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EFFECT OF ASYMMETRIC PULSED PERIODIC ENERGY SUPPLY ON AERODYNAMIC CHARACTERISTICS OF AIRFOILS

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The possibility of controlling the aerodynamic characteristics of airfoils in transonic flight regimes by means of local pulsed periodic energy supply is considered. The numerical solution of two-dimensional unsteady equations of gas dynamics allowed determining the changes in the flow structure near a symmetric airfoil and its aerodynamic characteristics depending on the magnitude of energy in the case of its asymmetric (with respect to the airfoil) supply. The results obtained are compared with the calculated data for the flow around the airfoil at different angles of attack without energy supply. With the use of energy supply, a prescribed lift force can be obtained with a substantially lower wave drag of the airfoil, as compared with the flow around the airfoil at an angle of attack.

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

Introduction. The study of transonic flow around airfoils with pulsed periodic energy supply [1–4] provided the first results on nonlinear effects arising if the energy is supplied in thin zones located along the airfoil. The energy-supply regime proposed in [1–4] made it possible to reduce the wave drag of the airfoil by more than a factor of 2. Such a significant change in the flow structure with moderate consumption of energy was previously observed for supersonic flows only.

The energy can be supplied along the airfoil contour, for instance, with the use of a sliding pulsed arc discharge. The corresponding experiments with Mach numbers $1.7 < \mathrm{M} < 3.4$ were performed in [5]. The experiments described in [6] involved a glow discharge on the wing of an aerodynamic model in a subsonic flow (with a flow velocity of 150 m/sec). In [7], similar experiments were performed at $\mathrm{M} = 4$. Based on a plasma sheet in a transonic flow with a shock wave, a near-surface distributed energy-supply zone was obtained in [8].

In the present work, the calculations were performed for asymmetric energy supply, which allowed us to obtain the lift force and pitching moment. This paper continues the investigations of the shock-wave structure of the transonic flow around a symmetric airfoil [1–4, 9, 10]. Asymmetric energy supply in a supersonic flow was considered, for instance, in [11–14].

Formulation of the Problem. A system of two-dimensional unsteady equations of gas dynamics (Euler equations) in conservative form for an ideal gas with a constant ratio of specific heats γ is used as a mathematical model of the flow. A total variation diminishing (TVD) scheme is used in the intervals between instances of energy supply to solve this system numerically. Integration in time is performed by the Runge–Kutta method. The 352×320 computational grid in the physical domain is geometrically adapted to the airfoil contour and is refined in the vicinity of the latter. In the model considered, pulsed supply of energy is performed instantaneously, and the gas density and velocity remain unchanged thereby. The energy density of the gas e in energy-supply zones increases by $\Delta e = \Delta E/\Delta S$ (ΔE is the total energy supplied in one zone per unit length in the direction perpendicular to the airfoil plane and ΔS is the area of this zone). The energy-supply zones were extended along the airfoil and were located in an immediate vicinity of the airfoil contour. Energy supply was asymmetric with respect to the airfoil. The parameters used for normalization were the airfoil chord length l for all linear dimensions, a_∞ for

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TABLE 1

$\Delta E_1 \cdot 10^4$	C_x	C_y	C_m
0	0.045 91	0	0
1	0.04669	0.1470	−0.5467
2	0.04790	0.2225	−0.8274
4	0.04921	0.2890	−1.074
6	0.05932	0.5238	−1.950
8	0.06345	0.5899	−2.191
10	0.06366	0.6000	−2.224
20	0.06350	0.6393	−2.352
30	0.06343	0.6698	−2.453

TABLE 2

α, deg	C_x	C_y	C_m
1	0.05330	0.2793	−1.003
2	0.07153	0.5025	−1.798
3	0.09556	0.6753	−2.408
4	0.12290	0.8154	−2.900

the gas-velocity components u and v and velocity of sound a, ρ_0 for the density ρ, $\rho_0 a_\infty^2$ for the pressure p and total energy per unit volume of the gas e, $\rho_0 a_\infty^2 l^2$ for the supplied energy ΔE, and l/a_∞ for the time t and the energy-supply period Δt; ρ_0 is found from the condition $p_\infty = \rho_0 a_\infty^2$ (p_∞ and a_∞ are the dimensional pressure and velocity of sound in the incoming flow).

