WEST-EAST HIGH SPEED FLOW FIELD CONFERENCE
19-22, November 2007
Moscow, Russia

CONTROL OF STREAMLINE OF THE TRANSONIC AIRFOILS BY PERIODIC PULSE LOCAL ENERGY SUPPLY

V.P. Zamuraev, S.M. Aulchenko and A.P. Kalinina

Khristianovich Institute of Theoretical and Applied Mechanics SB RAS,
Novosibirsk, Russia
Email: zamuraev@itam.nsc.ru, aultch@itam.nsc.ru, kalinina@academ.org

Key words: transonic flow, airfoil's aerodynamic characteristics, energy supply, Euler equations.

Abstract. The possibility of controlling the aerodynamic characteristics of airfoils with the help of local periodic pulsed energy supply 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 and energy supply frequency are examined. The energy supply in front of the closing shock wave within extended zones in the immediate vicinity of the streamlined contour leads to a significant decrease in the wave drag of a given airfoil. The nature of this phenomenon is elucidated and it is established that there exists a limiting frequency of energy supply. The influence of an asymmetrical supply of energy on aerodynamic characteristics of the symmetric airfoil was studied.

1. PROBLEM STATEMENT

The progress of modern space aircraft technologies is often based on successful control of gas flow. Traditional aerodynamic techniques do not meet the increasing requirements concerning aircraft operating performances. Only comprehensive approaches and use of new technologies can solve this problem. Energy supply to a gas flow is a promising method of control of aerodynamic characteristics of aircrafts and their components (in particular, wings). There are different means of energy supply: laser radiance, SHF, electric discharge etc.

The authors' previous researches [1–4] concerning pulsed-periodic energy supply in compact zones have shown that the airfoil wave drag coefficient weakly depends on the form and locations of the energy supply zones downstream of the airfoil midsection. This is a consequence of linear dependence of airfoil wave drag coefficient on energy supply.

In this work we present the results partially published in the papers [5–8] which testify to the existence of nonlinear effects that arise at energy supply in a pulsed-periodic regime in the thin zones lying along the profile. In the model under consideration, the pulsed energy supply is carried out instantaneously, and this implies no change in the gas density and velocity. The gas energy density e in the zones of its supply increases by the amount $\Delta e = \Delta E/\Delta S$, where ΔE is the total energy supplied to a single zone, ΔS is the zone area. The energy is supplied symmetrically with respect to the airfoil. The initial distribution of parameters corresponds to a steady flow around the airfoil without the energy supply. The time of reaching the periodic solution was determined from a comparison of the mean values of the profile drag coefficient C_x.

2. POWER SUPPLY EFFICIENCY

The efficiency of external energy supply to the wing profile can be determined by comparing a decrease in the wave drag to an increase in the thrust of a vehicle for the same energy supplied via the thruster. The efficiency of a thruster is $\eta = Ru_\infty/W$, where R is the thrust, u_∞ is the velocity of motion, and W is the power supplied to the thruster [9]. In the cruise flight regime, the thrust is equal to the drag. Then, an estimate for the effective energy supply to the wing profile can be readily obtained and expressed in dimensionless variables as

$$\Delta E \le \gamma \cdot \Delta C_x \mathrm{M}_\infty^3 \Delta t/(4\eta), \tag{1}$$

where ΔC_x is the decrease in the wave drag coefficient, M_∞ is the Mach number of the incident flow, and Δt is the time interval between energy pulses. For a given energy, this expression provides an estimate of the thruster efficiency at which the energy supply to the streamlined contour becomes favorable.

3. COMPUTATONAL RESULTS

The numerical results were obtained for a NACA-0012 wing profile streamlined by an ideal gas with an ratio of specific heats $\gamma = 1.4$. The incident flow had a Mach number of $\mathrm{M}_\infty = 0.85$ and a zero angle of attack. The time interval Δt between energy pulses was varied from 0.005 to 0.5. The position and area of the zone of energy supply were varied at a constant average power (per period) $\Delta E/\Delta t = 0.02$ supplied to the zone (here and below, all variables are dimensionless).

