Journal of Applied Mechanics and Technical Physics, Vol. 50, No. 5, pp. 760–767, 2009

AERODYNAMIC CHARACTERISTICS OF AIRFOILS WITH ENERGY SUPPLY

S. M. Aulchenko[1], **V. P. Zamuraev**[1,2], **and A. P. Kalinina**[1,2]

UDC 533.6.011

The possibility of controlling the aerodynamic characteristics of airfoils with the help of one-sided pulsed-periodic energy supply is studied. The change in the flow structure near the airfoil and its aerodynamic characteristics are determined as functions of the magnitude of energy supply and of the energy-supply location by means of the numerical solution of two-dimensional unsteady equations of gas dynamics. It is demonstrated that external energy supply can substantially improve the aerodynamic characteristics of airfoils with a high lift-to-drag ratio. The moment characteristics of the airfoil are found.

Key words: *transonic flow, airfoil, aerodynamic characteristics, energy supply, Euler equations.*

Introduction. The effect of energy supply on the aerodynamic characteristics of a symmetric airfoil in a flow with a free-stream Mach number $\mathrm{M}_\infty = 0.85$ was studied in [1–4]. At the same Mach number M_∞, the influence of energy supply on the aerodynamic characteristics of an airfoil was considered in [5]. The effect of energy supply in the case of transonic flows around asymmetric airfoils with a substantially higher lift-to-drag ratio typical for lower Mach numbers, however, was not give proper attention. The aerodynamic characteristics of bodies in transonic flow are known to change substantially. Yuriev (see, e.g., [6]) demonstrated an ambiguous behavior of the drag of the NACA-0012 airfoil with energy supply, depending on the free-stream Mach number varying in the range $\mathrm{M}_\infty = 0.8$–0.9: it can either increase or decrease. In contrast to [1–6], Starodubtsev [7] performed a pioneering study with numerical simulations of a transonic flow around an airfoil with local volume heat supply on the basis of Reynolds-averaged Navier–Stokes equations. Various aspects of the influence of energy supply on the flow around an airfoil were considered, and an upstream shift of the closing shock wave was found, which confirmed the previously established (see, e.g., [1]) character of flow reconstruction. It should be noted that the chosen location, compact shape, and power of the energy source did not improve the lift-to-drag ratio K of the airfoil. The influence of heat transfer between the flow and the surface was considered in the examined range of the free-stream Mach numbers, in addition to the effect of volume energy supply (see, e.g., [8, 9]).

In the present paper, we study the effect of energy supply on the flow around an optimal airfoil (with respect to its lift-to-drag ratio for the Mach number $\mathrm{M}_\infty = 0.75$ in a certain class of configurations). As the Mach number M_∞ is smaller and the shape is more optimal, the lift-to-drag ratio of this airfoil is substantially higher than that in the cases considered in [1–7]. Therefore, it seems of interest to study the effect of energy supply as a method of controlling the aerodynamic characteristics of the airfoil.

Formulation of the Problem. As a mathematical model for the description of a plane unsteady flow of an inviscid heat-non-conducting gas with a constant ratio of specific heats γ, we use the Euler equations in a conservative form

$$\frac{\partial \boldsymbol{U}}{\partial t} + \frac{\partial \boldsymbol{F}}{\partial x} + \frac{\partial \boldsymbol{G}}{\partial y} = \boldsymbol{Q},$$

[1]Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090; aultch@itam.nsc.ru. [2]Novosibirsk State University, Novosibirsk 630090; zamuraev@itam.nsc.ru. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 50, No. 5, pp. 36–45, September–October, 2009. Original article submitted July 18, 2008; revision submitted November 18, 2008.

$$\boldsymbol{U} = (\rho, \rho u, \rho v, e), \qquad \boldsymbol{F} = (\rho u, p + \rho u^2, \rho uv, u(p+e)), \tag{1}$$

$$\boldsymbol{G} = (\rho v, \rho uv, p + \rho v^2, v(p+e)), \qquad \boldsymbol{Q} = (0, 0, 0, q).$$