The initial distribution of parameters corresponds to a steady flow around the airfoil without energy supply. The problem was solved as an unsteady problem in the interval from the beginning of energy supply to obtaining a periodic solution. The moment of reaching the periodic solution was determined by comparing the period-averaged aerodynamic coefficients.

Criterion of Efficiency. The efficiency of external energy supply can be determined by comparing the decrease in the wave drag and the increase in the thrust of the vehicle in the case of supplying the corresponding amount of energy in the engine. The engine efficiency is $\eta = Ru_\infty/W$ (R is the thrust force, u_∞ is the flight velocity, and W is the power supplied) [15]. In the cruising flight regime, the thrust force equals the drag force. We can easily estimate the energy supplied near the airfoil as

$$\sum_i \Delta E_i \leqslant \gamma \Delta C_x \mathrm{M}_\infty^3 \Delta t/(2\eta),$$

where ΔC_x is the decrease in the wave drag coefficient and M_∞ is the free-stream Mach number; summation in the left side is performed over the energy-supply zones. For a prescribed supplied energy, this formula yields the estimate of the engine efficiency at which external energy supply becomes beneficial. This estimate is obtained in accordance with the traditional definition of efficiency of energy supply in a steady flight regime. The total energy balance is ignored here. In addition to this efficiency, Luk'yanov [16] introduced a parameter determining the ratio of the total energy spent per unit time on horizontal motion with a constant velocity and equal to the sum of the realized power of the thrust force of the engine and the power of the energy source used to the power of the thrust force of the engine in the absence of energy supply. The values of both parameters as functions of energy supply were given for $\mathrm{M} = 10$.

Latypov and Fomin [17] obtained criteria for efficiency of energy supply to a supersonic air flow ahead of the body with allowance for the total energy balance and functional application of the flying vehicle. In obtaining these criteria, an important fact was the assumption that there is an infinite thermal wake from the energy source ahead of the body. For the transonic range of velocities, however, there are no estimates of efficiency similar to those obtained in [16, 17].

Calculation Results. The results were obtained for an ideal gas flow ($\gamma = 1.4$ and $\mathrm{M}_\infty = 0.85$) around a NACA-0012 airfoil at an angle of attack $\alpha = 0°$ in the case of energy supply and $\alpha = 0$–$4°$ without energy supply. The supplied energy ΔE was varied from 0.0001 to 0.0085. The period of energy supply was $\Delta t = 0.05$. Hereinafter, all quantities are dimensionless.

The values of C_x, C_y, and C_m are summarized in Table 1 as functions of the energy ΔE_1 supplied in the zone under the airfoil (C_x, C_y, and C_m are the period-averaged wave drag, lift force, and pitching moment coefficients for the periodic solution, respectively). Such a method of energy supply leads to an increase in both lift force and drag of the airfoil. Beginning from a certain value of ΔE_1 (in our calculations, from $\Delta E_1 > 0.001$), however, the drag coefficient C_x ceases to increase further, while the lift coefficient C_y continues to increase.

For comparison, Table 2 gives the values of C_x, C_y, and C_m versus the angle of attack α in the absence of energy supply. An increase in the angle of attack in the range considered leads to an increase in both lift force and drag of the airfoil.

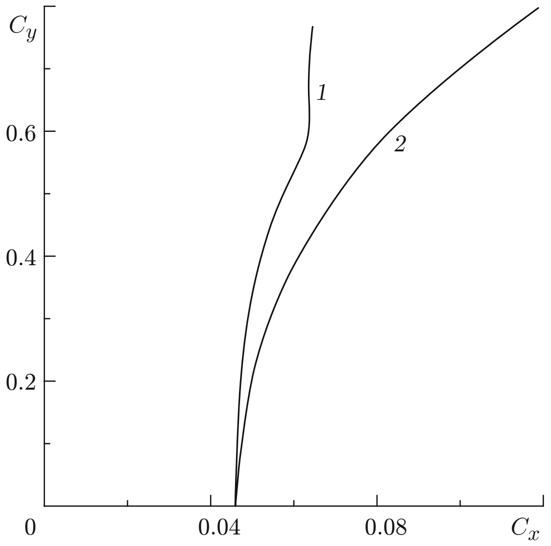

Fig. 1. Polars in the case of energy supply for $\alpha = 0°$ (curve 1) and without energy supply for $\alpha = 0$–$4°$ (curve 2).