Table 1 presents the values of C_x determined for various time intervals Δt between energy pulses (the first line indicates the drag in a stationary regime without energy supply). The energy was deposited immediately at the streamlined contour (x_1 and x_2 are the coordinates of the left and right boundaries of the energy supply zone; the profile occurs within $3 \le x \le 4$).

№	x_1	x_2	$\Delta S \cdot 10^4$	Δt	$C_x \cdot 10^2$	$\Delta C_x \cdot 10^2$	$\Delta C_x/C_x$, %
1	–	–	–	–	4.588	–	–
2	3.609	3.693	0.839	0.5	3.916	0.672	14.6
3	3.609	3.693	0.839	0.05	3.498	1.090	23.8
4	3.609	3.693	0.839	0.025	3.526	1.062	23.1
5	3.609	3.693	0.839	0.005	~3.57	~1.02	22.2

Table 1. Average wave drag coefficient for various frequencies of pulsed energy supply (at a constant average power of $\Delta E/\Delta t = 0.02$).

At low pulse repetition frequencies, the flow topology is partly restored before arrival of the next energy pulse. In this case, an upstream shift of the closing shock wave does not provide for a significant decrease in C_x. As the time interval between energy pulses decreases, the flow topology cannot be restored and the upstream shift of the closing shock wave reaches a maximum that provides for a substantial decrease in C_x. Figure 1 shows profiles of the pressure coefficient C_p for the energy supply regimes presented in Table 1.

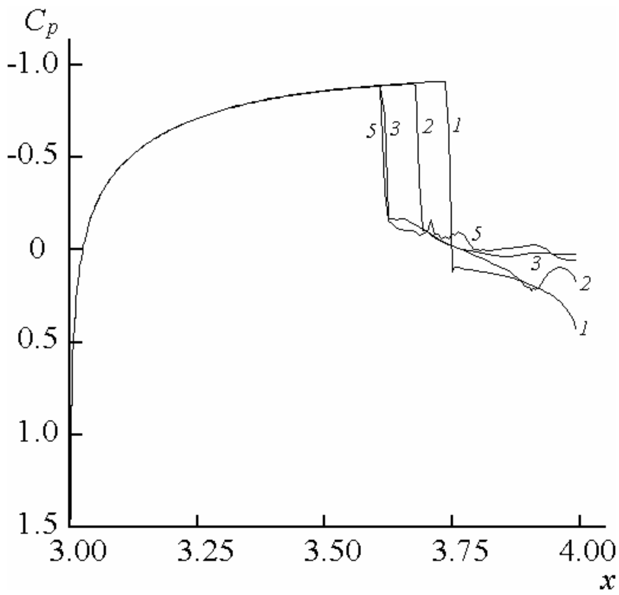

Fig. 1. Profiles of the pressure coefficient C_p along the wing chord for various time intervals between energy pulses (the curve numbers correspond to the regimes presented in Table 1).

Table 2 presents data on the average wave drag coefficient C_x and its decrease for $\Delta t = 0.05$ and variable position and area of the zone of energy supply (the first line indicates the drag in a stationary regime without energy supply). The last column in Table 2 indicates the level of thruster efficiency for which the energy supply in a given regime is favorable. As can be seen, the upstream shift of the energy supply zone (regimes 2-7) up to the middle line ($x \approx 3.303$) leads to a significant decrease in C_x (about 60% in regime 7). However, the further shift of the zone towards the leading edge decreases the effect (regim 8). A comparison of the C_x values in regimes 6 and 9 shows that a twofold decrease in the zone length (along the x axis) at approximately the same area (2.5% difference) does not significantly alter the wave drag. Figure 2 shows profiles of the pressure coefficient C_p for the energy supply regimes presented in Table 2.

