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EFFECT OF LOCALIZATION OF PULSED ENERGY ADDITION ON THE WAVE DRAG OF AN AIRFOIL IN A TRANSONIC FLOW

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The possibility of controlling the aerodynamic characteristics of airfoils with the help of local pulsed-periodic energy addition into the flow near the airfoil contour at transonic flight regimes is considered. By means of the numerical solution of two-dimensional unsteady equations of gas dynamics, changes in the flow structure and wave drag of a symmetric airfoil due to changes in localization and shape of energy-addition zones are examined. It is shown that the considered method of controlling airfoil characteristics in transonic flow regimes is rather promising. For a zero angle of attack, the greatest decrease in wave drag is obtained with energy addition at the trailing edge of the airfoil.

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

Introduction. The study of the effect of external heating (energy addition outside the flying vehicle) at supersonic velocities was started in the middle of the past century by Oswatich (1946). Energy addition into a gas flow alters the flow structure and gives rise to additional forces acting on the body. These can be either driving forces or forces leading to a decrease in drag. Lift forces or moments of forces can arise. They can be used to control the vehicle flight. Energy addition to a subsonic flow was examined previously (from methodical considerations and to better understand the influence of energy addition at supersonic velocities). Of major interest, however, was the aerodynamic research of energy addition to a supersonic flow. The papers published in 1950s–1960s were reviewed in [1]. A steady ideal-gas flow was considered in these papers and even later. The flow region was divided into stream tubes, and a one-dimensional approximation was used for the analysis in each stream tube. Linearization of equations and other simplifications were used. Some understanding of the processes that occur owing to energy addition to a supersonic flow was reached, and formulas suitable for estimating the influence of this energy addition were derived. Nevertheless, the approximations used did not reveal the fact that the flow structure can be qualitatively changed by using comparatively small amounts of energy or matter. An example of such a change in the flow structure can be found in [2], where it was demonstrated that interaction of a shock wave with an extended slender channel of a low-density gas leads to cardinal reconstruction of the flow if this channel is oriented at a sufficiently large angle to the wave front. It was found [3] that, if a powerful pulsed optical discharge is used ahead of a body (cone or sphere) in a supersonic flow, the body drag decreases twofold with increasing laser-pulse repetition frequency. The significant effect of these actions is associated with the nonlinear nature of the process considered. These examples suggest that local actions can be used to control supersonic flows.

The effect of local energy addition on the supersonic gas flow structure was considered with the use of advanced numerical methods in [4–6] and many other papers. The energy efficiency of energy addition to a supersonic air flow ahead of the body was estimated in [7].

For the transonic range of velocities, the publications seem to be limited to [8–12]. The effect of steady energy addition to a local supersonic region above a symmetric airfoil at a zero angle of attack with the governing parameters varied in a wide range was numerically examined in [8]. At the same time, the influence of the shape of

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the energy source and its size along the airfoil has not been examined. The mechanism of variation of aerodynamic characteristics of the airfoil, namely, attenuation and shift of the shock wave closing the supersonic zone upon shock-wave interaction with the low-density wake formed behind the source, was revealed in that paper. The change (increase) in pressure in the energy-addition zone turned out to be insignificant. The energy efficiency of using a steady external source of energy was also estimated.

Unsteady energy addition, however, seems to be more realistic, at least if unconventional energy sources are used (laser radiation, microwave radiation, and electric discharge). Possibly, the results of steady energy addition are limiting in a certain sense (with increasing frequency of energy addition). This possibility was first established experimentally in [3] for the case of energy addition ahead of a body in a supersonic flow. For the transonic regime, this issue requires additional investigations.

Unsteady addition of energy in the vicinity of a symmetric airfoil (the same as in [8]) at a zero angle of attack was considered in [9–12]. These papers demonstrated the principal possibility of controlling both local and integral characteristics of airfoils in the transonic flow regime by means of pulsed-periodic addition of energy. The mechanism of changes in aerodynamic characteristics of the airfoil is principally different from the mechanism of their changes in the steady regime considered in [8]. Pulsed-periodic addition of energy generates a complicated shock-wave structure of the flow. Shock waves moving upstream from the energy source decelerate the supersonic flow and attenuate the closing shock, whereas the shock waves moving downstream from the energy source form a quasi-periodic flow structure. Decomposition of the supersonic region is possible, and the pressure distribution is drastically different from the classical pressure distribution on the airfoil. It is necessary to further study the mechanism of changes in aerodynamic characteristics of an airfoil in the case of unsteady (pulsed-periodic) addition of energy. There are practically no parametric studies in [9–12].

