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EFFECT OF ONE-SIDED UNSTEADY ENERGY SUPPLY ON AERODYNAMIC CHARACTERISTICS OF AIRFOILS IN A TRANSONIC FLOW

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The possibility of controlling the aerodynamic characteristics of airfoils in transonic flight regimes by means of one-sided pulsed-periodic energy supply is studied. Based on the numerical solution of two-dimensional unsteady gas-dynamic equations, the change in the flow structure in the vicinity of a symmetric airfoil at different angles of attack and the aerodynamic characteristics of the airfoil as functions of the amount of energy supplied asymmetrically (with respect to the airfoil) are determined. The results obtained are compared with the data calculated for the flow past the airfoil at different angles of attack without energy supply. It is found that a given lift force can be obtained with the use of energy supply at a much better lift-to-drag ratio of the airfoil, as compared to the case of the flow past the airfoil at an angle of attack. The moment characteristics of the airfoil are found.

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

Introduction. In contrast to papers [1–3] dealing with a transonic flow past symmetric airfoils at a zero angle of attack with pulsed-periodic symmetric energy supply, we consider one-sided energy supply, which allows us to obtain the governing forces and moments necessary for controlling the flight of various vehicles. Based on the numerical solution of two-dimensional unsteady gas-dynamic equations, the change in the flow structure in the vicinity of a symmetric airfoil is studied, and the wave drag is obtained as a function of the amount of energy supplied on the lower part of the airfoil in a transonic flow at different angles of attack. The results obtained are compared with the calculations for such an airfoil at different angles of attack without energy supply. It is found that a given lift force can be obtained with the use of energy supply at a much better lift-to-drag ratio of the airfoil, as compared to the case of the flow past the airfoil at an angle of attack. Some results of such a study (for a flow past an airfoil at a zero angle of attack) were published [4, 5].

The study of a transonic flow past airfoils with pulsed-periodic energy supply [1, 2] revealed some new nonlinear effects observed if energy supply is performed in narrow regions aligned along the airfoil. The regime of energy supply proposed in [1, 2] allowed the wave drag of the airfoil to be more than halved. The energy can be supplied along the airfoil, for instance, by using a sliding pulsed arc discharge. Such a discharge was initiated in a supersonic flow (at Mach numbers $1.7 < \mathrm{M} < 3.4$) in [6]. The experiments performed in [7] involved a glow discharge on an aerodynamic model wing in a subsonic flow (with a flow velocity of 150 m/sec). Skvortsov et al. [8] performed similar experiments at $\mathrm{M} = 4$. In the experiments performed in [9, 10], a plasma sheet was used to obtain a near-surface zone of energy supply in a transonic flow with a shock wave. The plasma sheet parameters (layer thickness and amount of the supplied energy) agree with the corresponding parameters of the energy-supply zone in [1, 2].

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In the present work, we calculated the energy supply in a narrow zone on one side of the airfoil, which allowed us to obtain the lift force and the pitching moment.

Formulation of the Problem. The mathematical model of the flow is based on a system of two-dimensional unsteady gas-dynamic equations for an ideal gas with a ratio of specific heats γ. The numerical solution of this system is obtained on the basis of a total variation diminishing finite-volume scheme. In the model considered, pulsed energy supply is instantaneous, and the gas density and velocity remain unchanged thereby. The energy density of the gas e in the zone of energy supply increases by $\Delta e = \Delta E/\Delta S$ (ΔE is the total supplied energy and ΔS is the zone area). The energy is supplied in a narrow zone adjacent to the lower part of the airfoil, ahead of the undisturbed closing shock wave (at an angle of attack $\alpha = 0°$). All linear sizes are scaled by the airfoil chord length l; the increment of the total energy of the unit volume of the gas Δe is normalized to $\rho_0 a_\infty^2$; the supplied energy ΔE is normalized to $\rho_0 a_\infty^2 l^2$; the energy-supply period Δt is normalized to l/a_∞; ρ_0 is determined from the condition $p_\infty = \rho_0 a_\infty^2$ (p_∞ and a_∞ are the dimensional free-stream pressure and velocity of sound).

