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CONTROL OF FLOW PAST A BODY OF REVOLUTION, MINIMIZING THE BODY'S DRAG IN A VISCOUS FLUID

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The problem of determination of the parameters and shape of a running wave on the surface of a body of revolution, which minimize the body's drag, has been solved. The physical effects occurring in such a control have been analyzed.

A mechanism of reduction in the hydrodynamic drag of bodies has theoretically been substantiated in [1, 2] and has been checked by numerical experiment in [3–7]; this mechanism involves such a reorganization of flow in which the boundary layer is replaced by a periodic flow. A positive answer to the question of whether a periodic flow can be formed under the action of a wave running on the body's surface was obtained and the qualitative and quantitative influence of the parameters on the control of conic flow and flow past bodies of revolution was investigated. In the present work, which is a continuation of [5–7], we have modeled flow past a body of revolution, which minimizes its hydrodynamic drag, on the basis of the parametric investigations of [6] and an additional study of the influence of the wave shape on the the body's drag and the influence of a growing pressure gradient on the destabilization of a system of running waves.

The formulation of a boundary-value problem and the method for solving it have been presented in [5] in detail. The results of parametric calculations, in which the phase velocity, amplitude, position of the amplitude maximum, and circular frequency of a surface wave were variable parameters, have been given in [6, 7]. A variation of the phase velocity was determined by the values of the relative (normalized to the value of the velocity of potential flow at a running point) velocity at the beginning of the frame, at the point x^*, where the wave's amplitude attains its maximum, and astern (in the afterbody). A variation of the amplitude was specified by its values at the beginning of the frame, at the point x^*, and at the end of the frame, where it is always equal to zero. The quantities to be computed were the total work of pressure forces (pressure work) from the beginning to the running point, the running shortage of energy in the flow, and the work of friction forces (friction work). The value of the energy shortage at the stern point is numerically coincident with half the drag coefficient of the body [2]. As a result, we determined the basic variant of running-wave parameters which reduces the drag of the body of revolution under study by an order of magnitude: $\mathrm{Re} = 10^6$, $\omega = 6\cdot10^4$, $x^* = 0.35$, $A_0 = 5\cdot10^{-4}$, $A^* = 10^{-3}$, $U_{\rm ph}/U_0 = 0.5$, $U_{\rm ph}/U^* = 1$, $U_{\rm ph}/U_{\rm f} = 2$, and $S_E = -6.56\cdot10^{-3}$.

To determine the influence of the shape of the running wave on the drag of the body we carried out calculations in which the wave shape as a function of the coordinate x was specified according to the formulas

$$y_A(x) = \sum_{l=1}^{L} A(l, n) \sin (lx) \ , \quad y_B(x) = \sum_{l=1}^{L} B(l, n) \sin (lx) \ ,$$

where $A(l, n) = \sin (l\pi/n)$ and $B(l, n) = n \sin^2 (l\pi/n)/l$. Figure 1a and b shows the form of the wave for $L = 5$ and $n = 2$ for $y(x) = y_A(x)$ and $y(x) = y_B(x)$, whereas Fig. 1c shows the basic shape of the running wave.

Calculation Results. Table 1 gives the shape parameters and the results of the numerical experiments carried out: the friction drag, the sum of the pressure work, and the drag of the body. Variant No. 1 corresponds to the basic shape of the running wave. The distribution of these quantities as a function of x along the body's chord for the basic

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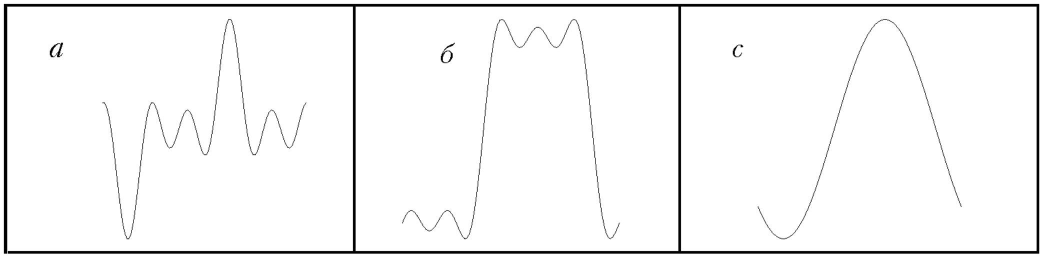

Fig. 1. Shape of the running wave.

