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CONTROL OF TRANSONIC FLOW ABOUT AIRFOILS BY MEANS OF PERIODIC PULSE LOCAL ENERGY SUPPLY

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A study has been made of the possibility of controlling the aerodynamic characteristics of airfoils with the use of local pulse-periodic energy supply to the flow near the contour of the airfoil in transonic modes of flight. The influence of energy supply of different intensity to the supersonic region on the structure of the flow and the wave resistance of the airfoil has been studied based on mathematical modeling. The flow is modeled based on the two-dimensional unsteady equations of gas dynamics.

At present, progress in the development of aeronautical engineering is impossible without using new technologies. These include the use of modern facilities of energy supply (laser and microwave radiation, electric charge) to control the aerodynamic characteristics of airfoils, in particular, to decrease wave resistance, which can enable one to make further advances in investigating the region of higher flying speeds with preservation of a high aerodynamic efficiency.

The transonic range of flow about the airfoils remains the least understood field of aerodynamics. The main effort of researchers went into the designing of such configurations in the case of flow about which the occurrence of a supersonic zone is delayed (as far as the Mach number of the incoming flow is concerned) and/or the intensity of a closing compression shock becomes weaker. These configurations include supercritical airfoils of the first and second generation (for example, those created at the Central Aero-Hydrodynamics Institute) the possibilities of improving which have, apparently, been exhausted [1–4].

The issues of the action of local energy supply on the structure of gas flow have been studied by G. G. Chernyi, V. A. Levin, P. Yu. Georgievskii, P. K. Tret'yakov, V. P. Zamuraev, A. F. Latypov, and others (see [5–10]). The analysis of the experimental and calculated results given in these works shows that one can substantially change the structure of supersonic flow up to its cardinal transformation with a relatively low consumption of energy. The transonic range of speeds has been covered only in the work of A. S. Yuriev et al. ([11]), in which the influence of the energy supply to the local supersonic zone angle above a symmetric airfoil at the zero angle of attack is studied numerically within the framework of the steady-state problem, and in [12] in which the fundamental possibilities of controlling both the local and integral characteristics of airfoils in transonic modes of flow with the use of pulse-periodic energy supply have been shown within the framework of the unsteady problem.

Formulation of the Problem. As a mathematical model of flow we employ the system of two-dimensional unsteady equations of gas dynamics, i.e., we solve the Euler equations in conservative form for a gas with a constant adiabatic exponent:

$$\partial \mathbf{U}/\partial t + \partial \mathbf{F}/\partial x + \partial \mathbf{G}/\partial y = \mathbf{Q}\,,$$

$$\mathbf{U} = (\rho, \rho u, \rho v, e)\,, \quad \mathbf{F} = (\rho u, p + \rho u^2, \rho uv, u\,(p + e))\,, \quad \mathbf{G} = (\rho v, \rho uv, p + \rho v^2, v\,(p + e))\,, \quad \mathbf{Q} = (0, 0, 0, q)\,.$$

For the gas model in question we have

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

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TABLE 1. Coefficient of Resistance of the Airfoil as a Function of the Mach Number, the Dimensions of the Computational Region, and the Number of Grid Nodes

No. of the variant of calculation	M_0	$N_x \times N_y$	$L_x \times L_y$	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

In pulse-periodic energy supply, the quantity q is determined by the expression

$$q = \Delta p/(\gamma - 1)\, f(t)\,, \quad f(t) = \sum_i \delta\,(t - i\Delta t)\,.$$

The system of equations is supplemented with the boundary conditions at the boundaries of a doubly connected computational region which represents a rectangle with the internal boundary corresponding to the contour of the NACA-0012 airfoil. The conditions of an unperturbed flow are set at the left-hand, upper, and lower boundaries, "soft conditions" are set at the right-hand boundary, and the nonflow condition is set on the contour of the airfoil.