№	x_1	x_2	$\Delta S \cdot 10^4$	$C_x \cdot 10^2$	$\Delta C_x \cdot 10^2$	$\Delta C_x / C_x$, %	η, %
1	–	–	–	4.588	–	–	–
2	3.609	3.693	0.839	3.498	1.090	23.8	11.7
3	3.567	3.656	0.865	3.243	1.345	29.3	14.5
4	3.523	3.609	0.812	2.920	1.668	36.4	17.9
5	3.477	3.567	0.830	2.589	1.999	43.6	21.5
6	3.433	3.523	0.819	2.250	2.338	51.0	25.1
7	3.352	3.442	0.806	~1.80	~2.79	60.8	30.0
8	3.271	3.367	0.845	~2.85	~1.74	37.9	18.7
9	3.433	3.477	0.799	2.224	2.364	51.5	25.4

Table 2. Average wave drag coefficient for various positions and areas of the energy supply zone (at a constant period of $\Delta t = 0.05$).

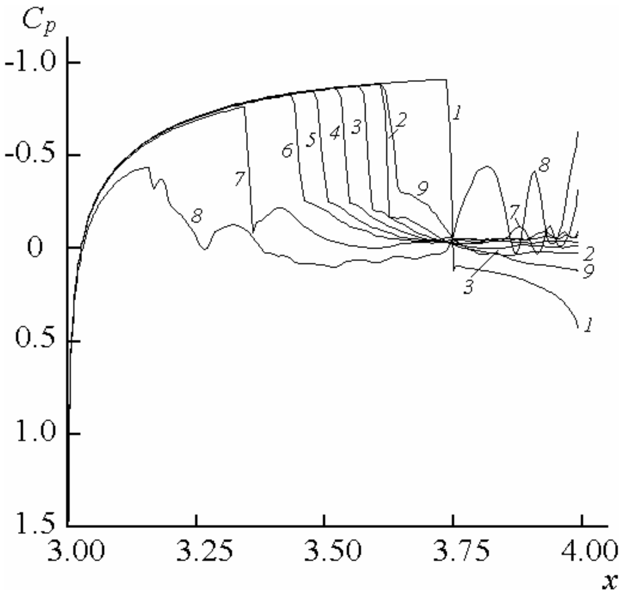

Fig. 2. Profiles of the pressure coefficient C_p along the wing chord for various positions and areas of the energy supply zone (the curve numbers correspond to the regimes presented in Table 2).

It should be noted that periodic solutions were not obtained (to within 10^{-7}) for regime 5 in Table 1 and regimes 7 and 8 in Table 2 because of instabilities related to discontinuities arising in the flow. On the whole, the wave drag coefficient exhibits a rather uniform distribution over most of the period (with a deviation from the average within 5%).

The nature of these nonlinear effects has been clarified. The mechanism of influence of the energy supply on transonic airfoil has been investigated in detail. This mechanism is in essence different from the known mechanism based on a trace with lower density, which concerns supersonic streamline usually. Figure 3 illustrates dynamics of the formation process of periodic shock-wave structure at a limit frequency of energy supply in one of the studied variants at the free stream Mach number M = 0.85.

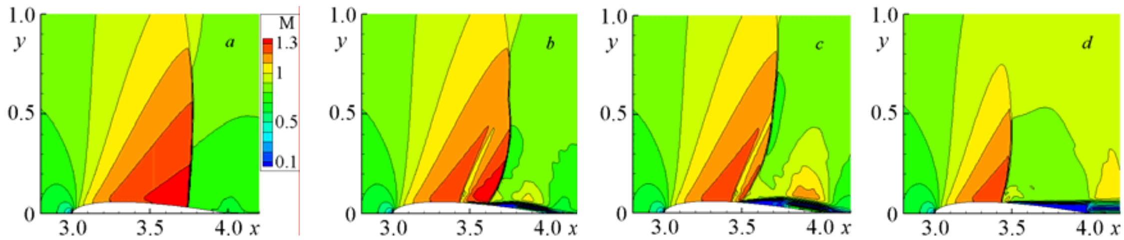

Fig. 3. Fields of the Mach number: *a* – stationary solution without energy supply; *b*-*c* – solution with energy supply after 30, 50 periods; *d* – periodic solution with energy supply.

