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CONTROL OF THE AERODYNAMIC CHARACTERISTICS OF WING AIRFOILS BY NONSTATIONARY ENERGY SUPPLY IN TRANSONIC FLOW

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The possibility of controlling the aerodynamic characteristics of wing airfoils in transonic regimes of flight using one-sided pulse-periodic energy supply has been studied. The flow structure near the symmetric airfoil at different angles of attack and its aerodynamic characteristics as functions of the value of energy in its non-symmetric (about the airfoil) supply have been determined by numerical solution of two-dimensional nonstationary gasdynamic equations. A comparison of the obtained results and the data of calculation of flow past the airfoil at different angles of attack without energy supply has been made. It has been established that a prescribed lift can be obtained, using energy supply, with a much higher fineness ratio of the airfoil than that in the case of flow past it at an angle of attack.

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

Introduction. Unlike in [1–4] where the symmetric problem on transonic flow past a wing airfoil with energy supply was solved, in the present work, we have considered one-sided energy supply, which enables us to obtain forces and moments necessary for controlling aircraft flight. We have numerically studied the flow structure near a symmetric airfoil and its wave drag as a function of the energy supplied on the underside of the airfoil in transonic flow at different angles of attack. It has been established that a prescribed lift can be ensured using energy supply with a much higher fineness ratio of the airfoil than that in the case of flow past it at angles of attack. Certain results of this investigation (for flow past an airfoil at the zero angle of attack) were published in [5, 6].

Nonlinear effects that occur if energy is supplied in the thin zones along the airfoil were first established in the investigations of the authors [2, 3]. The proposed method of controlling flow past the airfoil allowed a more than two-fold reduction in its wave resistance. Energy can be supplied along the contour using, e.g., a creeping pulsed arc discharge. Such a discharge was initiated in a supersonic flow (for Mach numbers $1.7 < M_\infty < 3.4$) in [7]. Glow discharge on the wing of the aerodynamic model in a subsonic flow was realized in the experiments of [8] (the flow velocity was equal to 150 m/sec). In [9], analogous experiments were carried out for $M_\infty = 4$. The surface distributed the region of energy contribution in the transonic flow with a shock wave realized on the basis of a plasma sheet in [10]. The parameters of the plasma sheet (layer thickness and the size of energy contribution) independently agreed with the corresponding parameters of the zone of energy supply in [2, 3, 11]. In the present work, energy supply is carried out in a thin zone on one side of the airfoil, which enables us to obtain the lift and the pitching moment.

Formulation of the Problem. As a mathematical model of flow, we use a system of two-dimensional nonstationary gasdynamic equations for an ideal gas with an adiabatic exponent γ. Test calculations [1] have shown that the error in calculating the drag coefficient of the airfoil has the order of the friction coefficient [12] disregarded in this model.

To numerically solve it we use a finite-difference scheme diminishing the total variation (TVD reconstruction) in intervals between the instants of energy supply. The fluxes at the cell boundaries are computed by the method of [13]. Time integration is by the Runge–Kutta method of second order. In the model in question, pulsed energy supply is instantaneous; the density of the gas and its velocity remain constant, whereas the density of the gas energy e grows by $\Delta e = \Delta E/\Delta S$. The zone is thin; it is adjacent to the airfoil on the underside and has a nearly rectangular shape.

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TABLE 1. Aerodynamic Coefficients as Functions of the Supplied Energy