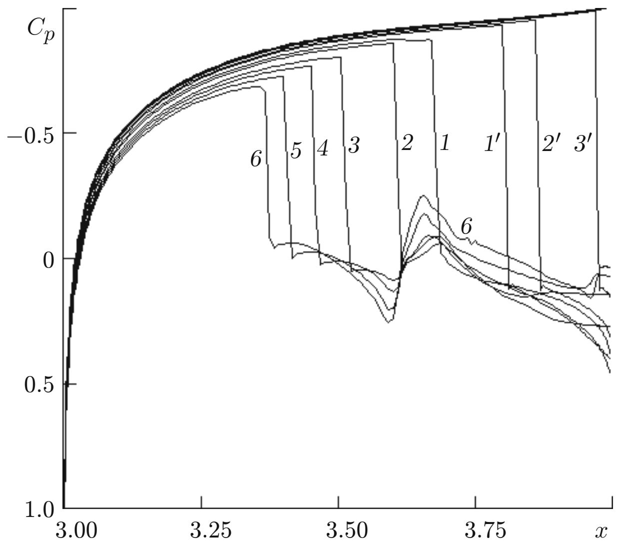

Fig. 2. Distribution of the pressure coefficient along the airfoil chord for different values of supplied energy: $\Delta E_1 = 0.0001$ (1 and 1′), 0.0004 (2 and 2′), 0.0006 (3 and 3′), 0.001 (4), 0.002 (5), and 0.003 (6); curves 1–6 refer to the lower part of the airfoil; curves 1′–3′ refer to the upper part of the airfoil.

Figure 1 shows the polars for the case of energy supply for a zero angle of attack (curve 1) and without energy supply for angles of attack $\alpha = 0$–$4°$ (curve 2) for calculation variants summarized in Tables 1 and 2. In the flow around the airfoil at an angle of attack, the lift force increases more slowly than in the case with energy supply; therefore, the slope of the corresponding polar is smaller. Thus, an identical lift force is reached by means of energy supply with a substantially smaller wave drag of the airfoil, as compared to the case of the flow around the airfoil at an angle of attack.

The character of the dependence $C_y(C_x)$ in the case of energy supply may be understood on the basis of the distribution of the pressure coefficient C_p along the airfoil immediately before the next instant of energy supply