Thus, investigation of the possibility of controlling aerodynamic characteristics of transonic airfoils by means of unsteady addition of energy into the flow is an urgent problem. It should also be noted that the main flight regimes for the currently existing flying vehicles are the transonic regimes.

The present paper is a logical continuation of studying the shock-wave structure of a transonic flow around a symmetric airfoil [12]. In particular, the effect of the position and shape of energy-addition zones on the wave drag of the airfoil is considered. The energy is added both in the supersonic region upstream of the closing shock and behind the latter, in the rear part of the airfoil, as well as ahead of the airfoil.

Formulation of the Problem. The mathematical model of the flow involves a system of two-dimensional unsteady equations of gas dynamics (Euler equations) in a conservative form for a gas with a constant ratio of specific heats γ. To solve this problem numerically, a finite-volume total variation diminishing scheme (TVD reconstruction) is used in intervals between the moments 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. The computational grid in the physical domain is geometrically adapted to the airfoil contour and is refined in the vicinity of the contour; a rectangular grid is used in the canonical domain; the number of computational nodes is 352×320. In the model considered, the pulsed energy addition occurs instantaneously with no changes in gas velocity and density. The energy density of the gas e in the energy-addition zone increases by $\Delta e = \Delta E/\Delta S$, where ΔE is the total energy added and ΔS is the area of the energy-addition zone.

The initial distribution of parameters, corresponding to a 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. The problem was solved in an unsteady formulation from the beginning of energy addition until a periodic solution was obtained. The moment of reaching a periodic solution was determined by comparing the drag coefficient of the airfoil in time intervals equal to the energy-addition period. The absolute error was within 10^{-6}. The test computations showed that the absolute error of computing the wave-drag coefficient is approximately 7% [12]. The total force arising on the body is the sum of elementary forces acting on the body surface in the normal and tangential directions. Friction drag is caused by tangential forces generated by the boundary layer. For most subsonic aircraft, the friction coefficient is approximately 0.003–0.005 [14], which is within the absolute error of the wave-drag coefficient. The values of the wave-drag coefficient C_x were averaged over the period.

Results of Computations. The results were obtained for a NACA-0012 airfoil at a zero angle of attack in a flow of an ideal gas with $\gamma = 1.4$; the free-stream Mach number was $\mathrm{M}_\infty = 0.85$. The positions and sizes of energy-addition zones were varied; the energy added was $\Delta E = 0.01$ and the period was $\Delta t = 0.25$ or 0.5.

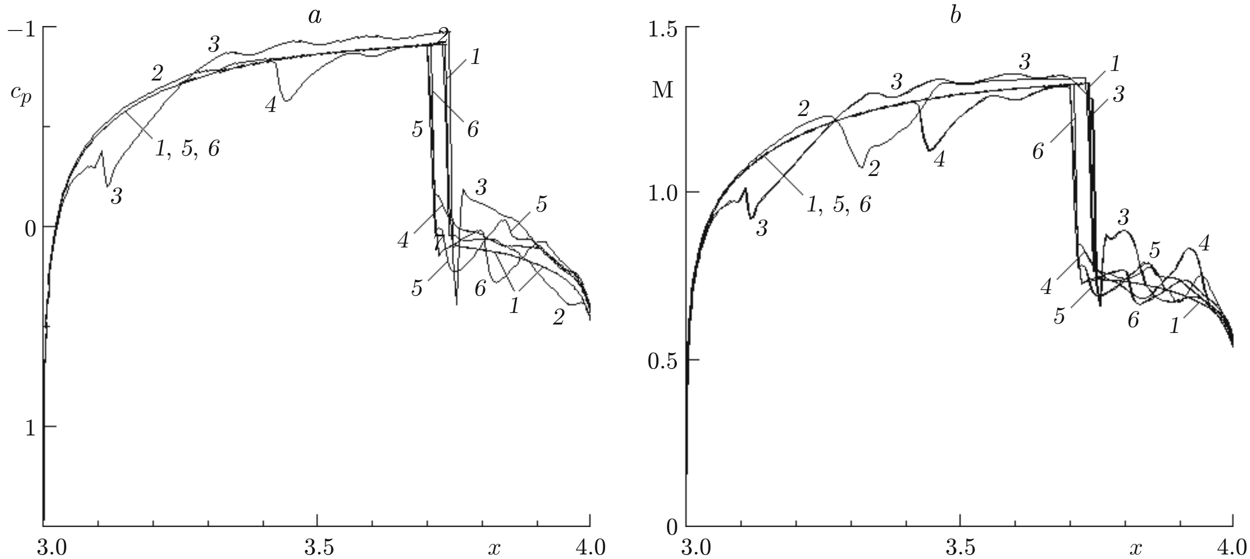


Fig. 1. Distribution of the pressure coefficient (a) and Mach number (b) over the airfoil with different positions of energy-addition zones.