α, deg	Coefficients	$\Delta E \cdot 10^4$									
		0	1	2	4	6	8	10	20	30	80
0	$C_x \cdot 10$	0.459	0.467	0.479	0.492	0.593	0.635	0.637	0.635	0.634	0.647
	C_y	0	0.147	0.223	0.289	0.524	0.590	0.600	0.639	0.670	0.784
	K	0	3.148	4.645	5.873	8.830	9.297	9.425	10.07	10.56	12.12
1	$C_x \cdot 10$	0.533	0.555	0.581	0.655	0.767	0.789	0.794	0.804	0.811	—
	C_y	0.279	0.337	0.398	0.530	0.682	0.704	0.715	0.753	0.784	—
	K	5.242	6.083	6.847	8.092	8.884	8.925	8.995	9.371	9.662	—
2	$C_x \cdot 10$	0.715	0.748	0.787	0.868	0.960	0.984	0.992	1.013	1.026	—
	C_y	0.503	0.550	0.601	0.697	0.790	0.810	0.820	0.855	0.886	—
	K	7.025	7.351	7.639	8.030	8.230	8.226	8.260	8.437	8.635	—
4	$C_x \cdot 10$	0.956	0.993	—	—	—	—	1.154	—	1.260	—
	C_y	0.675	0.714	—	—	—	—	0.917	—	0.981	—
	K	7.067	7.191	—	—	—	—	7.943	—	7.786	—

TABLE 2. Aerodynamic Coefficients as Functions of the Angle of Attack

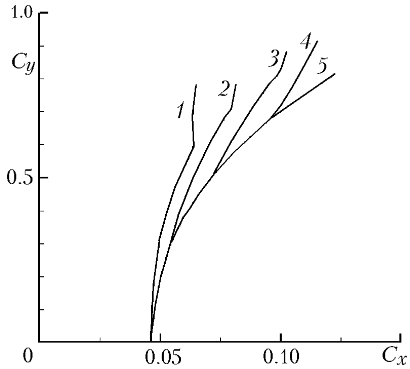
Coefficients	α, deg			
	1	2	3	4
$C_x \cdot 10$	0.533	0.715	0.956	1.229
C_y	0.279	0.503	0.675	0.815
K	5.240	7.025	7.066	6.634

We consider flow past a symmetric airfoil at different angles of attack. The initial distribution of the parameters corresponds to stationary flow past the airfoil without energy supply, whereas the periodic solution is attained by a comparison of the mean values of the aerodynamic coefficients (lift coefficients C_y, airfoil-drag coefficients C_x, and pitching-moment coefficients C_m) at a time interval equal to ten periods of energy supply.

Calculation Results. The results have been obtained for the NACA-0012 airfoil in ideal-gas flow with an adiabatic exponent $\gamma = 1.4$ for the freestream Mach number $M_\infty = 0.85$ with the angles of attack $\alpha = 0–3^o$. The zone of energy supply was arranged ahead of the unperturbed position of the breakdown shock; its area was $\Delta S = 0.839 \cdot 10^{-4}$. The supplied energy ΔE was varied from 0.0001 to 0.0085. The selected energy values were close to experimental ones [10, 11].

The period of energy supply was $\Delta t = 0.05$ (here and in what follows all the quantities are dimensionless). Numerical experiments on its variation [2] have shown that the position of the breakdown shock is substantially dependent on Δt. For high Δt values (e.g., $\Delta t = 0.5$), the flow topology has time to be partially restored; the breakdown shock is displaced upstream only slightly and its position changes within the period. For the selected value $\Delta t = 0.05$, the shock is established ahead of the energy-supply zone and its position remains constant within the period. This value of Δt is considered as the limiting one, and all calculations in this work have been carried out for it.

Table 1 gives the values of C_x and C_y and of the fineness ratio K of the airfoil as functions of the supplied energy ΔE in the indicated range of angles of attack. For the sake of comparison, Table 2 gives the values of the same quantities in the range of angles of attack $\alpha = 0–4^o$ in the absence of energy supply. A prescribed value of the lift coefficient (e.g., $C_y \approx 0.5$) is attained for a much lower value of the wave-drag coefficient and hence for a higher fineness ratio. This is clearly seen in Fig. 1 which plots C_y as a function of C_x for fixed angles of attack (curves 1–4) (these plots correspond to the data of Table 1 and have been obtained with variation of the supplied energy) and gives the classical polar curve without energy supply (curve 5). In the case of flow past the airfoil at an angle of attack without energy supply the drag increases faster than that in energy supply for a fixed angle of attack, when the $C_y(C_x)$ curve is steeper. Thus, the prescribed lift is attained using energy supply for a much lower wave drag of the airfoil than that in the case of flow past it at angles of attack.