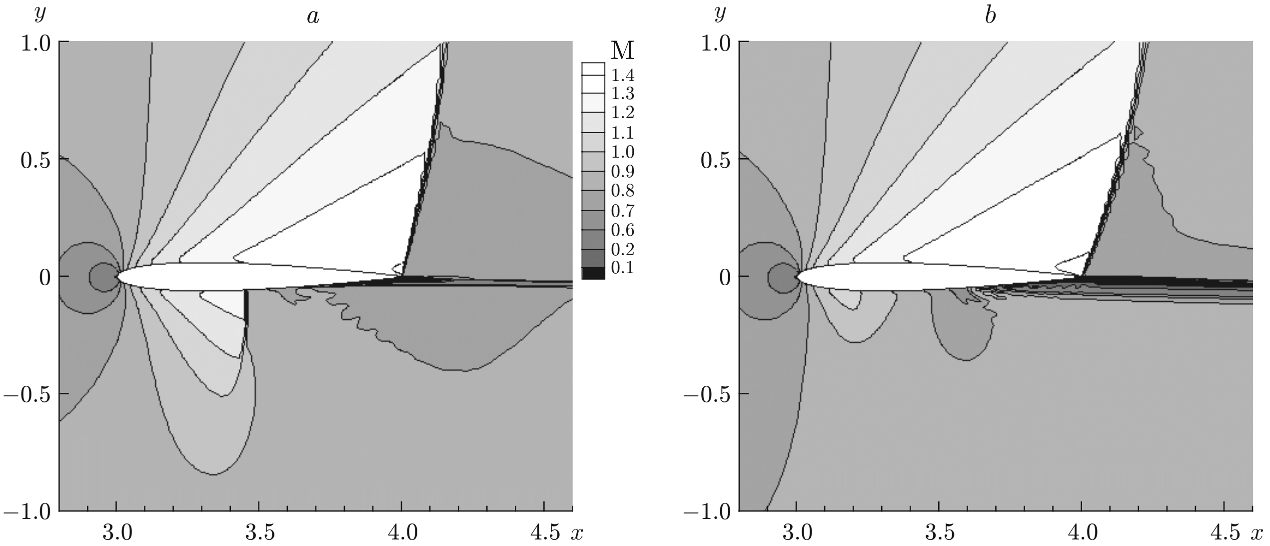

Fig. 3. Mach number fields for $\Delta E_1 = 0.001$ (a) and 0.0085 (b).

(Fig. 2). If the energy is supplied only under the airfoil (zero angle of attack), the pressure distribution becomes asymmetric. In the region under the airfoil, the closing shock moves upstream, and the supersonic zone is destroyed (curves 1–6). This leads to a decrease in wave drag. In the region above the airfoil, the closing shock moves closer to the trailing edge (curves $1'$–$3'$), which leads to an increase in wave drag. Beginning from the supplied energy equal to $\Delta E_1 \approx 0.001$, the closing shock in the region above the airfoil becomes stabilized on the trailing edge. After this moment, the wave drag coefficient remains almost unchanged.

In the considered variant of energy supply in the region $x = 3.609$–3.693, the closing shock under the airfoil is established in a much more upstream position in the flow (Fig. 2) than it is possible with symmetric energy supply [1–3]. The pressure behaves nonmonotonically near the energy-supply zone: the pressure is increased ahead of the zone and lower in the zone because of gas spreading.

Figures 3a and 3b show the Mach number fields immediately before the next instant of energy supply, which were obtained for the periodic solution for values of the supplied energy $\Delta E_1 = 0.0010$ and 0.0085, respectively. For $\Delta E_1 = 0.001$, the closing shock above the airfoil is already established on the trailing edge of the airfoil. A subsequent increase in supplied energy results in acceleration of the supersonic flow above the airfoil and a corresponding change in the angle of inclination of the closing shock. Below the airfoil, there is a substantially attenuated closing shock shifted upstream in Fig. 3a, while this shock can be hardly seen in Fig. 3b. Correspondingly, the pressure on the diffuser part of the airfoil somewhat decreases above the airfoil and increases under the airfoil As a result, the wave drag of the airfoil remains almost unchanged (the difference is 1.5%), and the lift force substantially increases (the value of C_y increases from 0.6 to 0.8). An increase in the supplied energy leads to an increase in thickness of the low-density wake behind the source of energy. Figure 3b shows the fluctuations of the contact discontinuity separating the wake from the cocurrent flow.

It follows from Tables 1 and 2 that the pitching moment for one value of the lift force is almost identical for both methods of flow control.

Table 3 shows the results calculated for variants with and without energy supply above the airfoil. An analysis of variants 1–3 shows that the change in the location of the energy-supply zone along the airfoil ($\Delta E_1 = 0.001$; x_1 and x_2 are the coordinates of the left and right boundaries of the energy-supply zone, respectively) has only a weak effect on the aerodynamic characteristics. In the first variant, the periodic solution is not established because of instability of the contact discontinuity separating the flows from different sides of the airfoil.