TABLE 1. Results of a Numerical Experiment on Determination of the Drag of a Body as a Function of the Shape of a Running Wave

Variant No.	Wave shape	l	n	S_f	S_p	S_E
1	$y_A(x)$	1	1	$-6.10\cdot10^{-3}$	$-4.60\cdot10^{-4}$	$-6.56\cdot10^{-3}$
2	$y_B(x)$	3	2	$-6.30\cdot10^{-3}$	$5.70\cdot10^{-3}$	$-6.00\cdot10^{-4}$
3	$y_B(x)$	3	4	$-6.31\cdot10^{-3}$	$5.30\cdot10^{-3}$	$-1.01\cdot10^{-3}$
4	$y_B(x)$	3	8	$-6.40\cdot10^{-3}$	$4.30\cdot10^{-3}$	$-2.10\cdot10^{-3}$
5	$y_A(x)$	3	2	$-6.30\cdot10^{-3}$	$-1.09\cdot10^{-3}$	$-7.39\cdot10^{-3}$
6	$y_A(x)$	3	4	$-6.40\cdot10^{-3}$	$-1.90\cdot10^{-3}$	$-8.30\cdot10^{-3}$
7	$y_A(x)$	3	8	$-6.60\cdot10^{-3}$	$-1.00\cdot10^{-3}$	$-7.60\cdot10^{-3}$
8	$y_B(x)$	5	2	$-6.40\cdot10^{-3}$	$6.00\cdot10^{-3}$	$-4.00\cdot10^{-4}$
9	$y_B(x)$	5	4	$-6.40\cdot10^{-3}$	$6.10\cdot10^{-3}$	$-3.00\cdot10^{-4}$
10	$y_B(x)$	5	8	$-6.60\cdot10^{-3}$	$5.10\cdot10^{-3}$	$-1.50\cdot10^{-3}$
11	$y_A(x)$	5	2	$-6.30\cdot10^{-3}$	$-7.9\cdot10^{-4}$	$-7.10\cdot10^{-3}$
12	$y_A(x)$	5	4	$-6.60\cdot10^{-3}$	$-2.7\cdot10^{-4}$	$-6.87\cdot10^{-3}$
13	$y_A(x)$	5	8	$-6.70\cdot10^{-3}$	$-7.70\cdot10^{-4}$	$-7.47\cdot10^{-3}$
14	$y_B(x)$	7	2	$-6.30\cdot10^{-3}$	$6.40\cdot10^{-3}$	$1.00\cdot10^{-3}$

variant and the typical variant decreasing the drag from the series of calculations carried out (No. 9, see Table 1) is presented in Fig. 2. An analysis of the data in the table shows that the shape of the running wave influences the friction drag only slightly (therefore, the distribution of the friction work is not given in Fig. 2)), whereas the total friction work changes several times, which can be used to decrease the flow-energy shortage. Noteworthy is the following fact: the sign of the total pressure work for waves of the type $y_B(x)$, having a "saturated" profile, suggests that finally the surface wave has done a large amount of work on the fluid, which has generated a decrease in the drag. And conversely, a "peak" shape of running waves of the type $y_A(x)$ leads to a larger amount of work done by the flow on the body's surface than the basic variant for which this work is virtually zero, which increases the drag. The above trend has been confirmed by the last variant of the table with harmonic No. 7.