The computational grid in the physical region is geometrically adaptive to the contour of the airfoil and is bunched in its vicinity; it is rectangular in the canonical region. The number of computational nodes is 352 × 320. We employ the finite-volume scheme diminishing the total variation (Total-Variation-Diminishing Scheme, or TVD reconstruction) at the intervals between the instants of energy supply to find the numerical solution. Time integration is carried out according to the Runge–Kutta method of third order. The pulse energy supply is so rapid each time that changes in the density of the gas and in its velocity over a very short period of time are considered to be negligibly small. The density of the gas energy in the zone of its supply increases by a prescribed value (in the calculations, the density of the supplied energy is taken to be constant and equal to $\Delta E/\Delta S$). The initial distribution of the parameters which corresponds to the steady-state flow about the airfoil without energy supply has been obtained with an absolute error of 10^{-4} for simple variables (ρ, u, v, p) at all the grid nodes. With the beginning of energy supply and until the periodic solution is obtained, the unsteady problem is solved with the same accuracy.

Test Calculations. We have carried out test calculations evaluating the error of computation of the coefficient of resistance of the airfoil for the values (indicated in Table 1) of the Mach number of the incoming flow, the dimensions of the computational region, and the number of computational nodes.

When $M_0 = 0.70$, the flow is subsonic everywhere. In this connection, the value of the aerodynamic resistance $C_x = 0.003$ obtained in variant 6 can be used as the estimate of the accuracy of the method. Successive duplication of the number of computational nodes in each direction yields a monotone decrease in the error (variants 4, 5, and 6). Extension of the computational region for a fixed number of nodes leads to an error growth (equivalently to a decrease in the number of nodes for a fixed region, variants 5 and 7). As the Mach number decreases, the computational error grows ($\sim M_0^{-2}$, variants 1, 2, and 3). Shock waves, where the order of the accuracy of calculating the flow decreases, are formed in the flow when $M_0 = 0.85$. Therefore, it has been assumed that the aerodynamic resistance is overstated by $\Delta C_x = 0.003$ in the calculations. The corresponding relative error of computation of the coefficient of resistance for variant 10 amounts to ~7%.

Results of the Calculations. The results have been obtained for an ideal gas at $\gamma = 1.4$ for $M_\infty = 0.85$ and the zero angle of attack of the airfoil with a fixed position of the zones of energy supply and different values of the

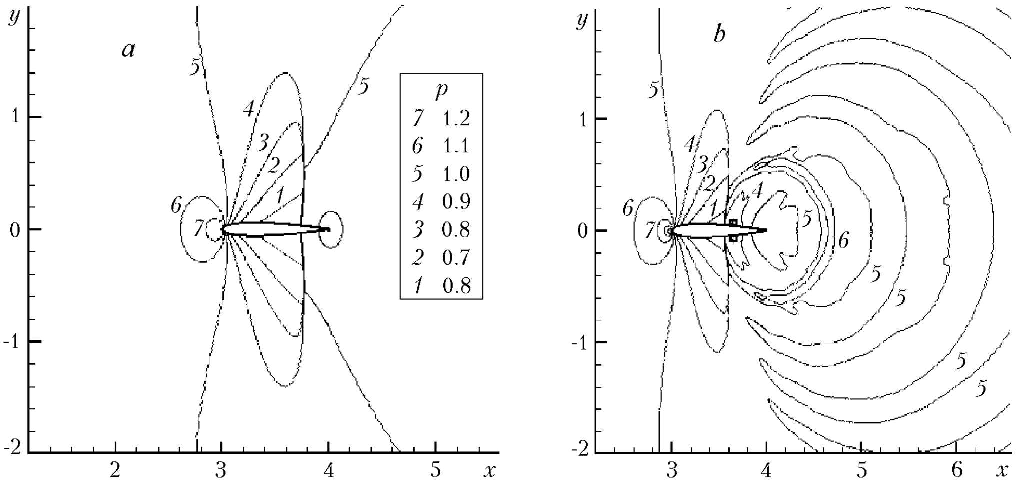


Fig. 1. Isolines of pressure of the steady-state flow about the airfoil without energy supply (a) and with energy supply (b).