Also, influence of an asymmetrical supply of energy on aerodynamic characteristics of the airfoil NACA-0012 was studied under the following conditions: streamline by ideal gas with $\gamma = 1.4$, $M_\infty = 0.85$, at a zero angle of attack in case of a supply of energy and angle of attack $\alpha = 0 \div 4^\circ$ without a supply of energy. The energy ΔE varied within the limits from 0.0001 up to 0.007. The period of a supply of energy $\Delta t = 0.05$.

Table 3 presents the values of C_x, C_y, and C_m determined for various supplied energies ΔE (C_y – lift coefficient, C_m – pitching moment coefficient). As can be seen, the energy supply initially leads to an increase in both lift and drag coefficients. However, as the energy is increased above certain level (in these calculations, $\Delta E > 0.0010$), the drag coefficient C_x ceases to grow further while the lift continues to increase.

$\Delta E \cdot 10^4$	2	4	6	8	10	12	20	30
$C_x \cdot 10$	0.4790	0.4921	0.5932	0.6345	0.6366	0.6369	0.6350	0.6343
C_y	0.2225	0.2890	0.5238	0.5899	0.6000	0.6090	0.6393	0.6698
$C_m \cdot 10$	-8.274	-10.74	-19.50	-21.91	-22.24	-22.53	-23.52	-24.53

Table 3. The aerodynamic characteristics for various supplied energies.

For the comparison, Table 4 gives the values of C_x, C_y, and C_m for various attack angles α without energy supply. As can be seen, an increase in α (within indicated limits) leads to an increase in both lift and drag of the airfoil.

α (deg.)	1	2	3	4
$C_x \cdot 10$	0.5330	0.7153	0.9556	1.2290
C_y	0.2793	0.5025	0.6753	0.8154
$C_m \cdot 10$	-10.03	-17.98	-24.08	-29.00

Table 4. The aerodynamic characteristics for various attack angles α.

Figure 4 shows the wing polars calculated for the variants presented in Table 3 (curve *1* refers to the case with energy supply and a zero angle of attack) and Table 4 (curve *2* refers to the case without energy supply for the indicated angles of attack). When the profile is streamlined at a nonzero angle of attack, the airfoil drag grows at a higher rate and the corresponding polar is steeper. Therefore, in a regime with energy supply the same lift can be achieved at a much lower wing drag as compared to that in the case of streamlining at a nonzero angle of attack.

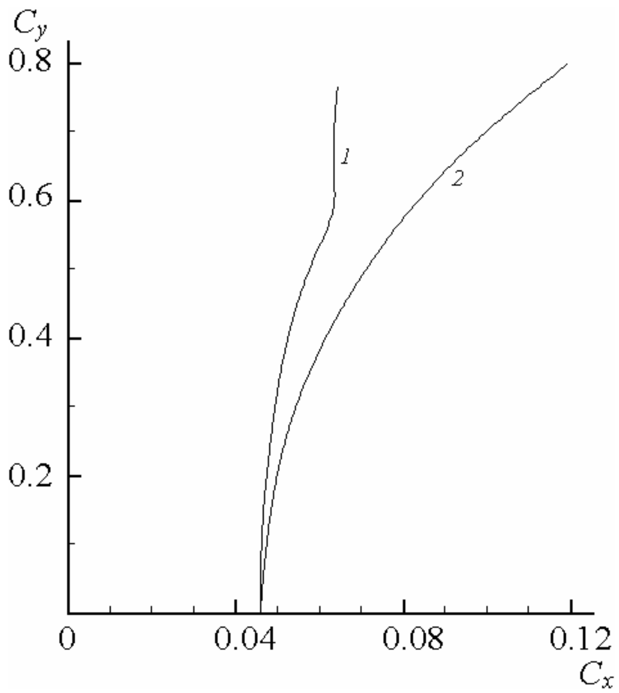

Fig. 4. The wing polars calculated for regimes: (*1*) with energy supply and a zero angle of attack and (*2*) without energy supply.