Table 3 also shows the behavior of the aerodynamic coefficients in the case of supply of the energy ΔE_2 above the airfoil, depending on the magnitude of this energy and location of the energy-supply zone ($\alpha = 0°$). The energy supplied below the airfoil was $\Delta E_1 = 0.001$ at $3.609 \leqslant x \leqslant 3.693$ in all variants. In variants 4 and 5, the energy was supplied symmetrically, and the values of ΔE_2 were different. A comparison of data obtained in variants

TABLE 3

Calculation variant	x_1	x_2	$\Delta S \cdot 10^4$	ΔE_2	C_x	C_y	K	C_m
1	3.523	3.609	0.812	0	≈0.06530	≈0.603	≈9.23	≈−2.22
2	3.609	3.693	0.839	0	0.06366	0.6000	9.425	−2.224
3	3.686	3.768	0.848	0	0.06267	0.5948	9.491	−2.211
4	3.609	3.693	0.839	0.0001	0.06168	0.5826	9.446	−2.157
5	3.609	3.693	0.839	0.0002	0.05514	0.4856	8.807	−1.792
6	3.344	3.433	0.796	0.0001	0.06215	0.5860	9.429	−2.171
7	3.523	3.609	0.812	0.0001	0.06181	0.5837	9.443	−2.162
8	3.609	3.693	0.839	0.0001	0.06168	0.5826	9.446	−2.157
9	3.686	3.768	0.848	0.0001	0.06155	0.5798	9.420	−2.147
10	3.755	3.833	0.834	0.0001	0.06140	0.5784	9.420	−2.141

TABLE 4

t	C_x	C_y	$-C_m$	t	C_x	C_y	$-C_m$
0.1	0.05412	0.7057	2.609	0.6	0.06503	0.5848	2.168
0.2	0.06306	0.6062	2.246	0.7	0.06507	0.5845	2.167
0.3	0.06428	0.5928	2.197	0.8	0.06509	0.5844	2.166
0.4	0.06477	0.5876	2.178	0.9	0.06509	0.5844	2.166
0.5	0.06496	0.5855	2.171	1.0	0.06509	0.5844	2.166

2, 4, and 5 shows that an increase in ΔE_2 results in less intense overflow from the region under the airfoil to the region above the airfoil, and the closing shocks are shifted to a smaller distance (upstream on the lower part of the airfoil and downstream on the upper part of the airfoil). As a result, the drag and the pitching moment of the airfoil decrease, and the lift force increases. If a small amount of energy is supplied above the airfoil, its lift-to-drag ratio K remains almost unchanged.

The calculation variants 4 and 6–9 in Table 3 show that changes in the location of the energy-supply zone with $\Delta E_2 = 0.0001$ affect the aerodynamic characteristics of the airfoil only weakly.

Let us consider the efficiency of controlling the aerodynamic characteristics of the airfoil by means of asymmetric energy supply. In the case of one-sided energy supply with $\Delta E_1 = 0.0006$, the aerodynamic coefficients have the values $C_x = 0.05932$ and $C_y = 0.5238$. A similar value $C_y = 0.5233$ is obtained without energy supply at an angle of attack $\alpha = 2.107^\circ$. In this case, we have $C_x = 0.07388$. Using the criterion of efficiency, we obtain the engine efficiency $\eta \approx 52\%$ at which external energy supply $\Delta E_1 = 0.0006$ becomes beneficial. The “beneficial” efficiency somewhat decreases with increasing energy supply, but the lift-to-drag ratio of the airfoil increases.

In comparing the method of controlling the force characteristics of the airfoil by means of energy supply with the traditional method, one should take into account the ranges of changes in the airfoil characteristics during the period. Table 4 gives the aerodynamic coefficients of the airfoil with one-sided energy supply with $\Delta E_1 = 0.001$ (variant 2 in Table 3), which were obtained by averaging over the time interval $\tau = 0.1\Delta t$. The first column in Table 4 indicates the time after the beginning of the next instant of energy supply ($t = k\tau$, where k is the number of the interval). The deviation of the aerodynamic coefficients from the mean values $C_x = 0.06366$, $C_y = 0.6000$, and $C_m = -2.224$ is very small during the larger part of the period (about 2%).

Thus, it is found that a prescribed value of the lift force can be obtained with the use of one-sided energy supply for a substantially lower wave drag of the airfoil, as compared with the case of the flow around the same airfoil at an angle of attack. This effect is caused by stabilization of the closing shock above the airfoil on the trailing edge and a simultaneous decrease in the size of the supersonic region below the airfoil.

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