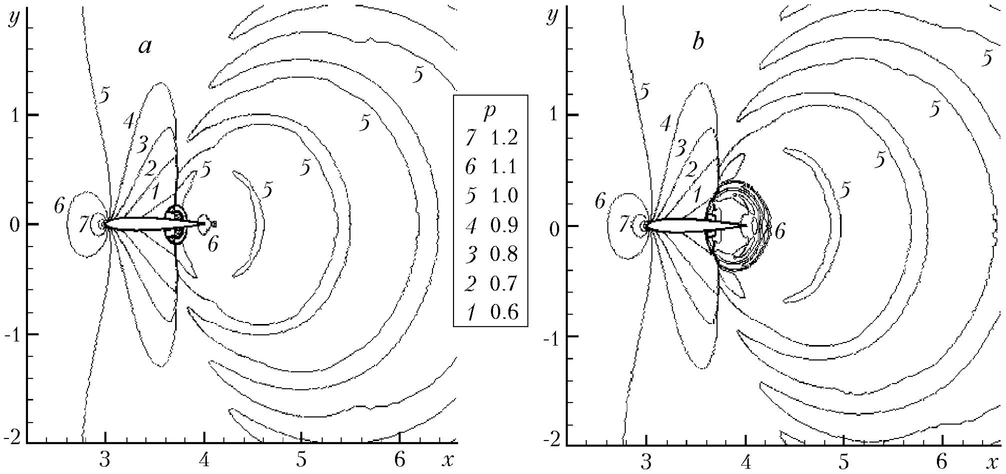
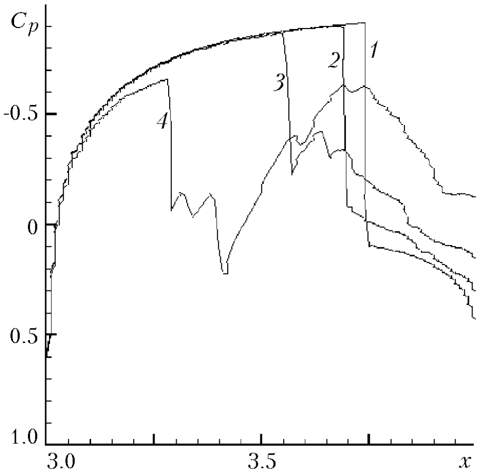


Fig. 2. Pressure isolines for the instants of time: a) t = 0.01 and b) t = 0.05 from the beginning of energy supply.

supplied energy for the period Δt = 0.5. In all the variants considered below, the zones of energy supply are located in supersonic regions ahead of the compression shocks in steady-state flow.

Figure 1 gives the isolines of pressure of the initial steady-state flow and periodic flow with an energy supply of ΔE = 0.03 at the instant of time just before the supply of an energy "pulse." A fractal structure of the lines of the level, which reflects the pulse-periodic character of energy supply (the energy-supply zones are tetragons located symmetrically at the top and at the bottom near the airfoil) is observed in Fig. 1b. For the same variant of calculation Fig. 2 gives the evolution of the structure of flow about the airfoil: the pressure isolines are shown at time intervals of $0.01\Delta t$ and $0.05\Delta t$ respectively after the next energy supply. In Fig. 2a, the pressure behind the shock wave resulting from the energy supply and propagating in the flow attains a value of C of higher than 1.5.