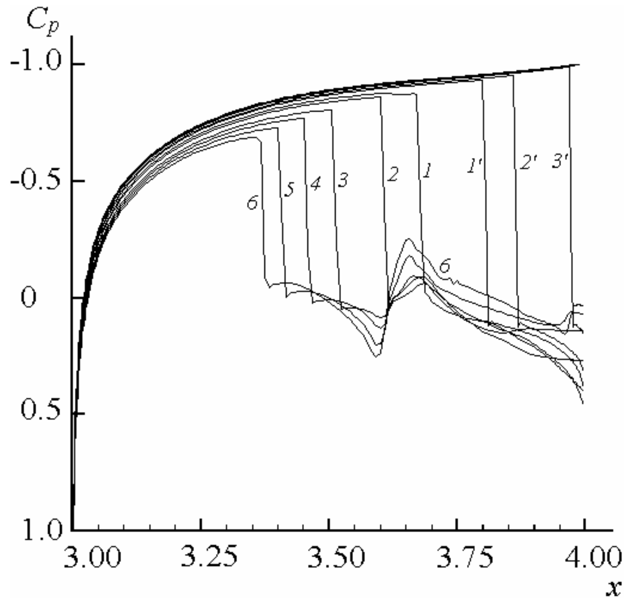

Fig. 5. The pressure coefficient along the wing chord for various supplied energies: ΔE = 0.0001 (*1*, *1′*), 0.0004 (*2*, *2′*), 0.0006 (*3*, *3′*), 0.0010 (*4*), 0.0020 (*5*), 0.0030 (*6*).

This behavior of the wing polar in the regimes with energy supply can be better understood using Fig. 5, which shows variation of the pressure coefficient along the wing chord for various supplied energies 1 – ΔE = 0.0001, 2 – 0.0004, 3 – 0.0006, 4 – 0.0010, 5 – 0.0020, 6 – 0.0030. The energy supply from the lower side at a zero angle of attack leads to the breakage of symmetry in the pressure distribution. As a result, the closing shock wave on the lower side exhibits an upstream shift that leads to breakage of the supersonic zone (Fig. 5, left curves *1*, *2*, etc.) with a resulting decrease in the wave drag. On the upper side, the closing shock wave shifts towards the rear edge (Fig. 5, right curves *1′*, *2′*, *3′*) and the wave drag increases. For a supplied energy above ΔE = 0.0010, the closing shock wave on the upper side sets at the rear edge and, beginning with this moment on, the wave drag coefficient remains virtually constant (or only slightly decreases). In the case of energy supply in the regimes under consideration, the closing shock wave on the lower side (in a zone with the longitudinal coordinate x 3,609 - 3,693) is set significantly upstream relative to the corresponding zone (Fig. 5) in comparison to the case of symmetric energy supply. Near the zone of energy supply, the pressure profile exhibits a non-monotonic character, with a pressure increase in front of this zone and reduced pressure (as a result of gas expansion) inside the zone.