Here, the coordinate axes x and y are directed along the airfoil chord and perpendicular to it, respectively, and are normalized to the chord length b; the following quantities are used for normalization of other parameters: b/a_0 for the time t, a_0 for the gas velocity components u and v and the velocity of sound a, ρ_0 for the density ρ, $\rho_0 a_0^2$ for the pressure p and the total energy per unit volume of the gas e, and $\rho_0 a_0^3/b$ for the power q supplied to a unit volume of the gas; p_0 and a_0 are the dimensional free-stream pressure and velocity of sound; ρ_0 is found from the condition $p_0 = \rho_0 a_0^2$. For the gas model considered, we have

$$p = (\gamma - 1)(e - \rho(u^2 + v^2)/2), \qquad a^2 = \gamma p/\rho.$$

In pulsed-periodic energy supply, the value of q is determined by the expression

$$q = \Delta e f(t),$$

where $f(t) = \sum_i \delta(t - i\Delta t)$, $\delta(t)$ is the pulsed Dirac function, Δt is the period of energy supply, and Δe is the energy supplied to a unit volume of the gas.

System (1) is supplemented by the boundary conditions on the boundary of the doubly connected computational domain Ω, which is a rectangle with the inner boundary corresponding to the contour of the airfoil considered. The free-stream conditions are imposed on the left, upper, and lower boundaries of this domain, the "soft" conditions are set on the right boundary, and the no-slip condition is imposed on the airfoil contour.

System (1) is numerically solved by the method described, for instance, in [3].

In the model considered, pulsed energy supply is performed instantly; the gas density and velocity are not changed in this process. The energy density of the gas e in the energy-supply zone increases by $\Delta e = \Delta E/\Delta S$ (ΔE is the total supplied energy normalized to $\rho_0 a_0^2 b^2$ and ΔS is the area of the energy-supply zone). The energy is supplied in thin zones shaped approximately as rectangles and adjacent to the airfoil. Significant nonlinear effects were observed in this case in [1]. In particular, the numerical experiments [1] with variation of the energy-supply period Δt in a flow with the Mach number $\mathrm{M}_\infty = 0.85$ around the NACA-0012 airfoil showed that the shock-wave structure of the flow depends substantially on the value of Δt. At high values of the parameter Δt, for instance, at $\Delta t = 0.5$, the flow structure is partly reconstructed, and the upstream shift of the closing shock wave is rather small. Its position changes within one period. At $\Delta t = 0.05$, the closing shock wave is stabilized ahead of the energy-supply zone, and its position remains unchanged during one period. This value of Δt is considered as the limiting value.

The initial distribution of parameters corresponding to a steady flow around the airfoil with no energy supply was obtained for the variables ρ, u, v, and p with an absolute error of 10^{-4} in all nodes of the grid. The problem is solved as an unsteady problem since the beginning of energy supply till the moment when a periodic solution is obtained. This moment was determined by comparing the averaged values of the drag coefficient of the airfoil on time intervals multiple to the energy-supply period. The absolute error was smaller than 10^{-7}.

Airfoil Design. To solve the problem posed, we designed an airfoil with a fixed thickness (12%), possessing the maximum lift-to-drag ratio with a restriction on the minimum admissible lift coefficient $C_y = 0.5$ for the free-stream Mach number $\mathrm{M}_\infty = 0.75$ in a given class of configurations. In airfoil design, we used a standard parametric presentation of its contour by the midline and thickness function. Two geometric parameters (midline bending deflection f and its abscissa x_f) and one aerodynamic parameter (angle of attack) were varied. The airfoil chord length b and the maximum airfoil thickness c are assumed to be fixed. The thickness function corresponds to the NACA airfoil series:

$$L(x) = c(0.2969x^{1/2} - 0.1260x - 0.3516x^2 + 0.2843x^3 - 0.1036x^4),$$

while the midline is shaped as a parabola. As a result, we designed an airfoil shown in Figs. 1–4. The maximum lift-to-drag ratio of the airfoil $K_{\max} = 69$ was reached at the angle of attack $\alpha = -0.1°$ and satisfied restriction on the lift coefficient. At higher values of K, the restriction on the minimum lift coefficient is not satisfied. A typical feature of transonic airfoils is their high sensitivity to the angle of attack. In particular, this airfoil at $\alpha = 0$ has the lift-to-drag ratio $K = 62.4$. In practice, this drawback is compensated by wing twisting owing to which the

TABLE 1

Aerodynamic Coefficients of the Airfoil as Functions of the Angle of Attack without Energy Supply

