Journal of Applied Mechanics and Technical Physics, Vol. 45, No. 5, pp. 665–669, 2004

CONTROLLING TRANSONIC FLOW AROUND AIRFOILS BY MEANS OF LOCAL PULSED ADDITION OF ENERGY

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UDC 533.6.011

The influence of local pulsed-periodic addition of energy into a supersonic region on the flow structure and wave drag of an airfoil in transonic flow regimes is considered by methods of mathematical modeling. The study reveals significant prospects of the considered method of controlling airfoil performance in transonic flow regimes, including wave-drag reduction.

Key words: *transonic flow, wave drag, energy addition, Euler equations.*

Introduction. The progress in aviation engineering is currently impossible without the use of new technologies. They include advanced methods for energy addition: laser and microwave radiation, electric discharge. The use of these methods for controlling the aerodynamic characteristics of airfoils, in particular, for decreasing wave drag, can increase the velocity of the flying vehicle and retain a high lift-to-drag ratio.

The issues of the action of local energy addition on the gas-flow structure were considered in many papers (see, e.g., [1–8] and the references therein). The analysis of results obtained in these papers shows that comparatively moderate energy addition can significantly alter the supersonic flow structure up to its cardinal reconstruction. The transonic range of velocities is considered in [9], where the effect of energy addition in a local supersonic region above a symmetric airfoil at zero incidence is numerically studied in a steady formulation, and also in [10–12], where it is shown within the framework of an unsteady problem that it is principally possible to control both local and integral characteristics of airfoils in transonic flow regimes by means of pulsed-periodic energy addition. Thus, the study of the possibility of controlling the aerodynamic performance of transonic airfoils by means of energy addition into the flow is a new problem that requires consideration.

1. Formulation of the Problem. The mathematical model of the flow is based on a system of two-dimensional unsteady gas-dynamic equations, i.e., the Euler equations in a conservative form for a gas with a constant ratio of specific heats γ are solved:

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

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

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

Here the coordinates x and y are directed along and across the airfoil chord, respectively, and are normalized to its length L, the normalization parameters are L/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 total energy per unit volume of the gas e, and $\rho_0 a_0^3/L$ for the power added per unit volume of the gas q; p_0 and a_0 are the dimensional free-stream pressure and velocity of sound; ρ_0 is determined from the condition $p_0 = \rho_0 a_0^2$. For the gas model considered, we have

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

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TABLE 1

Variant No.	M_∞	$N_x \times N_y$	$L_x \times L_y$	C_x
1	0.50	88×80	7×8	0.0172
2	0.50	176×160	7×8	0.0082
3	0.50	176×160	13×16	0.0148
4	0.70	88×80	7×8	0.0122
5	0.70	176×160	7×8	0.0059
6	0.70	352×320	7×8	0.0030
7	0.70	176×160	13×16	0.0103
8	0.85	88×80	7×8	0.0501
9	0.85	176×160	7×8	0.0468
10	0.85	352×320	7×8	0.0450

For the pulsed-periodic addition of energy, the value of q is determined as

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

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

The system of equations is supplemented by the boundary conditions at the boundaries of the doubly connected domain Ω, which is a rectangle with an internal boundary corresponding to the contour of the NACA-0012 airfoil. Free-stream conditions are imposed on the left, upper, and lower boundaries, "soft" conditions are set at the right boundary, and impermeability conditions are used for the airfoil contour.

The computational grid in the physical region is geometrically adapted to the airfoil contour: the grid is refined in the vicinity of the airfoil and rectangular in the canonical region; the number of nodes is 352×320. To find a numerical solution, a total variation diminishing finite-volume scheme (TVD reconstruction) is used between the instants of energy addition. The fluxes at the cell boundaries are calculated by the method described in [13]. Integration in time is performed by the third-order Runge–Kutta method. In the model considered, the pulsed addition of energy is performed instantaneously; the gas density and velocity remain unchanged. The energy density of the gas e in the zone of energy addition increases by $\Delta e = \Delta E/\Delta S$ (ΔE is the total energy being added and ΔS is the area of the energy-addition zone). The initial distribution of parameters corresponding to the steady flow around the airfoil without energy addition was obtained with an absolute error of 10^{-4} for simple variables ρ, u, v, and p in all grid nodes. From the beginning of energy addition to obtaining the periodic solution, the problem is solved in an unsteady formulation. The moment of reaching the periodic solution was determined by comparing the drag coefficients of the airfoil with a period of time equal to the period of energy addition. The absolute error was within 10^{-6}.