The energy was added symmetrically with respect to the airfoil (all linear dimensions are normalized to the chord length l, the added energy ΔE is normalized to the parameter $\rho_0 a_\infty^2 l^2$, and the energy-addition period is normalized to the quantity l/a_∞, where ρ_0 is determined by the condition $p_\infty = \rho_0 a_\infty^2$, and p_∞ and a_∞ are the dimensional pressure and velocity of sound in the free stream).

Figure 1 shows the distributions of the pressure coefficient and Mach number over the airfoil after establishment of a periodic solution ($\Delta t = 0.5$) at the time immediately before energy addition for different positions of energy-addition zones. There are five variants of positions of energy-addition zones. Curves 1 refer to the situation without energy addition; curves 2–6 show the influence of energy addition ahead of the airfoil ($x = 2.936$), near the frontal part of the airfoil in the very beginning of the supersonic region ($x = 3.219$), in the supersonic region at a certain distance from the closing shock ($x = 3.442$), near the airfoil tail ($x = 3.971$), and immediately behind the airfoil ($x = 4.076$); the numbers given above indicate the right boundary of the energy-addition zone; the airfoil is located in the interval $3 < x < 4$. The area of the energy-addition zone is $\Delta S = 0.0292$ (the difference is less than 1%); hence, the energy density is almost identical: $\Delta e = 3.42$. The influence of energy addition ahead of the airfoil (curves 2) is insignificant: the position and intensity of the shock wave closing the supersonic flow region remain almost unchanged; only some pressure redistribution behind this shock is observed (an increase in pressure near the trailing edge). As a consequence, the wave-drag coefficient C_x slightly decreases to 0.0428, as compared with $C_x = 0.0450$ in the absence of energy addition. The corresponding distribution of the Mach number over the airfoil indicates alternation of regions with reduced and elevated density.

Curves 3 refer to energy addition on both sides of the airfoil near its leading edge (in the zone of transition of the subsonic to the supersonic flow). The pressure in the adjacent flow region increases, the shock wave is shifted downstream, its intensity increases, but the level of pressure on the tail part of the airfoil as a whole decreases, which leads to a drastic increase in the wave-drag coefficient to $C_x = 0.0635$. This results is widely known [1].

Curves 4 are obtained for energy addition in a supersonic flow downstream of the airfoil cross section corresponding to its maximum thickness. A drastic decrease in intensity of the shock wave closing the supersonic flow region is observed. Decomposition of the supersonic region is observed. The shock wave itself is shifted upstream. The level of pressure near the tail part of the airfoil slightly increases. As a consequence, the wave-drag coefficient of the airfoil decreases to $C_x = 0.0417$.

A further shift of the energy-addition zone toward the trailing edge of the airfoil leads to a further decrease in the wave-drag coefficient to $C_x = 0.0394$ and 0.0387 (curves 5 and 6, respectively). These cases involve an approximately the same upstream shift of the closing shock wave as that in the variant described by curve 4.