Calculation variant	α, deg	$C_x \cdot 10^3$	C_y	C_m	K
1	−1	2.61	0.366	−1.34	140.0
2	−0.1	8.06	0.556	−1.97	69.0
3	0	9.26	0.578	−2.04	62.4
4	1	31.60	0.790	−2.75	25.0
5	2	57.20	0.995	−3.45	17.4

TABLE 2

Dependence of the Aerodynamic Coefficients of the Airfoil on the Location of the Energy-Supply Zone

Calculation variant	x_1–x_2	$C_x \cdot 10^3$	C_y	C_m	K
1	—	9.26	0.578	−2.04	62.4
2	3.157–3.184	9.12	0.492	−1.72	53.9
3	3.195–3.226	7.69	0.469	−1.65	61.0
4	3.238–3.271	7.40	0.485	−1.70	65.6
5	3.558–3.600	8.48	0.570	−2.01	67.2
6	3.838–3.864	8.68	0.582	−2.05	67.0
7	3.985–3.994	9.44	0.583	−2.06	61.8

Note. The first line gives the values of the coefficients without energy supply.

airfoil cross sections in the spanwise direction are aligned at different angles of attack. Therefore, the effect of energy supply was further investigated mainly for the angle of attack $\alpha = 0$ rather than for the flow regime with the maximum lift-to-drag ratio. The aerodynamic coefficients of the airfoil without energy supply are summarized in Table 1 (C_x, C_y, and C_m are the wave drag, lift, and pitching moment coefficients, respectively).

Calculation Results. The calculations were performed for the above-mentioned optimal airfoil in an ideal gas ($\gamma = 1.4$) flow at an angle of attack $\alpha = 0$ with the limiting value of the period $\Delta t = 0.05$ (the corresponding dimensionless frequency of energy supply was $\omega = 20$). The free-stream Mach number $\mathrm{M}_\infty = 0.75$, the location of the energy-supply zone (the energy was supplied from the lower side of the airfoil), and the magnitude of energy supply were varied.

Table 2 shows the aerodynamic coefficients of the airfoil, depending on the geometric parameters of the energy source with a power $\Delta E/\Delta t = 0.005$ (x_1 and x_2 are the coordinates of the left and right boundaries of the source; the airfoil chord is located on the interval $3 \leqslant x \leqslant 4$). It follows from Table 2 that the energy source location exerts a significant, but an ambiguous effect on the aerodynamic characteristics of the airfoil. In variant 2, the source is located in a local supersonic region, actually, in the mid-section area (more exactly, ahead of it, $x_{\mathrm{mid}} = 3.204$), which is ineffective, because a low-density wake of significant thickness is formed behind the source owing to a large local curvature of the airfoil contour. Because of instability of the contact discontinuity separating the wake from the main flow, origination and shedding of vortices are possible even with moderate values of energy. A secondary supersonic region can be formed in the main flow. As a result, a periodic solution is not established (in variant 2, the power supplied is small, and a periodic solution was reached). In variant 4, the energy source is located directly behind the undisturbed position of the closing shock wave, in the subsonic region of the flow, and the situation is improved: the wave drag coefficient of the airfoil decreases approximately by 16% and the lift-to-drag ratio increases. The best results are obtained in variant 6 (in variants 2–4 and 6, the source has an almost identical power and, in addition, an almost identical size) (Fig. 1). Figures 1a and 1b show the pressure fields in a steady flow without energy supply for variant 1 and in a periodic flow with energy supply $\Delta E = 2.5 \cdot 10^{-4}$ for variant 4, respectively. Figures 1c and 1d show the Mach number fields for variant 4 and for the case with a doubled power of energy