Test Computations. The error of calculating the drag coefficient of the airfoil for the free-stream Mach number M_∞, computational domain size, and number of nodes indicated in Table 1 was evaluated.

For $M_\infty = 0.70$, the flow is subsonic everywhere. Therefore, the value of drag $C_x = 0.003$ obtained in variant No. 6 can serve as an estimate for the accuracy of the method. The computation on nested grids yields a monotonic decrease in the error (variant Nos. 4–6). Expansion of the computational domain with a fixed number of nodes leads to a higher error, which is equivalent to a decrease in the number of nodes in a fixed domain (variant Nos. 5 and 7). The error increases with decreasing Mach number, since the relative error of computing the gas workability is $\delta \sim M_\infty^{-2}$ (variant Nos. 1–3). Therefore, it was assumed in computations with $M_\infty = 0.85$ that the wave drag is overrated by approximately $\Delta C_x \approx 0.003$. The corresponding relative error of computing the drag coefficient for variant No. 10 is approximately 7%.

Computation Results. The results were obtained for an ideal gas with $\gamma = 1.4$, $M_\infty = 0.85$, and zero angle of attack of the airfoil with varied positions of energy-addition zones for different values of added energy and a period $\Delta t = 0.5$ (the corresponding dimensionless frequency of energy addition is $\omega = 2$).

Figures 1 and 2 show the pressure fields for the initial steady flow without energy addition and for the periodic flow with energy addition $\Delta E = 0.03$ at the time immediately before the energy "pulse." In Fig. 2, one can see the fractal structure of pressure contours, reflecting the pulsed-periodic character of energy addition (the boundaries of the energy-addition zone are shown by the white line; the y scale is increased to show the energy-addition zones). For the same computation variant, Fig. 3 shows the evolution of the flow structure around the

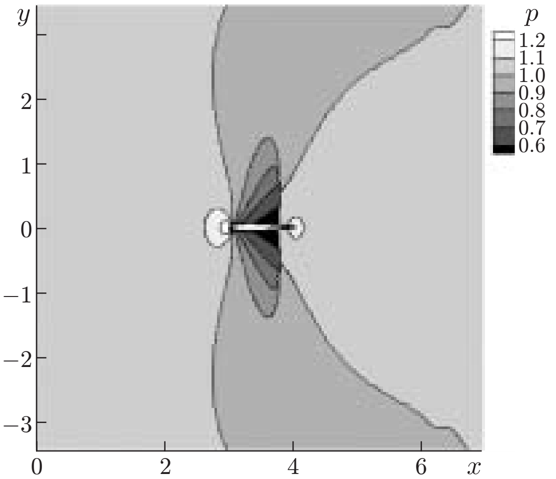

Fig. 1

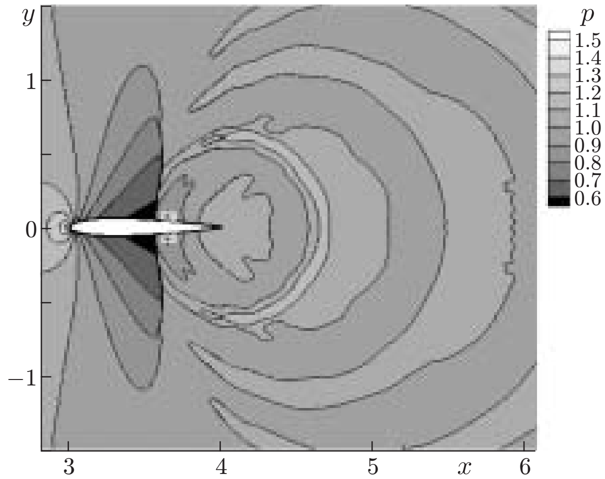

Fig. 2

Fig. 1. Pressure contours in a steady flow around the airfoil without energy addition.

Fig. 2. Pressure contours with energy addition.