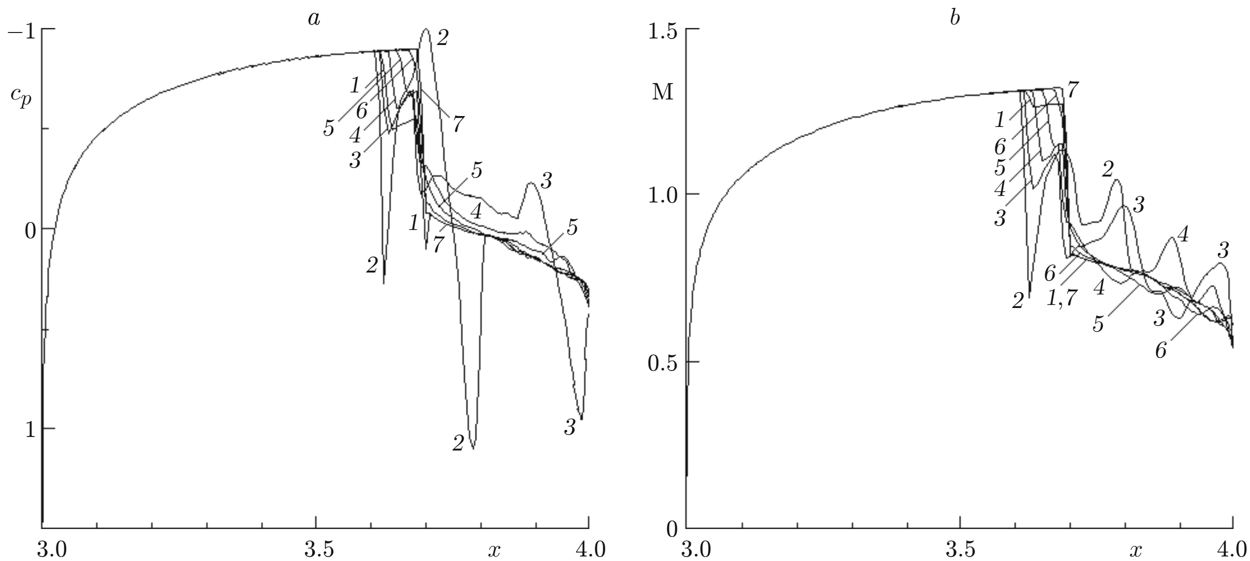


Fig. 2. Distributions of the pressure coefficient (a) and Mach number (b) over the airfoil at different times.

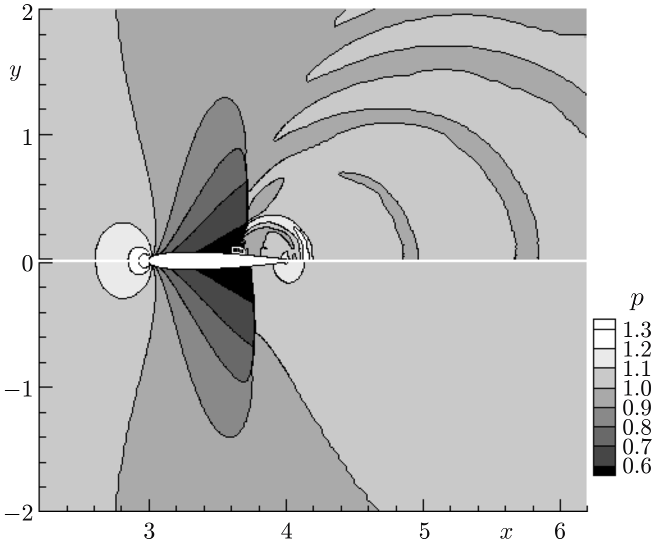
Nevertheless, the pressure behind the closing shock wave as a whole is higher, which is the reason for the decrease in the wave-drag coefficient.

Figure 1 shows the spatial distributions of parameters at a certain time. The distributions of these parameters over the airfoil at different times are plotted in Fig. 2. Energy addition is performed ahead of the closing shock wave (the coordinate of the right boundary of the energy-addition zone is $x = 3.693$, and the position of the shock wave corresponds to $x \approx 3.74$). Curves 1–7 refer to the times (in fractions of Δt) equal to 0.01 (1), 0.1 (2), 0.3 (3), 0.5 (4), 0.7 (5), 0.9 (6), and 1.0 (7). Energy addition leads to formation of shock waves propagating upstream and downstream (this is evidenced by curves 1 and 2). At the time corresponding to curve 2, the velocity behind the upstream-propagating shock wave is subsonic; expansion waves attenuating the shock waves are observed in the region between the shock waves; a contact discontinuity is seen in Fig. 2b. Subsequently (curves 3–6), the shock waves become less intense and are entrained by the flow; the distributions preceding the next energy addition are formed (curves 7). In contrast to [8], the low-density wake is not observed.

The formation of the shock-wave flow structure in this variant is illustrated in Fig. 3 (upper part), which shows the pressure distribution at the time of $0.1\Delta t$ after the next addition of energy; for comparison, the lower part of the figure shows the pressure distribution in the absence of energy addition. The shock wave propagating from the energy-addition zone shifts the closing shock wave in the upstream direction and attenuates it. Alternation of comparatively light and dark bands (zones with different levels of pressure) in the flow region adjacent to the tail part of the airfoil is the result of periodic energy addition.