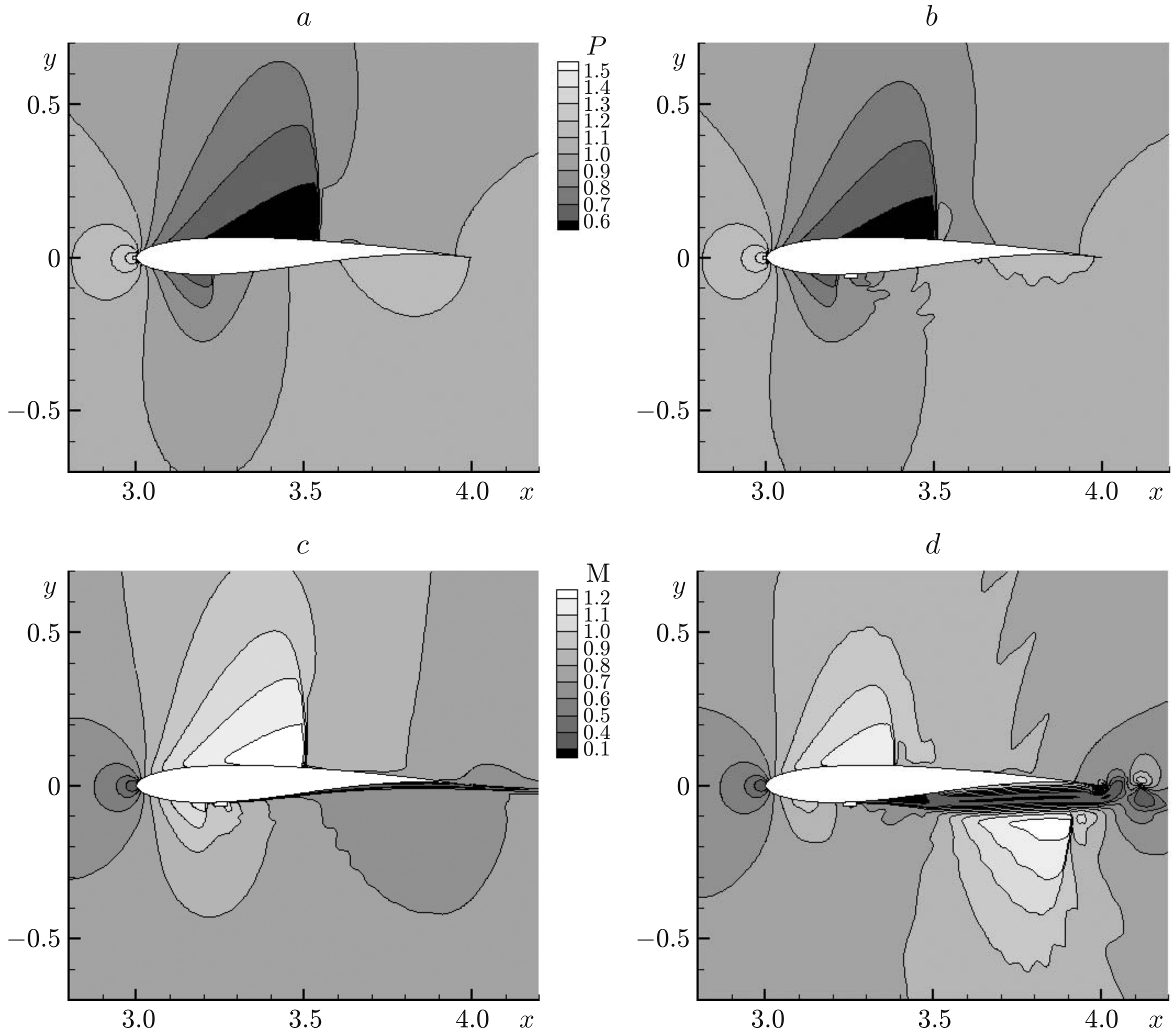

Fig. 1. Fields of pressure (a and b) and Mach numbers (c and d) in a steady flow without energy supply (a) and in a periodic flow with energy supply in the zone $3.238 \leqslant x \leqslant 3.271$ with $\Delta E = 2.5 \cdot 10^{-4}$ (b and c) and $5 \cdot 10^{-4}$ (d).

supply, i.e., $\Delta E/\Delta t = 0.01$, with the same location of the energy source. [The energy-supply zone is shown as a white band (of conventional thickness) near the lower surface of the airfoil.] With the energy-supply power twice greater than that in variant 4, a periodic solution is not obtained for the reason described above, and the lift-to-drag ratio of the airfoil drops down almost to zero (see Fig. 1d). By comparing the steady solution (see Fig. 1a) and periodic solution (see Fig. 1b), we can see that energy supply in the zone below the airfoil can shift the closing shock wave in the upstream direction and reduce the size of the supersonic zone not only below the airfoil, but also above it. This phenomenon, which was not observed previously, leads to a decrease in the drag coefficient and the lift coefficient and to an insignificant increase in the lift-to-drag ratio. The phenomenon observed can be explained as follows. As in an unsteady flow in a variable-section channel with pulsed-periodic energy supply [10], the flow is accelerated owing to energy supply in the considered case with subsonic velocities, and a velocity equal to the local velocity of sound is reached. After that, the flow is accelerated to supersonic velocities owing to its expansion. In the problem of the channel flow, the energy was not supplied at supersonic velocities, and the wall generatrix was a straight line. In the problem considered here, the flow is accelerated despite the continued energy supply, which is caused by a large local curvature of the contour (see Fig. 1c). Energy supply to a small supersonic flow region formed leads to an increase in pressure in the rear part of the airfoil and, hence, to attenuation of the closing shock