We consider the flow past a symmetric airfoil at different angles of attack. The initial distributions of parameters correspond to a steady flow past the airfoil without energy supply, and the periodic solution is stabilized over the mean values of aerodynamic coefficients (lift coefficient C_y, drag coefficient C_x, and pitching moment coefficient C_m).

Calculation Results. The results were obtained for a NACA-0012 airfoil in an ideal gas flow ($\gamma = 1.4$) at a free-stream Mach number $\mathrm{M}_\infty = 0.85$ and angles of attack $\alpha = 0$–$3°$. The supplied energy ΔE was varied from 0.0001 to 0.0085. The energy-supply period was $\Delta t = 0.05$. Here and in what follows, all quantities are dimensionless.

The values of C_x and C_y and the lift-to-drag ratio K_a of the airfoil are listed in Table 1 as functions of the supplied energy ΔE in the indicated range of the angles of attack. For comparison, Table 2 contains the values of C_x, C_y, and K_a in the range of the angles of attack $\alpha = 0$–$4°$ for the case without energy supply. It follows from Table 1 that a given value of the lift coefficient (for instance, $C_y \approx 0.5$) is reached at a substantially lower value of the wave drag coefficient and, hence, at a higher lift-to-drag ratio. Figure 1 shows the dependences of C_y on C_x, corresponding to the data in Table 1, for different angles of attack (curves 1–4) obtained with energy supply and the classical polar obtained for the case without energy supply (curve 5). In the case of the flow past the airfoil at an angle of attack without energy supply, the drag increases faster than in the case with energy supply and a fixed angle of attack; hence, the curve $C_y(C_x)$ is steeper. Thus, a given lift force is reached with the help of energy supply at a much lower wave drag of the airfoil, as compared to the case of the flow past the airfoil at an angle of attack.

Beginning from the supplied energy $\Delta E \approx 0.001$, the drag coefficient C_x ceases to increase, whereas the lift coefficient C_y continues to grow.

We can get an idea about the character of the dependence $C_y(C_x)$ with energy supply on the basis of the distribution of the pressure coefficient C_p along the airfoil at $\alpha = 2°$ (Fig. 2). In the case of energy supply near the lower surface of the airfoil, the closing shock is shifted upstream and becomes attenuated; hence, the supersonic zone is destroyed (curves 2–5 in Fig. 2). As a result, the wave drag decreases. On the upper surface of the airfoil, the closing shock is shifted closer to the trailing edge (curves $1'$–$3'$), which leads to an increase in the wave drag. Beginning from the value of the supplied energy $\Delta E \approx 0.001$, the closing shock on the upper surface of the airfoil becomes stabilized on the trailing edge, and the closing shock in the region below the airfoil becomes comparatively weak. After that moment, the wave drag coefficient remains almost unchanged. The pressure near the energy-supply zone behaves nonmonotonically. The pressure is elevated ahead of the energy-supply zone, whereas the pressure in the zone proper is lower because of gas spreading.

In the considered variant of energy supply in the region $x = 3.609$–3.693, the closing shock on the lower surface of the airfoil is established significantly more upstream (see Fig. 2) than in the case of symmetric energy supply [1, 2]. This fact is responsible for the weak dependence of the lift and wave drag coefficients on the energy-supply zone location along the airfoil.

Figure 3 shows the lift-to-drag ratio of the airfoil as a function of the supplied energy for different angles of attack. The dashed curve corresponds to the maximum lift-to-drag ratio for the considered airfoil in the case without energy supply. The fact of energy supply ensures a substantially higher lift-to-drag ratio of the airfoil, which agrees with the results plotted in Fig. 1. In the case of supply of a moderate amount of energy, the lift-to-drag ratio

TABLE 1

Aerodynamic Coefficients of the Airfoil as Functions of the Supplied Energy ΔE for Different Angles of Attack