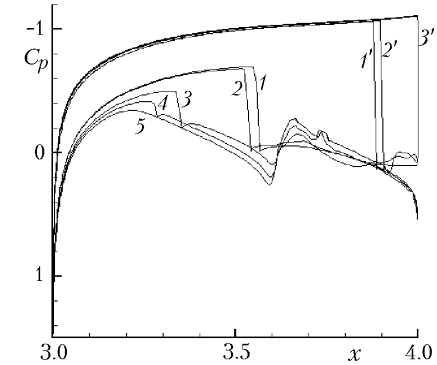


Fig. 1. Polar curves in energy supply for fixed angles of attack: 1) $\alpha = 0^o$; 2) 1^o, 3) 2^o, 4) 3^o, and 5) in the absence of energy supply at $\alpha = 0–4^o$.

Fig. 2. Pressure-coefficient distribution along the airfoil chord for the angle of attack $\alpha = 2^o$ for different values of the supplied energy; (1–5) lower part of the airfoil; 1′–3′) upper part of the airfoil): 1 and 1′) $\Delta E = 0$, 2 and 2′) 0.0001, 3 and 3′) 0.001, 4) 0.002, and 5) 0.003.

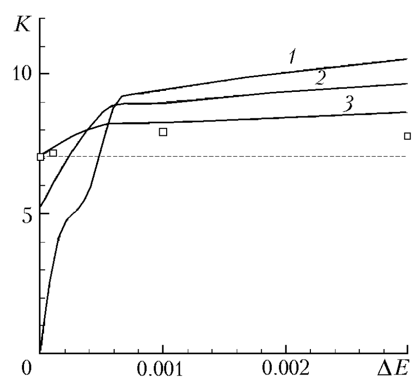


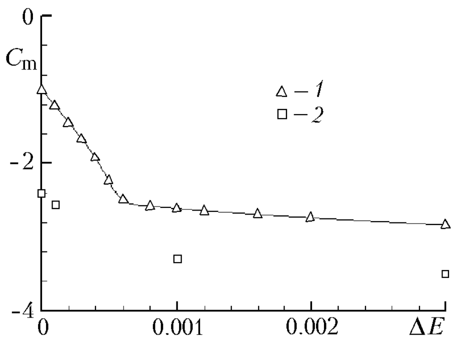
Fig. 3. Fineness ratio K of the airfoil vs. supplied energy ΔE for the angles of attack: 1) $\alpha = 0^o$, 2) 1^o, and 3) 2^o; points, 3^o; dashed line, K_{max} for $\Delta E = 0$.

Increase in the supplied energy after a certain value (in these calculations, this corresponds to $\Delta E > 0.001$) does not cause the drag coefficient C_x to grow, whereas the lift coefficient C_y continues to grow.

The reason for such behavior of the dependence $C_y(C_x)$ in energy supply can somewhat be understood using the distribution of the pressure coefficient C_p over the airfoil for $\alpha = 2^o$ (see Fig. 2). In energy supply on the underside of the airfoil, the breakdown shock moves upstream and becomes weaker; we have a destruction of the supersonic zone (Fig. 2, curves 2–5). This causes the wave drag to decrease. On the overside of the airfoil, the breakdown shock is displaced closer to the trailing edge (Fig. 2, curves 1′–3′), which causes the wave drag to increase. For the supplied energy, from approximately $\Delta E = 0.001$, the breakdown shock on the overside of the airfoil is established on the trailing edge, and the breakdown shock below the airfoil becomes relatively weak. From this point on, the wave-drag coefficient remains virtually constant. We observe a nonmonotonic character of change in the pressure near the energy-supply zone: the pressure is higher ahead of the zone and lower in the region of the zone.

