$	$3.0{\cdot}10^4$	0.65	$1.0{\cdot}10^{-3}$	$2.0{\cdot}10^{-3}$	0.5	1.0	2.0	$-9.90{\cdot}10^{-3}$
7	$1.0{\cdot}10^6$	$1.2{\cdot}10^5$	0.25	$2.5{\cdot}10^{-4}$	$5.0{\cdot}10^{-4}$	0.5	1.0	2.0	$-3.30{\cdot}10^{-2}$
8	$1.0{\cdot}10^6$	$1.2{\cdot}10^5$	0.25	$2.5{\cdot}10^{-4}$	$5.0{\cdot}10^{-4}$	0.5	1.0	2.5	$-2.85{\cdot}10^{-2}$

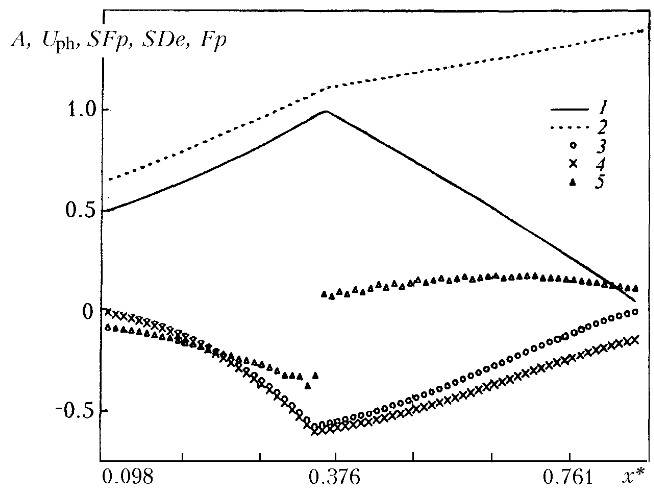

Fig. 1. Distribution of the parameters and the results of calculation along the body's chord of: the amplitude A (1), the phase velocity U_{ph} (2), the sum of the work of pressure forces *SFp* (3), the energy shortage of the flux *SDe* (4), and the density of the work of pressure forces *Fp* (5). The dimensionless values of the indicated quantities are presented on a scale: $A{\cdot}1000$, $U_{ph}{\cdot}1$, $SFp{\cdot}20$, $SDe{\cdot}20$, and $Fp{\cdot}200$.

ning point) velocity in the forebody, at the point x^*, where the wave amplitude is maximum, and in the afterbody. Variation of the amplitude is determined by its values in the forebody of the frame, at the point x^*, and in the afterbody of the frame, where it is always prescribed to be equal to zero.

The quantities computed are: work of pressure forces in a unit time per unit surface (energy-flux density), total work of pressure forces from the beginning to the running point, running energy shortage (gap) in the flux, and work of friction. The value of the energy shortage at the backward point numerically coincides with half the coefficient of resistance of the body [2].

A larger growth in the phase velocity was prescribed from the point x^*, which ensured a change of sign of the work of pressure forces. Whereas to this point, the energy flux was directed from the fluid to an elastic coating, after this point the fluid gives energy to the flux.

Since the energy shortage in the afterbody is made up of the work of friction and the work of pressure forces, minimization of the total work of pressure forces is the condition of minimization of resistance.

Table 1 gives parameters and results of the numerical experiments carried out. The distribution of the parameters of the traveling wave along the chord of the body and of those computed in calculating the characteristics of flow past the body is given in Fig. 1.

A comparison of variants 1 and 2, which differ only in wave amplitude, enables us to infer that a twofold decreasing the amplitude had only a slight effect on the resistance. This circumstance can be used for decreasing in the power of internal vibration sources, which are determined by the amplitude squared.

A comparison of variants 1 and 3, which differ only in Reynolds number, shows that the coefficient of resistance decreases with growth in the Reynolds number more rapidly than $1/\sqrt{\mathrm{Re}}$. This enables us to evaluate the resistance for different values of the Reynolds number.

The influence of the frequency that determines the wavelength on the resistance can be elucidated from variants 4 and 5. The frequency is equal to 300 rad/sec in the first case and to 1200 rad/sec in the second case. The amplitude changed simultaneously with frequency to preserve the amplitude-to-wavelength ratio.

As is seen from the calculations, a twofold decrease in the frequency with simultaneous increase in the amplitude resulted in the tractive force. The energy efficiency of such a method of creation of the thrust can be evaluated only after the loss in the elastic coating has been determined.

A comparison of variants 4 and 6 enables us to reveal the influence of the downstream displacement of the point x^* by the value of the resistance for the case where the wavelength is twice as large as the basic value.

A comparison of variants 7 and 8 shows that increase in the phase velocity in the afterbody influences the resistance only slightly.

CONCLUSIONS

We draw the following conclusions according to the results of the numerical experiments carried out. Just as for the conical flow considered in [5], a finite-length wave traveling on the surface of the frame of a body of revolution reorganizes fluid flow so that a stationary periodic flow with closed streamlines (if it is considered in a moving coordinate system) is formed. Such a flow is characterized by the fact that it is independent of the Reynolds number, as is the case in Couette annular flow. Mathematically this means that the steady-state solution may be sought for any Reynolds number only if it is much more than unity. Unlike the fixed boundary, the traveling wave carries out exchange of energy with the fluid flow not only due to viscous forces but to pressure forces as well. Depending on the sign of the velocity gradient and on the relative value of the phase velocity, the energy flux may be directed either from the traveling wave to the fluid or conversely. The phase velocity in the forebody of the frame must be selected so that the energy flux is negative (from the fluid flow to the elastic medium). This ensures a growth in the amplitude and a formation of annular flow. In the afterbody of the frame, the phase velocity must be selected so that the energy flux is positive (from the elastic boundary to the fluid) and the energy contained in the vibrations of the elastic coating is used for acceleration of the fluid and keeping the flow from separating. Since the parameters of the surface wave are determined by the elastic parameters of the coating and the internal vibration sources, a conclusion on the energy expediency of such a method of reduction in viscous loss is never possible until the work of the internal sources has been evaluated, which is the subject of further investigations apart from purpose-oriented parametric minimization of the total work of pressure forces.

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NOTATION

A_0, relative amplitude of the traveling wave at the beginning of the body; A^*, maximum relative amplitude of the traveling wave; *Fp*, density of the work of pressure forces; *SDe*, value of the energy shortage at the backward point, which is numerically coincident with half the coefficient of resistance; *SFp*, sum of the work of pressure forces; Re, Reynolds number; U_{ph}, phase velocity of propagation of the traveling wave; U_0, phase velocity of the traveling wave at the forward point; U, phase velocity of the traveling wave at the point x^*; U_{f}, phase velocity of the traveling wave at the end of the body; x^*, abscissa of the body's chord where the amplitude of the surface wave attains its maximum; ω, angular frequency of the wave. Subscripts: 0, initial; f, final; ph, phase.

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