$\Delta E \cdot 10^4$	$\alpha = 0°$			$\alpha = 1°$			$\alpha = 2°$			$\alpha = 3°$		
	C_x	C_y	K_a	C_x	C_y	K_a	C_x	C_y	K_a	C_x	C_y	K_a
0	0.0459	0	0	0.0533	0.279	5.24	0.0715	0.503	7.03	0.0956	0.675	7.07
1	0.0467	0.147	3.15	0.0555	0.337	6.08	0.0748	0.550	7.35	0.0993	0.714	7.19
2	0.0479	0.223	4.65	0.0581	0.398	6.85	0.0787	0.601	7.64	—	—	—
4	0.0492	0.289	5.87	0.0655	0.530	8.09	0.0868	0.697	8.03	—	—	—
6	0.0593	0.524	8.83	0.0767	0.682	8.88	0.0960	0.790	8.23	—	—	—
8	0.0635	0.590	9.30	0.0789	0.704	8.93	0.0984	0.810	8.23	—	—	—
10	0.0637	0.600	9.43	0.0794	0.715	9.00	0.0992	0.820	8.26	0.1154	0.917	7.94
20	0.0635	0.639	10.07	0.0804	0.753	9.37	0.1013	0.855	8.44	—	—	—
30	0.0634	0.670	10.56	0.0811	0.784	9.66	0.1026	0.886	8.64	0.1260	0.981	7.79
80	0.0647	0.784	12.12	—	—	—	—	—	—	—	—	—

TABLE 2

C_x, C_y, and K_a Versus the Angle of Attack Without Energy Supply

α, deg	C_x	C_y	K_a
1	0.0533	0.279	5.24
2	0.0715	0.503	7.03
3	0.0956	0.675	7.07
4	0.1229	0.815	6.63

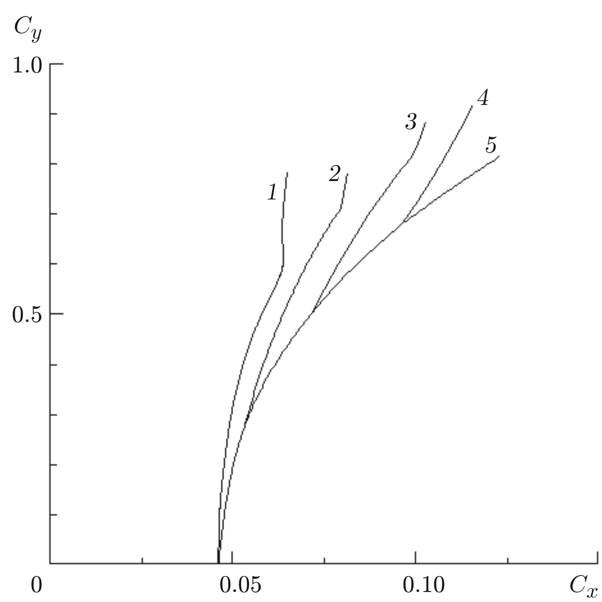

Fig. 1. Polars for the case with energy supply for different angles of attack α (1–4) and for the case without energy supply for $\alpha = 0$–$4°$ (5): $\alpha = 0$ (1), 1 (2), 2 (3), and 3° (4).