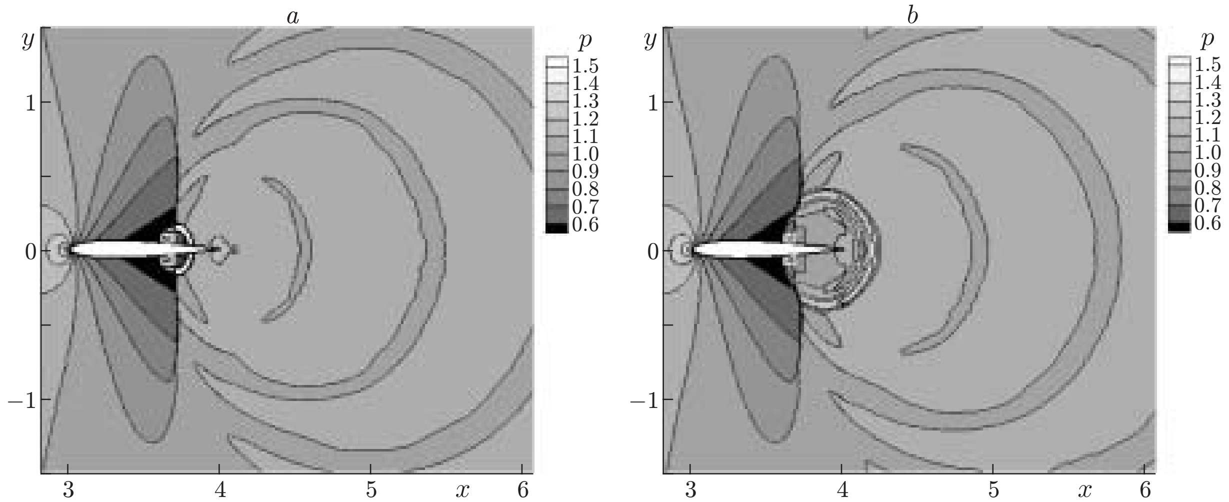

Fig. 3. Pressure contours for different times after the beginning of energy addition: $t = 0.01$ (a) and 0.05 (b).

airfoil: the pressure contours are plotted in time intervals of $0.01\Delta t$ and $0.05\Delta t$ after the next instant of energy addition. Energy addition gives rise to a shock wave. Part of the shock-wave front moving upstream decelerates the flow, attenuates the intensity of the terminal shock, and decreases the size of the supersonic region. The shock wave moving downstream is attenuated and forms the fractal structure of the flow.

Figure 4 shows the distributions of the pressure coefficient c_p over the airfoil contour in the flow without and with energy addition ($\Delta E = 0.01$, 0.03, and 0.10). Curves 2–4 are plotted for the periodic solution at the time immediately before energy addition. In the case with $\Delta E = 0.01$, the size of the supersonic zone decreases, the shock wave is shifted upstream (and approaches the energy-addition zone), and the shock-wave intensity decreases, which results in a pressure increase behind the shock wave. Two latter factors are responsible for the decrease in wave drag of the airfoil. Figure 5 shows the pressure distribution in the vicinity of the shock wave for $\Delta E = 0.01$, which illustrates the above-mentioned changes in the flow structure due to energy addition. The flow regime around the airfoil with $\Delta E = 0.03$ is characterized by an even greater shift of the main supersonic zone in the upstream direction; as a result, the energy-release zones are located behind the terminal shock in the secondary transonic