The distribution of the pressure coefficient over the chord of the airfoil in the case of flow without supply (curve 1) and with an energy supply of ΔE = 0.01, 0.03, and 0.1 (curves 2, 3, and 4) is given in Fig. 3. Curves 2–4 are constructed for the periodic solution at the instant of time just before the energy supply. In the variant with ΔE = 0.01, we observe a decrease in the dimensions of the supersonic zone, forward displacement of the compression shock with it adjoining the zone of energy supply, and a decrease in the intensity of the compression shock, leading to a decrease in the pressure behind it. Both these factors determine a decrease in the wave resistance of the airfoil. Figure 4 gives a close-up view of the distribution of the pressure isolines in the vicinity of the compression shock for curve 2 in Fig. 3; this distribution is illustrated by the changes noted in the structure of the flow in energy supply (the en-



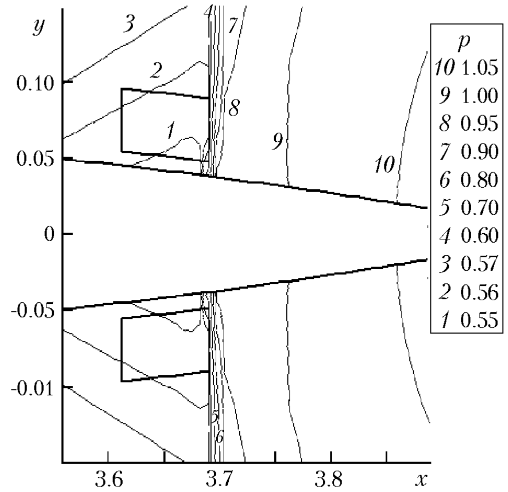


Fig. 3. Distribution of the pressure coefficients along the contour of the airfoil.

Fig. 4. Pressure distribution in the vicinity of the compression shock in the case of energy supply.

ergy-supply zones are tetragons located near the contour of the airfoil symmetrically to its chord). In the absence of energy supply, the position of the compression shock corresponds to $x = 3.75$; its abscissa is equal to 3.70 for the flow presented in Fig. 4. The mode of flow about the airfoil with $\Delta E = 0.03$ is characterized by an even larger upstream displacement of the main supersonic zone so that the zones of energy release are located behind the closing shock in the secondary transonic region of low intensity. Further increase in the level of supplied energy (curve 4) leads a destruction of the supersonic zone to form two compression shocks of nearly equal (but lower than in the initial flow) intensity. Notwithstanding the considerable decrease in the wave resistance in the last case, the diagram of the pressure coefficient obtained can hardly be assumed to be aerodynamically expedient. Furthermore, it is also necessary to take into account the energy expediency of such control.

Thus, the investigations carried out have shown considerable opportunities to control both the local and integral characteristics of the airfoils in transonic modes of flow with the use of pulse periodic volume energy supply. We have established the periodic character of flow formed in such a method of energy supply, which can enable one to employ it in cruising modes of flight; examples of both the global and local transformation of the flow have been given. The developed procedure of modeling of transonic flow with energy supply and the results obtained are also promising for investigations of the influence of the location of energy sources and their dimensions, shape, and intensity and of the frequency of energy supply on the aerodynamic characteristics of flow about lifting airfoils. The possibility of designing transonic airfoils possessing the maximum cruising Mach number with observance of the geometric and gasdynamic limitations and preservation of a prescribed lifting force under energy-supply conditions is offered.

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NOTATION

a, dimensionless velocity of sound, referred to a_0; a_0, velocity of sound in the incoming flow; C_p, pressure coefficient; C_x, coefficient of resistance of the airfoil; e, total energy of a unit volume of the gas, referred to $\rho_0 a_0^2$; L, length of the airfoil chord; L_x and L_y, dimensions of the computational region Ω in x and y, referred to L; M_0, Mach number of the incoming flow; N_x and N_y, number of computational nodes in x and y; p, pressure referred to $\rho_0 a_0^2$; p_0, pressure in the incoming flow; q, power supplied to a unit volume of the gas and normalized to $\rho_0 a_0^3/L$; t, time referred to L/a_0; u and v, velocity-vector components referred to a_0; **F**, **G**, **Q**, and **U**, vectors in the standard representation of the gas-dynamics equations; x and y, Cartesian coordinates directed respectively along and across the airfoil chord and referred to L; ΔC_x, error of computation of the coefficient of resistance of the airfoil; ΔE, dimensionless total energy supplied over a period; $\delta(t)$, pulse Dirac function; Δt, period of energy supply; Δp, pressure increase corresponding to the energy supply; ΔS, area of the zone of energy supply, normalized to L^2; γ, adiabatic exponent; ρ, density referred to ρ_0; ρ_0 is determined from the condition $p_0 = \rho_0 a^2$; Ω, doubly connected computational region. Subscripts: i, index of summation; x, direction along the coordinate x; y, direction along the coordinate y; 0, incoming flow.