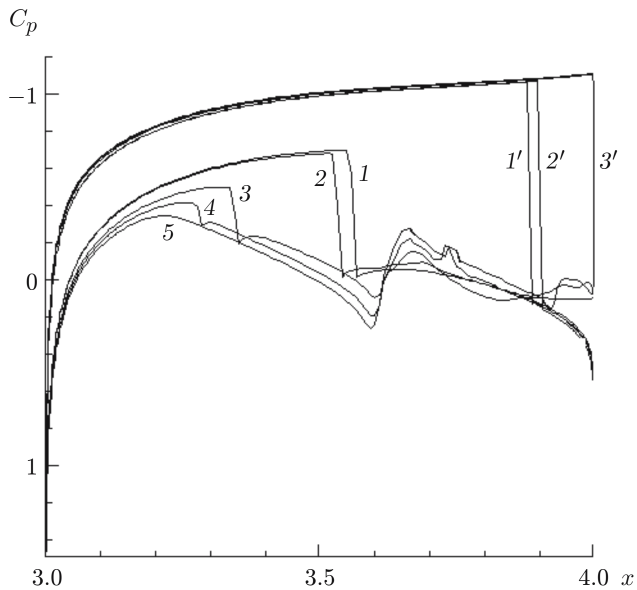

Fig. 2

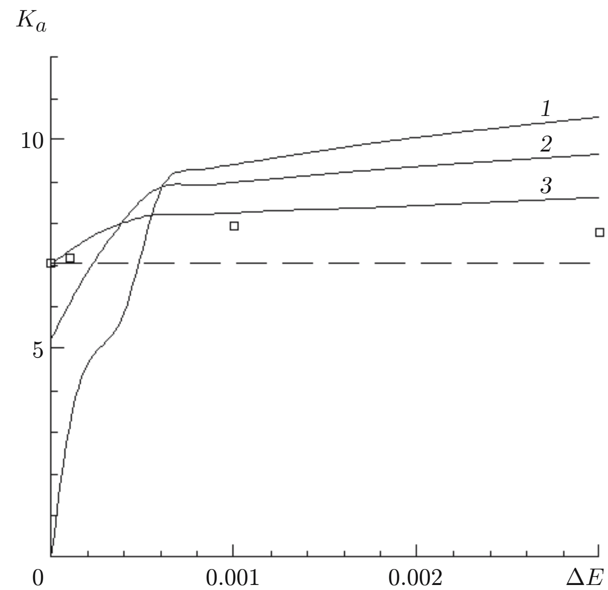

Fig. 3

Fig. 2. Pressure coefficient along the airfoil chord at $\alpha = 2°$ and different values of the supplied energy: curves 1–5 refer to the lower part of the airfoil and curves 1′–3′ refer to the upper part of the airfoil for $\Delta E = 0$ (1 and 1′), 0.0001 (2 and 2′), 0.001 (3 and 3′), 0.002 (4), and 0.003 (5).

Fig. 3. Lift-to-drag ratio K_a of the airfoil versus the supplied energy ΔE for different angles of attack: $\alpha = 0$ (1), 1 (2), and 2° (3); the points are the results for $\alpha = 3°$; the dashed curve shows the value of $(K_a)_{\max}$ for $\Delta E = 0$.

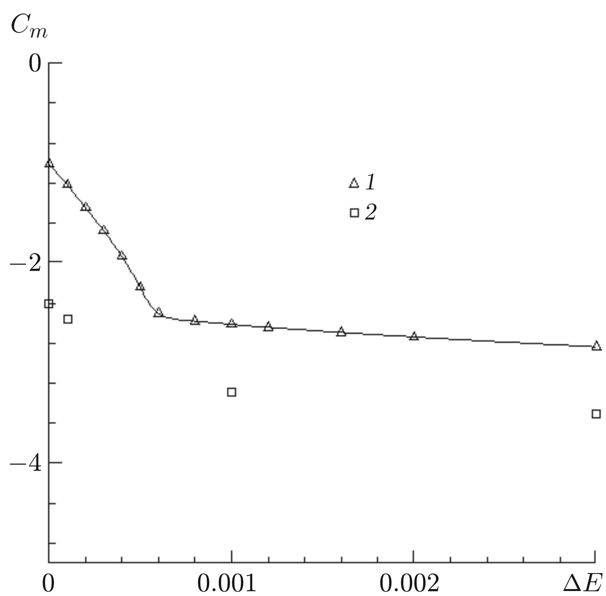

Fig. 4

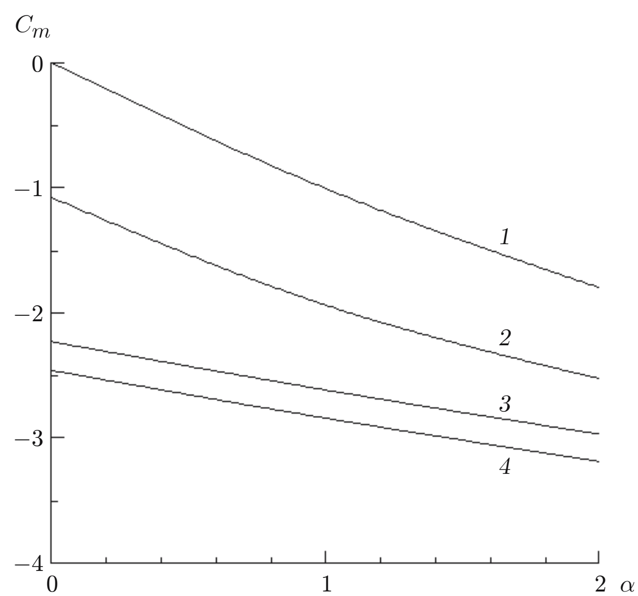

Fig. 5

Fig. 4. Pitching moment coefficient C_m versus the supplied energy ΔE for different angles of attack: $\alpha = 1$ (1), and 3° (2).