A natural question arises as to whether the unidirectional energy supply can provide effective control over the aerodynamic characteristics of wing profiles. In order to answer this question, let us use the estimate (1):

$$\eta = \gamma \cdot \Delta C_x \mathrm{M}_\infty^3 \Delta t / (2\Delta E), \qquad (2)$$

where ΔC_x is a decrease in the wave drug coefficient in the regime with energy supply relative to the value ensuring the same lift at a non zero attack angle in the regime without energy supply. For $\alpha = 2.107^\circ$, we have C_x = 0.073 88 and C_y = 0.5233. A close value of C_y is obtained for the unidirectional supply of ΔE = 0.0006 (see Table 3), in which case C_x = 0.059 32. Simple calculations yield an estimate of the thruster efficiency ($\eta \approx 52$ %) for which the energy supply ΔE = 0.0006 is favorable. It should be noted that the profile quality increases with the amount of supplied energy. The data presented in Tables 3 and 4 show that the pitching moment (at equal values of the lift) is virtually the same for both variants of the flow control.

4. CONCLUSIONS

A mechanism of the shock wave structure formation of the flow around an airfoil under a periodic energy supply has been investigated. The existence of a limiting frequency of energy supply is established. The interaction of disturbances introduced in the flow at energy supply with a closing shock and the airfoil surface has non-linear character. Because of that, we achieved the reduction of airfoil wave drag by 60 %, energy contribution efficiency being equal to 30 %. The periodic character of the forming flow enables its use at cruise flight regimes. It allows to design transonic profiles which possess the maximum cruise Mach number and satisfy geometric and gasdynamic limitations, while preserving the given lift force.

We have established that in the case of a unidirectional energy supply necessary lift force can be obtained at a significantly lower wave drag (energy contribution efficiency being equal to 52 %) than in the case of streamline at a nonzero angle of attack. This phenomenon is related to stabilization of the closing shock wave position at the rear edge on the upper side of the profile, with a simultaneous decrease in the supersonic area size on the lower side.

5. REFERENCES

[1] S.M. Aultchenko and V.P. Zamuraev, “Influence of periodic pulse local energy release on the structure of transonic flow around airfoils”, *Thermophysics and Aeromechanics*, 10, 189-195, (2003).

[2] S.M. Aultchenko, V.P. Zamuraev, and A.P. Kalinina, “Control of transonic flow about airfoils by means of periodic pulse local energy supply”, *J. Eng. Phys. and Thermophys.*, 76, 1257-1261, (2003).

[3] S.M. Aulchenko, V.P. Zamuraev, A.P. Kalinina, and A.F. Latypov, “Control of transonic flow around the airfoils by a local pulsed energy supply”, *J. Appl. Mech. Tech. Phys.*, 45, 665–669, (2004).

[4] V.P. Zamuraev and A.P. Kalinina, “Effect of localization of pulsed energy addition on the wave drag of an airfoil in a transonic flow”, *J. Appl. Mech. Tech. Phys.*, 46, 664–669, (2005).

[5] S.M. Aulchenko, V.P. Zamuraev, and A.P. Kalinina, “Nonlinear effects in the interaction of periodic pulsed energy supply and shock-wave structure during transonic streamlining of wing profiles”, *Technical Physics Lett.*, 32, 3-5, (2006).

[6] S.M. Aulchenko, V.P. Zamuraev, and A.P. Kalinina**,** “Nonlinear effects due to pulsed periodic supply of energy in the vicinity of a symmetric airfoil in a transonic flow”, *J. Appl. Mech. Tech. Phys.*, 47, 359–365, (2006).

[7] S.M. Aulchenko, V.P. Zamuraev, and A.P. Kalinina, “Nonlinear effects of pulsed periodic energy supply on shock wave structure of transonic flow around airfoils”, *Thermophysics and Aeromechanics*, 13, 173-181, (2006).

[8] S.M. Aulchenko, V.P. Zamuraev, and A.P. Kalinina, “Effect of one-sided periodic pulsed energy supply on aerodynamic characteristics of wing profiles”, *Technical Physics Lett.*, 32, 772–774, (2006).

[9] E. Torenbeek, *Synthesis of subsonic airplane design*, Delft University Press, (1976).