For the energy supply in question (in the zone with a longitudinal coordinate x of 3.609 to 3.693), the breakdown shock on the underside of the airfoil is established much more upstream of the corresponding zone (Fig. 2) than for symmetric energy supply [2, 3]. This is the reason why the dependence of the lift and wave-drag coefficients of the airfoil on the localization of the zone of energy supply (on x) is very weak.

Figure 3 plots the fineness ratio of the airfoil as a function of the supplied energy for different angles of attack. The dashed line shows the maximum value of the fineness ratio for the airfoil in question without energy supply. Energy supply ensures a considerable increase in the airfoil's fineness ratio, which is in agreement with the results in



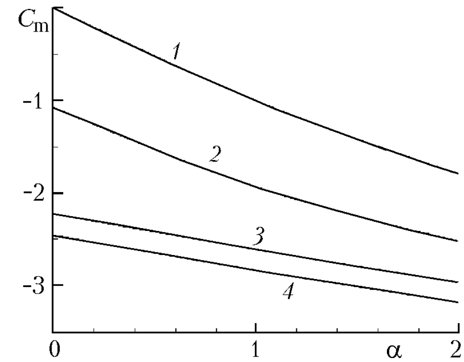


Fig. 4. Pitching-moment coefficient C_m vs. supplied energy ΔE for the angles of attack: 1) $\alpha = 1^o$ and 2) 3^o.

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

Fig. 1. Depending on specific designs, the fineness ratio can be controlled simultaneously by both the angle of attack and energy supply, which corresponds to the selection of one curve or another in Fig. 3 for an energy to 0.0006.

Figure 4 shows the influence of the energy supply on the moment coefficient C_m. Figure 5 gives the change in the moment coefficient C_m as a function of the angle of attack in supplying fixed energy. The considerable negative gradient of the moment in the range of the energies, for which we have a fundamental change in the shock-wave structure of flow near the airfoil (displacement of the breakdown shock on the upper surface downstream to the trailing edge and a strong weakening of an analogous shock on the lower surface), ensures the stability factor of an aircraft. This is confirmed by a comparison of both the data in Fig. 4 and curve 1 in Fig. 5 and curves 1–4 in Fig. 5.

Conclusions. It has been established that a prescribed lift can be ensured using one-sided energy supply for a much lower wave drag of the airfoil and accordingly a higher fineness ratio than those in the case of flow past it at angles of attack without energy supply. This effect is related to the stabilization of the position of the breakdown shock above the airfoil on its trailing edge and to the simultaneous reduction in the dimensions of the supersonic zone below the airfoil. The efficiency of the energy method of control of the aerodynamic characteristics of airfoils was shown in [5, 6].

The effect of stabilization of transonic flow past the airfoil as a function of the one-sided energy supply (Fig. 2), which is analogous to the stabilization effect established by S. A. Khristianovich [14], has been revealed for the pressure distribution along the airfoil contour as a function of the Mach number. It follows that in pulse-periodic energy supply, part of the lift is created by excess pressure for a constant angle of attack. In the case of the same lift this produces lower circulation, which can diminish the intensity of longitudinal vortices in the trail of the wing and accordingly the "induced" drag.

The considerable negative gradient of the pitching moment (in the range of the energies for which the shock-wave flow structure near the airfoil changes fundamentally) has been obtained, which must ensure the stability factor of the aircraft [12].

NOTATION

C_p, pressure coefficient; C_x, drag coefficient of the airfoil; C_y, lift coefficient of the airfoil; C_m, pitching-moment coefficient of the airfoil; K and K_{max}, fineness ratio of the airfoil and its maximum value; M_∞, freestream Mach number; x, coordinate along the airfoil chord; α, angle of attack; γ, adiabatic exponent; Δe, energy supplied to a unit volume of the gas; ΔE, dimensionless total supplied energy over a period; ΔS, area of the energy-supply zone, normalized to the airfoil-chord length squared; Δt, energy-supply period. Subscripts: m, moment; max, maximum; p, pressure; x, y, directions along the coordinates x, y; ∞, freestream.

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