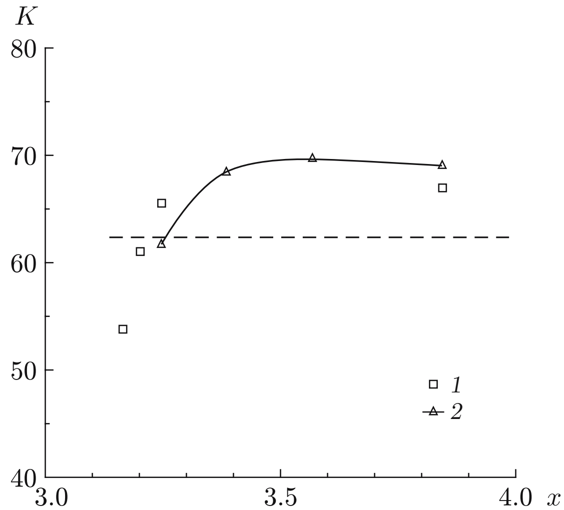

Fig. 2. Lift-to-drag ratio of the optimal airfoil versus the energy-source location for different values of power: points 1 refer to $\Delta E/\Delta t = 0.005$ ($\Delta E = 2.5 \cdot 10^{-4}$) and points 2 refer to $\Delta E/\Delta t = 0.007$ ($\Delta E = 3.5 \times 10^{-4}$); the dashed curve shows the results for $\Delta E = 0$.

TABLE 3

Aerodynamic Coefficients of the Airfoil as Functions of the Supplied Energy

Calculation variant	$\Delta E \cdot 10^4$	$C_x \cdot 10^3$	C_y	C_m	K
1	0	9.260	0.578	−2.04	62.4
2	2.5	8.680	0.582	−2.05	67.0
3	3.5	8.440	0.583	−2.05	69.1
4	4.5	8.230	0.585	−2.06	71.0
5	5.5	8.050	0.587	−2.07	72.9
6	6.5	7.890	0.589	−2.08	74.7
7	10.0	7.495	0.601	−2.11	80.2

wave above the airfoil. If the energy is supplied near the trailing edge ($x \approx 3.8$), where the airfoil-contour curvature is not too large, supersonic velocities are not reached, and the pressure in the rear part of the airfoil is lower than that in the steady flow, i.e., without energy supply, which shifts the closing shock wave above the airfoil toward the trailing edge [2, 3].

Figure 2 shows the lift-to-drag ratio of the airfoil considered as a function of the energy-source location for two values of the source power: $\Delta E/\Delta t = 0.005$ and 0.007 ($\Delta E = 2.5 \cdot 10^{-4}$ and $3.5 \cdot 10^{-4}$, respectively). For comparison, Fig. 2 also shows the lift-to-drag ratio of the airfoil for the case without energy supply (dashed line). It follows from Fig. 2 that the most beneficial (from the viewpoint of the lift-to-drag ratio of the airfoil) position of the energy source is located in a certain region behind the mid-section. With this position of the source, an increase in its power leads to an increase in the lift coefficient of the airfoil with a simultaneous substantial decrease in its drag coefficient and, as a consequence, to an increase in the lift-to-drag ratio. It follows from Fig. 3, which contains the data for the source location corresponding to variant 6 at $x_1 = 3.838$ (see Table 2). In variant 7 (see Table 3), the lift-to-drag ratio is almost 30% higher due to energy supply, and an even higher value can be obtained for a source with a greater power. Note that the lift-to-drag ratio for variants summarized in Table 3 increases both owing to the decrease in the wave drag and owing to the increase in the lift force.