REFERENCES

1. S. M. Aul'chenko, A. F. Latypov, and V. G. Samarin, Designing of symmetric profiles with a maximum critical Mach number of the flow at specified limitations, *Uch. Zap. TsAGI*, **19**, No. 2, 19–28 (1988).
2. S. M. Aul'chenko and A. F. Latypov, Construction of airfoils in a subsonic gas flow by methods of numerical optimization, *Izv. Ross. Akad. Nauk, Mekh. Zhidk. Gaza*, No. 2, 174–182 (1997).
3. S. M. Aul'chenko, A. F. Latypov, and Yu. V. Nikulichev, Methods of design and optimization of airfoils in a subsonic flow, *Teplofiz. Aéromekh.*, **6**, No. 4, 429–444 (1999).
4. S. M. Aul'chenko, A. F. Latypov, and Yu. V. Nikulichev, Experience gained in optimization in aerodynamic characteristics of airfoils under exploitation, *Prikl. Mekh. Tekh. Fiz.*, **43**, No. 1, 60–64 (2002).
5. V. P. Zamuraev, Influence of local energy release on the structure of a supersonic flow in a plane channel, *Teplofiz. Aéromekh.*, **6**, No. 4, 351–368 (1999).
6. V. P. Zamuraev, Possibility of controlling vorticity in a supersonic flow by means of instantaneous local supply of energy, *Teplofiz. Aéromekh.*, **8**, No. 1, 87–100 (2001).
7. V. P. Zamuraev, A. P. Kalinina, and A. F. Latypov, Estimation of the thrust of a ramjet engine with pulsed supply of energy, *Teplofiz. Aéromekh.*, **9**, No. 3, 405–410 (2020).
8. V. P. Zamuraev and A. F. Latypov, Control of supersonic flow vorticity by instant local and discrete distributed energy release, in: *Proc. 4rd Int. Workshop on Magneto-Plasma-Aerodynamics in Aerospace Applications*, Moscow (2002), p. 30.
9. A. F. Latypov, Evaluation of the energy efficiency of heat supply in front of the body in a supersonic flow, in: *Ext. Abstr. of Papers presented at 8th All-Russia Meeting on Theoretical and Applied Mechanics* [in Russian], Perm (2001), p. 392.
10. A. F. Latypov and V. M. Fomin, Evaluation of the energy efficiency of heat supply in front of the body in a supersonic flow, *Prikl. Mekh. Tekh. Fiz.*, **43**, No. 1, 71–75 (2002).
11. A. S. Yuriev, S. K. Korzh, S. Yu. Pirogov, N. P. Savischenko, S. B. Leonov, and E. V. Ryizhov, Transonic streamlining of profile at energy addition in local supersonic zone, in: *Proc. 3rd Int. Workshop on Magneto-Plasma-Aerodynamics in Aerospace Applications*, Moscow (2001), pp. 201–207.
12. S. M. Aul'chenko (Aulchenko), V. P. Zamuraev, and A. F. Latypov, On possibility to control a transonic streamlining of the airfoil by means of a periodic pulse local energy supply, in: *Abstr. of Papers presented at the 5th Int. Workshop on Magneto-Plasma-Aerodynamics in Aerospace Applications*, Moscow (2003), p. 92.