Fig. 5. Pitching moment coefficient C_m versus the angle of attack for different values of the supplied energy ΔE: $\Delta E = 0$ (1), $= 0.0004$ (2), 0.001 (3), and 0.003 (4).

can be simultaneously controlled by means of the angle of attack and energy supply, which corresponds to this or that curve in Fig. 3 for $\Delta E < 0.0006$.

An important characteristic of an airfoil is the pitching moment. Figure 4 illustrates the effect of energy supply on the pitching moment coefficient C_m. Figure 5 shows the coefficient C_m as a function of the angle of attack, the amount of the supplied energy being fixed.

A considerable negative gradient of the moment in the range of energies, which ensures a principal change in the shock-wave structure of the flow near the airfoil (downstream shifting of the closing shock on the upper surface toward the trailing edge and a significant decrease in the intensity of a similar shock on the lower surface), provides a certain reserve of stability for a flying vehicle. This fact is supported by a comparison of the data in Fig. 4 with curve 1 in Fig. 5 and curves 1–4 in Fig. 5 with each other.

Thus, we found that a given value of the lift force can be obtained by means of one-sided energy supply at a significantly lower wave drag of the airfoil and, hence, a better lift-to-drag ratio than in the case of the flow past the airfoil at an angle of attack without energy supply. This effect is caused by stabilization of the closing shock above the airfoil on the trailing edge and by simultaneous reduction of the size of the supersonic zone below the airfoil.

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, "Nonlinear effects caused by pulsed periodic supply of energy in the vicinity of a symmetric airfoil in a transonic flow," *J. Appl. Mech. Tech. Phys.*, **47**, No. 3, 359–365 (2006).
3. V. P. Zamuraev, A. P. Kalinina, and A. F. Latypov, "Nonlinear effects of pulsed periodic energy supply on shock wave structure of transonic flow around airfoils," *Thermophys. Aeromech.*, **13**, No. 3, 173–181 (2006).
4. 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).
5. 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).
6. V. S. Aksenov, V. V. Golub, S. A. Gubin, et al., "Sliding arc discharge as a method for controlling the flight trajectory of a flying vehicle," *Pis'ma Zh. Tekh. Fiz.*, **30**, No. 20, 62–68 (2004).
7. Yu. E. Kuznetsov, V. V. Skvortsov, and A. A. Uspenskii, "Studying the evolution of a glow discharge on the wing of an aerodynamic model," *Teplofiz. Vysok. Temp.*, **37**, No. 3, 508–512 (1999).
8. V. Skvortsov, Yu. Kuznetsov, V. Litvinov, et al., "Investigation of aerodynamic effects at the electric discharge creation on the models of different geometry," in: *Proc. of the 2nd Workshop on Magneto-Plasma-Aerodynamics in Aerospace Applications* (Moscow, April 5–7, 2000), High-Temp. Inst., Russian Acad. of Sci., Moscow (2000), pp. 102–106.
9. I. A. Znamenskaya, I. V. Mursenkova, D. M. Orlov, and N. N. Sysoev, "Localization of pulsed energy contribution in initiation of a transverse surface discharge in a flow with a shock wave," *Pis'ma Zh. Tekh. Fiz.*, **33**, No. 13, 72–77 (2007).
10. V. P. Zamuraev, A. P. Kalinina, S. M. Aulchenko, et al., "Transonic wing airfoil flow control by local energy supply using nanosecond discharge (plasma sheet)," in: *Proc. of the 7th Int. Workshop on Magneto-Plasma-Aerodynamics in Aerospace Applications* (Moscow, April 17–19, 2007), Inst. High. Temp., Russian Acad. of Sci., Moscow (2007), pp. 55–60.