Figure 3 shows the lift-to-drag ratio as a function of the supplied energy for different positions of the energy-supply zone. If the source is located near the mid-section, supply of a small amount of energy reduces the lift-to-drag

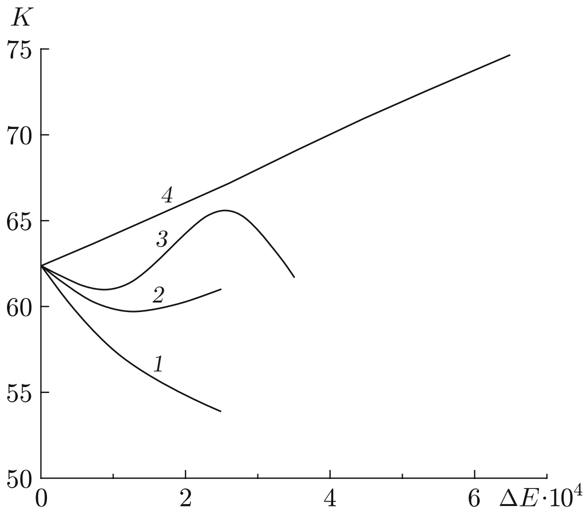

Fig. 3

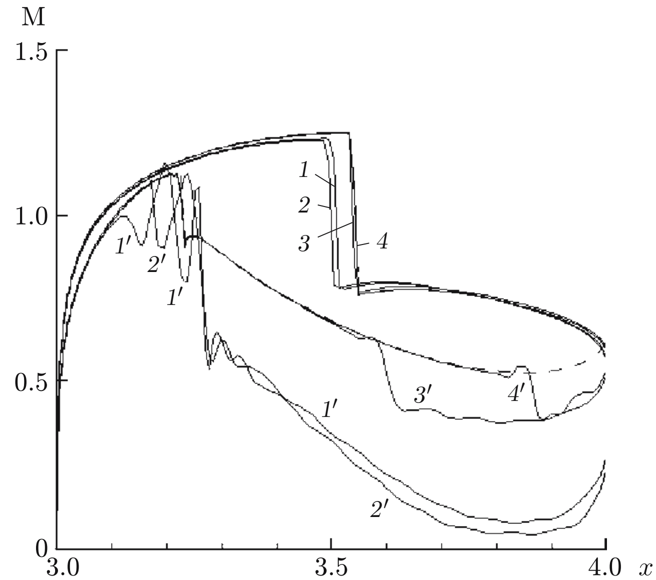

Fig. 4

Fig. 3. Lift-to-drag ratio versus the supplied energy in the zone with coordinates of the left boundary $x_1 = 3.157$ (1), 3.195 (2), 3.238 (3), and 3.838 (4).

Fig. 4. Distributions of the Mach number over the airfoil contour with different locations of the energy source ($\Delta E/\Delta t = 0.005$, where $\Delta E = 2.5 \cdot 10^{-4}$): curves 1–4 show the distributions over the upper surface of the airfoil and curves $1'$–$4'$ show the distributions over the lower surface of the contour; $x_1 = 3.162$ (curves 1 and $1'$), 3.201 (2 and $2'$), 3.567 (3 and $3'$), and 3.843 (4 and $4'$); the dashed curve refers to the case with $\Delta E = 0$.

ratio; if the source power is slightly increased, flow separation and a drastic decrease in the lift-to-drag ratio are observed. If the source is located near the trailing edge, an increase in the source power leads to a monotonic increase in the lift-to-drag ratio of the airfoil.

It should be noted that the maximum lift-to-drag ratio of the airfoil considered, $K_{\max} = 69$, is reached at the angle of attack $\alpha = -0.1°$. In this case, the energy supply with $\Delta E = 10^{-3}$ also improves the lift-to-drag ratio. For the energy-source location corresponding to variant 6 with $x_1 = 3.838$ (see Table 2), we have $K = 80.4$, which is approximately 30% higher than that in the case without energy supply. A comparison of data in Tables 1 and 3 shows that a specified lift force (with a given minimum value of the corresponding coefficient equal to 0.5) in the case with energy supply can be obtained with a considerably greater lift-to-drag ratio of the airfoil than in the case of its arrangement at an angle of attack.