All these effects are of importance just in the case of stable nonseparating flow past bodies and, consequently, we must analyze the influence of a growing pressure gradient on the destabilization of a system of running waves in the afterbody. A positive gradient is known to be capable of causing both stability loss by the laminar regime and separation of the flow. The first leads to an increase in the friction drag, and the second causes the pressure drag to grow. The calculations carried out show that periodic flow with a small amplitude possesses these properties, too, but the variants of calculations of flow formed by a running wave with a large amplitude confirm that its increase may give rise to a stable flow in the afterbody in the form of a series of vortices. As far as the separation of flow is con-

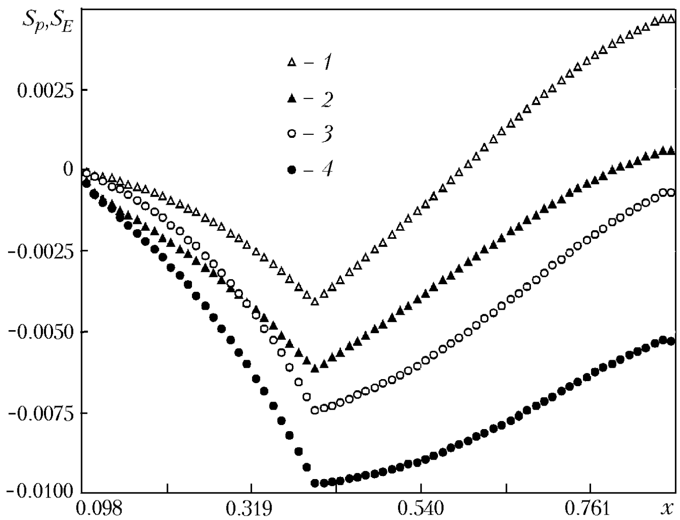

Fig. 2. Distribution of the sum of the pressure work S_p (1, 3) and the total shortage of the flow energy S_E (2, 4) for variant No. 9 (see Table 1) (1, 2) and for the basic variant (3, 4).

cerned, the calculations demonstrate that a running wave with the indicated law of variation in the phase velocity along the body's frame (in this case, with an excess of its values over the local flow velocity in the afterbody) is capable, for the corresponding amplitude, of transferring such a momentum to the wall flow, which turns out to be sufficient for a nonseparating flow up to the rear critical point.

Thus, the numerical experiments carried out enable us to draw the following conclusions. Just as for the flows considered in [5–7], a wave running on the surface of the frame of a body of revolution of finite length reorganizes fluid flow so that a stationary periodic flow with closed streamlines is formed, if it is considered in a moving coordinate system. This regime of flow is characterized by its independence from the Reynolds number. Not only do we have the exchange of energy with the fluid due to viscous forces on the source side of the body, but we also have the energy exchange due to pressure forces, which can be used to accelerate the fluid and to ensure against flow separation. Since the parameters of a surface wave are determined by the elastic parameters of a coating and the internal sources of vibration, the conclusion on the energy expediency of such a method for reducing viscous loss is never possible until the work of the internal sources is evaluated.

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NOTATION

A_0, relative amplitude of the running wave in the forebody; A^*, maximum relative amplitude of the running wave; $A(l, n)$ and $B(l, n)$, amplitudes of harmonics; L, number of harmonics in the representation of the running wave; l, harmonic No., n, parameter; Re, Reynolds number; S_E, total value of the energy shortage at the stern point, it is numerically coincident with half the drag coefficient; S_p, sum of the pressure work; S_f, sum of the friction work; $U_{\rm ph}$, phase velocity of propagation of the running wave; U_0, phase velocity of the running wave at the leading point; U^*, phase velocity of the running wave at the point x^*; $U_{\rm f}$, phase velocity of the running wave in the afterbody; x, coordinate axis guided along the body's chord; x^*, abscissa of the body's chord where the amplitude of the surface wave attains its maximum; ω, circular frequency of the wave. Subscripts: 0, initial; f, final; ph, phase; A and B, type of wave; E, energy; f, friction force; p, pressure.

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