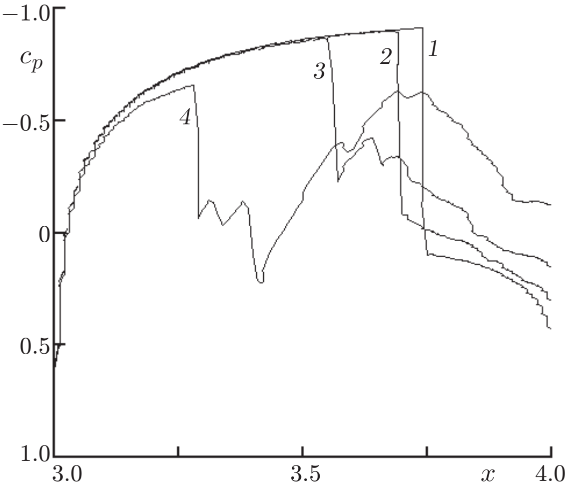

Fig. 4

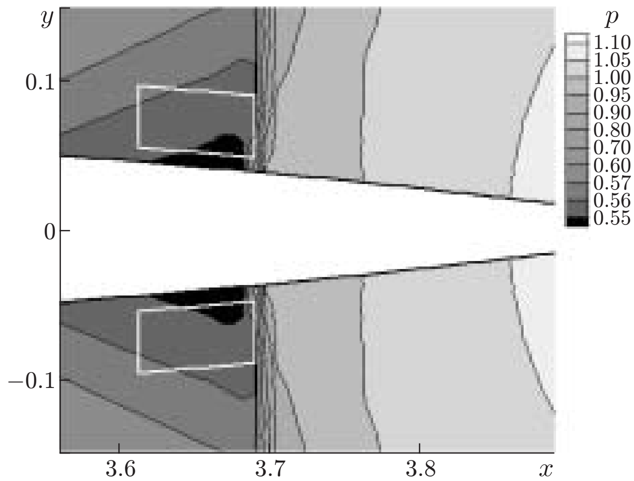

Fig. 5

Fig. 4. Distribution of the pressure coefficient over the airfoil contour without energy addition (1) and for $\Delta E = 0.01$ (2), 0.03 (3), and 0.10 (4).

Fig. 5. Pressure distribution in the vicinity of the shock wave with energy addition.

TABLE 2

ΔE	θ	C_x	ΔC_x, %
0	0	0.0450	0
0.010	0.	0.0397	12
0.030	0.3	0.0316	30
0.100	1.0	0.0307	32

region with low intensity. A further increase in the energy added with $\Delta E = 0.10$ destroys the supersonic zone and forms two shock waves of approximately identical intensity, which is yet weaker than that in the initial flow (without energy addition). Though a significant decrease in wave drag is observed in the latter case, the resultant pressure-coefficient diagram can be hardly considered as aerodynamically reasonable because the probability of earlier separation of the flow increases. In addition, one should take into account the energy expediency of the flow-control method under consideration.

The relative value of the added energy (ratio of the added power to the incoming total enthalpy flux) can be estimated as

$$\theta = \frac{\rho\omega\,\Delta e\,\Delta x\,\Delta y}{\rho u\,\Delta y\,(c_pT + 0.5u^2)} = \frac{(\gamma-1)\,\Delta E}{\gamma\,\Delta y\,\Delta t\,\mathrm{M}_\infty(1+0.5(\gamma-1)\mathrm{M}_\infty^2)},$$

where Δe is the energy added per unit mass, Δx and Δy are the sizes of the energy-addition zone, ω is the frequency, Δt is the period, and c_p is the heat capacity. The drag coefficients of the airfoil for different values of added energy are listed in Table 2. The last variant ($\theta = 1$) seems to be the limiting one, because the energy added for flow control becomes commensurable with the energy of fuel combustion in the engine. The realistic values are $\theta = 0.3$–0.4; in this case, $\Delta C_x = 20$–30%.

The study of the influence of positions of energy-addition zones on the airfoil drag shows that the drag coefficient increases from $C_x = 0.0397$ to $C_x = 0.0491$ as the energy-addition zones are shifted upstream to the subsonic region and exceeds the drag coefficient obtained without energy addition. Energy addition upstream of the airfoil also decreases the drag coefficient. In the computation performed, we have $C_x = 0.0428$.

Conclusions. An analysis of the computations performed shows that it is possible to control both the local (distributions of gas-dynamic parameters on the airfoil) and integral (drag coefficient) characteristics of airfoils in transonic flow regimes by means of local pulsed-periodic addition of energy. A periodic character of the flow being formed is established, which allows the use of this flow in cruising flight regimes; examples of global and local reconstruction of the flow are given. The technique of modeling a transonic flow with energy addition and the results obtained stimulate investigations on the influence of positions of energy sources, their size, shape, and intensity, and frequency of energy addition on aerodynamic parameters of the flow around airfoils. It becomes possible to design transonic airfoils with the maximum cruising Mach number with allowance for geometric and gas-dynamic constraints and retaining a prescribed lift force under conditions of energy addition.

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