A certain idea about the effect of energy supply on the shock-wave structure of the flow around the considered (optimal) airfoil can be obtained from Fig. 4, which shows the distributions of the Mach number over the airfoil contour for different locations of the source with the power $\Delta E/\Delta t = 0.005$. If the source is located near the mid-section, the closing shock wave above the airfoil is shifted upstream (curves 1 and 2), as compared with the case of the flow without energy supply (dashed curve), which was mentioned above. Below the airfoil, there arises a moderate-size supersonic region, which begins in the energy-supply zone (curves $1'$ and $2'$). The closing shock wave is shifted downstream. When the source is moved toward the trailing edge of the airfoil, both shock waves (above and below the airfoil) return back (curves 3, 4, $3'$, and $4'$). A drastic decrease in the Mach number below the airfoil in the case of energy supply near the mid-section should be noted, which leads to an upstream shift of the shock wave above the airfoil.

The lift-to-drag ratio obtained in the present work owing to energy-supply zones extended along the airfoil contour and to varying their positions is higher than that in [7], while the power of energy supply in the present work was lower by two orders of magnitude. In addition, the restriction on the lift force was satisfied. Nevertheless, it seems more reasonable to use such energy supply that can produce a positive effect for controlling transonic flow

TABLE 4

Aerodynamic Coefficients of the Airfoil as Functions of the Length of the Energy-Supply Zone

Calculation variant	x_1	x_2	$\Delta S \cdot 10^4$	$C_x \cdot 10^2$	$\Delta C_x \cdot 10^2$	$\Delta C_x / C_x$, %
1	3.433	3.609	1.630	2.329	2.259	49.2
2	3.433	3.523	0.819	2.250	2.338	51.0
3	3.433	3.485	0.483	2.170	2.418	52.7
4	3.433	3.451	0.157	3.976	0.612	13.3
5	3.433	3.442	0.080	4.094	0.494	10.8

around the airfoil at $M_\infty = 0.75$ in off-design flight regimes, in particular, in maneuvering of a flying vehicle, where it is necessary to compensate for adverse effects caused, for instance, by flow separation, etc.

It follows from Table 3 that the pitching moment is almost independent of the magnitude of energy supply if the latter is performed near the trailing edge of the airfoil ($3.838 \leqslant x \leqslant 3.864$). The reason is a weak change in the pressure distribution on the major part of the airfoil contour. Noticeable changes are observed only in a small region owing to the shift of the closing shock wave on the lower surface, which exerts only an insignificant effect on the moment characteristics, but a large effect on the drag force. At the same time, a comparison of the coefficients C_m in variants 2–4 and 5–7 (see Table 2) shows that the pitching moment can substantially depend on the location of the energy-supply zone.

The locations of the curves in Fig. 4 confirm the law of stabilization of Mach number distributions over the airfoil surface, which was generalized in [11].

The effect of energy supply substantially depends on the length of the energy source along the airfoil. In variant 7 (see Table 2), the source has a compact form; despite the source location near the trailing edge of the airfoil, energy supply exerts a minor effect (because of rapid scattering of the supplied energy).

An idea about the influence of the length of the energy-supply zone along the airfoil on its aerodynamic characteristics (in particular, on the wave drag) can be obtained from the calculations for the NACA-0012 airfoil mounted at a zero angle of attack in the flow with the Mach number $M_\infty = 0.85$ (Table 4). (ΔC_x is the reduction of the wave drag coefficient.) The thickness of the energy-supply zone is identical for all calculation variants presented in Table 4.

The data in Table 4 confirm that the shock-wave structure of the flow near the airfoil and its wave drag coefficient substantially depend on the length of the energy source along the airfoil contour. If the source length is small, nonlinear effects disappear in the case of pulsed-periodic energy supply near the airfoil. This fact can be easily explained from the physical viewpoint. In the case of a compact source, the supplied energy is rapidly scattered in space. The value of the drag coefficient is mainly determined by the value of ΔE. As the value of ΔE is small in the case considered, the coefficient C_x decreases insignificantly, i.e., the dependence $C_x(\Delta E)$ is linear. In the case of an extended (along the airfoil contour) energy-supply zone, an important factor is interaction between the arising region of comparatively high pressure with the airfoil and with the closing shock wave, which has a nonlinear character. With a significant increase in the length of the energy-supply zone, the supplied power density and, hence, the pressure in this zone decrease, which attenuates this interaction, and the value of ΔC_x gradually decreases. Note that the optimal length of the energy source was estimated on the basis of the criterion of the maximum decrease in the wave drag only for a symmetric flow. Apparently, the optimal length of the energy-supply zone is different for different flow regimes. In particular, energy supply $\Delta E = 3.5 \cdot 10^{-4}$ in the zone beginning at the point $x_1 = 3.838$, with the length of this zone being doubled as compared to variant 6 (see Table 2), does not lead to any significant changes in the aerodynamic characteristics of the airfoil.