The behavior of the period-averaged wave-drag coefficient versus localization of energy-addition zones along the x axis is illustrated in Fig. 4. The lower part of the figure shows the upper half of the airfoil (its transverse size is increased approximately by a factor of 16). The straight line parallel to the x axis corresponds to $C_x = 0.0450$ in the absence of energy addition. The points in the figure yield the values of the wave-drag coefficient in the case of energy addition and correspond to the centers of almost equivalent zones of energy addition. In the case of a transonic flow around a symmetric airfoil at a zero angle of attack, energy addition at the trailing edge of the airfoil is the most beneficial method of decreasing the wave drag.

The dynamics of variation of the wave-drag coefficient within a period can be assessed by the values of C_x listed in Table 1 for the variant shown in Figs. 2 and 3. These values of C_x were obtained by averaging over the time interval of $0.1\Delta t$. The first and third columns of Table 1 indicate the times $k\Delta t$ from the beginning of the next energy addition. The value averaged over the entire period is $C_x = 0.03964$.



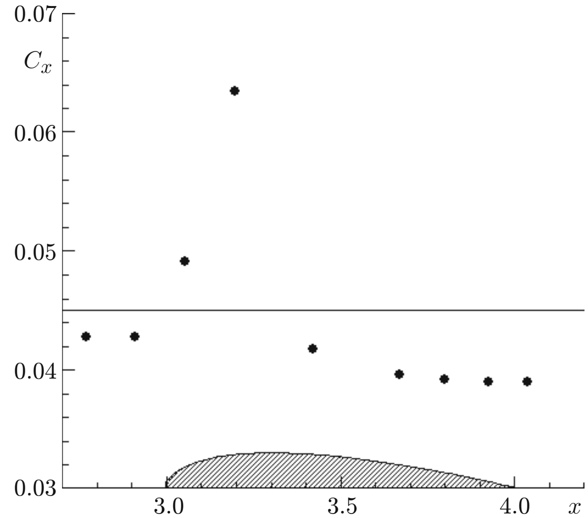


Fig. 3

Fig. 4

Fig. 3. Pressure isolines for the case of energy addition ahead of the closing shock wave at the time $t = 0.05$ after the beginning of energy addition (upper part) and steady flow around the airfoil without energy addition (lower part).

Fig. 4. Wave-drag coefficient averaged over the period versus localization of energy-addition zones along the x axis.

TABLE 1

k	$C_x \cdot 10$	k	$C_x \cdot 10$
0.1	0.1799	0.6	0.4314
0.2	0.3609	0.7	0.4255
0.3	0.3981	0.8	0.4236
0.4	0.4577	0.9	0.4188
0.5	0.4510	1.0	0.4174

Insignificant changes in the wave-drag coefficient C_x versus localization of energy-addition zones somewhere in the tail part of the airfoil gives grounds to believe that the value of C_x depends weakly on the shape of energy-addition zones. This is confirmed by results computed for energy addition directly ahead of the undisturbed shock wave. In one case, the energy-addition zone was extended by a factor of 2 along the x axis with its area being unchanged, and the value of C_x was almost the same as that obtained in a square zone, i.e., $C_x = 0.0397$. In another case, the zone location was approximately the same, but the zone was extended in the transverse direction (along the y axis) by a factor of 2, the area being also unchanged. The wave-drag coefficient in this case was $C_x = 0.0396$. An increase in area of energy-addition zones in this part of the gas flow exerts no effect either (with a corresponding decrease in density of added energy).

The area of energy-addition zones was increased by a factor of 2 in the case of energy addition immediately ahead of the undisturbed shock wave and in the vicinity of the trailing edge of the airfoil. The values of the wave-drag coefficient were $C_x = 0.0397$ and 0.0387, respectively. A twofold decrease in the period of energy addition does not lead to any noticeable changes in the wave-drag coefficient of the airfoil either. Actually, this is the result of the linear dependence of the decrease in the wave-drag coefficient on the energy added for the configuration of energy-addition zones under consideration.

Conclusions. The study performed revealed certain possibilities of controlling both local (distribution of gas-dynamic parameters over 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 was established, which can allow its use in cruising flight regimes. Investigations of the influence of positions of energy sources, their size and shape, and energy-addition frequency on aerodynamic characteristics of the flow around lifting airfoils showed that the most important parameter in the case of a zero angle of attack is the position of energy-addition zones. The most substantial decrease in wave drag was obtained in the case of energy addition in the vicinity of the trailing edge of the airfoil. It becomes possible to design transonic airfoils with the maximum cruising Mach number under geometric and gas-dynamic constrictions and retaining a given lift force under conditions of energy addition.

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