Conclusions. An analysis of the results obtained shows that external energy supply can be effectively used for controlling the aerodynamic characteristics of airfoils. For the airfoil considered, in particular, the lift-to-drag ratio is increased by 30–40% with the restriction on the minimum lift coefficient being satisfied.

This work was performed within the framework of Program No. 9 of the Presidium of the Russian Academy of Sciences and was partly supported by the Russian Foundation for Basic Research (Grant No. 08-09-90003_Bel_a).

REFERENCES

1. S. M. Aulchenko, V. P. Zamuraev, and A. P. Kalinina, "Nonlinear effects of the interaction of periodic pulsed energy supply and shock-wave structure during transonic streamlining of wing profiles," *Tech. Phys. Lett.*, **32**, No. 1, 3–5 (2006).
2. S. M. Aulchenko, V. P. Zamuraev, and A. P. Kalinina, "Effect of one-sided periodic pulsed energy supply on aerodynamic characteristics of wing profiles," *Tech. Phys. Lett.*, **32**, No. 17, 772–774 (2006).
3. S. M. Aulchenko, V. P. Zamuraev, and A. P. Kalinina, "Effect of asymmetric pulsed periodic energy supply on aerodynamic characteristics of airfoils," *J. Appl. Mech. Tech. Phys.*, **48**, No. 6, 834–839 (2007).
4. S. M. Aulchenko, V. P. Zamuraev, and A. P. Kalinina, "Control of the lift-to-drag ratio of airfoils by means of pulsed-periodic energy supply," *Pis'ma Zh. Tekh. Fiz.*, **34**, No. 12, 62–66 (2008).
5. S. M. Aulchenko, V. P. Zamuraev, and A. P. Kalinina, "Controling of the transonic streamline of the airfoils by external energy supply," in: *Proc. of the Int. Conf. on the Methods of Aerophysical Research*, Inst. Theor. Appl. Mech., Sib. Div., Russ. Acad. of Sci., Novosibirsk (2008); CD-ROM, ISBN 978-5-98901-040-0.
6. A. S. Yuriev, S. K. Korzh, S. Yu. Pirogov, et al., "Transonic streamlining of profile at energy addition in local supersonic zone," in: *Proc. of the 3th Workshop on Magneto-Plasma-Aerodynamics in Aerospace Applications* (Moscow, April 24–26, 2001), Inst. of High Temp., Russian Acad. of Sci, Moscow (2001), pp. 201–207.
7. M. A. Starodubtsev, "Controlling a transonic flow around an airfoil by means of heat supply," *Uch. Zap. TsAGI*, **38**, Nos. 1/2, 36–40 (2007).
8. S. Raghunathan and D. Mitchell, "Computed effects of heat transfer on the transonic flow over an aerofoil," *AIAA J.*, **33**, No. 11, 2120–2127 (1995).
9. A. V. Kazakov, M. N. Kogan, and V. A. Kuparev, "Optimization of delaying the laminar–turbulent transition by local heating of the surface," *Izv. Ross. Akad. Nauk, Mekh. Zhidk. Gaza*, No. 4, 90–99 (1995).
10. V. P. Zamuraev, A. P. Kalinina, and A. F. Latypov, "Evaluation of efficiency of a pulse-periodic supply of radiant energy in a ramjet channel," in: *Proc. of the 5rd Int. Workshop on Magneto-and Plasma-Aerodynamics in Aerospace Applications* (Moscow, April 17–19, 2003), Inst. High Temp., Russian Acad. of Sci., Moscow (2003), pp. 423–427.
11. V. M. Fomin, S. M. Aulchenko, V. P. Zamuraev, and A. P. Kalinina, "Law of stabilization of the distributions of gas-dynamic parameters along an airfoil in a transonic flow with pulsed-periodic energy supply," *Dokl. Ross. Akad. Nauk*, **401**, No. 1, 58–60 (2008).