TRANSONIC WING AIRFOIL FLOW CONTROL BY LOCAL ENERGY SUPPLY USING NANOSECOND DISCHARGE (PLASMA SHEET)

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Introduction

In recent years many works on airflow control by plasma actuator appeared [1, 2]. Different types of discharges were proposed as efficient sources of energy deposition in local area, for example, in field of transonic pattern streamline. The opportunity of local supersonic area control in transonic regime of flow was investigated. Influence of energy supply on aerodynamic wing profile characteristics was analyzed numerically.

The authors’ researches [3] 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.

Nanosecond high-current surface discharge can be used for creation of nonequilibrium area of pulse energy deposition. Use of quasi-continuous system of parallel discharges sliding on a dielectric surface – (plasma sheet) was offered as a source of energy supply. On the plasma sheet basis in transonic flow with a shock wave the distributed pulse energy supply area was realized near the surface. For experimental results correlation with computational investigation one pulse CFD was made. But the most significant results were obtained at frequency regime.

In the papers [4–8] we presented the results, 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. This work continues the investigations of the shock-wave structure of transonic flow around an airfoil. In the model under consideration, the pulsed energy supply was carried out instantaneously, and this implied no change in the gas density and velocity. The gas energy density \(e\) in the zones of its supply increased by the amount \(\Delta e = \Delta E/\Delta S\), where \(\Delta E\) is the total energy supplied to a single zone, \(\Delta S\) is the zone area.

Experiments

All experimental investigations were conducted on shock tube setup with a special discharge chamber mounted with a shock tube [9]. Shock tube and discharge chamber had rectangular cross-section 24x48 mm². Two side walls of the discharge chamber were the quarts plane glasses of 170 mm length. Surface discharges were initiated on upper or bottom wall of discharge chamber. Plasma sheets had a size 30×100 mm² and were positioned at distance 24 mm from each other. Depending on synchronization parameters discharge could be initiated at different incoming shock wave position inside discharge gap \(X\). The discharge section was located at 40 typical waveguide scales from the high pressure chamber, so formed in the test chamber flow could be considered as quasi two-dimensional. Achieved in experiments Mach numbers were 1.1 < \(M\) < 2. Gas pressure was 5-200 Tor. Work gas was air and the push gas was helium.

Discharge current \(\tau_c \sim 200\) ns. For estimation of plasma existence time experiments on glow recording on different stages using high-speed electro-optical camera Nanogate-2 (wave-length range 380-800 nm) were held. Energy deposition time \(\tau_{\text{disch}}\) could be considered as electric current time \(\tau_c\) and corresponding diffuse glow time \(\tau_{\text{dglow}}\) (\(\tau_{\text{disch}} \approx \tau_c \approx \tau_{\text{dglow}}\)). Pulse energy deposition
resulted in perturbations – weak shock waves moving from bottom wall. Typical gas dynamic times \( \tau_{\text{gas}} \sim 1 \mu s \). So, \( \tau_{\text{disch}} \ll \tau_{\text{gas}} \) and we could talk about instantaneous from gas dynamic point of view energy deposition.

Plasma sheets glow images (integral in time) with initial shock wave in discharge gap at various initial pressure and distance \( X \) magnitudes were obtained. The main glow was redistributed in surface area in front of initial shock wave without any glow behind the wave. Thus, all plasma sheet energy (judging by glow and shadow images) was localized in low pressure area. Discharge initiation at different initial shock wave position \( X \) allowed us to achieve various energy densities in front of shock wave. At constant full energy magnitude we observed energy density increasing while \( X \) decreasing.

At some critical parameters discharge was localized not only near surface in front of shock wave, and in surface behind the wave [10]. Basing on this effects it was possible to evaluate limit quantity of energy deposition per surface unit \( (S = d \times X, \ d - \text{plasma sheet thickness}, \ X - \text{shock wave position}) \). This limit was determined by \( p_0, M \) and \( X \) combination. Estimation of limit energy deposition gave us 0.1 J/cm\(^2\) and 2 J/cm\(^3\) per surface unit and per volume unit correspondingly. Estimation of limit energy deposition per particle was 5 eV (at pressures 75 Tor). The efficiency of discharge flow control is determined by relationship of electrical surface discharge energy and flow enthalpy.

Investigations of interaction between initial shock wave and shock waves formed by energy deposition were held. Shadow images were obtained at range of time delays from \( t = 0 \) (initiation moment) to \( t=50 \mu s \). Interaction analysis showed, that after energy release there are two mechanisms: independent interaction of shock waves (initial and formed by discharge); and initial shock wave propagation through heated nonequilibrium near-wall region. The general interaction configuration and its evolution were quite stable to experimental parameters modifications. With \( X \) decreasing only evolution accelerating without interaction morphology disturbance was occurred.

**Computational 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 \( M_{\infty} = 0.85 \). The angle of attack \( \alpha \) varied within the limits from 0 up to 3º. The energy \( \Delta E \) supplied with one (lower) side from profile. The magnitude of energy \( \Delta E \) changed from 0.0001 up to 0.0085. The period of a supply of energy \( \Delta t = 0.05 \) (here and below, all variables are dimensionless).

**Table 1. The aerodynamic characteristics for various supplied energies**

<table>
<thead>
<tr>
<th>( \alpha ) degree</th>
<th>( \Delta E ) ( \times 10^4 )</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>( C_x ) 10</td>
<td>0,4588</td>
<td>0,4669</td>
<td>0,4790</td>
<td>0,4921</td>
<td>0,5932</td>
<td>0,6345</td>
<td>0,6366</td>
<td>0,6343</td>
</tr>
<tr>
<td></td>
<td>( C_y )</td>
<td>0</td>
<td>0,1470</td>
<td>0,2225</td>
<td>0,2890</td>
<td>0,5238</td>
<td>0,5899</td>
<td>0,6000</td>
<td>0,6698</td>
</tr>
<tr>
<td>2</td>
<td>( C_x ) 10</td>
<td>0,7153</td>
<td>0,7481</td>
<td>0,7871</td>
<td>0,8680</td>
<td>0,9602</td>
<td>0,9843</td>
<td>0,9922</td>
<td>1,026</td>
</tr>
<tr>
<td></td>
<td>( C_y )</td>
<td>0,5025</td>
<td>0,5499</td>
<td>0,6013</td>
<td>0,6970</td>
<td>0,7902</td>
<td>0,8097</td>
<td>0,8196</td>
<td>0,8859</td>
</tr>
</tbody>
</table>

The values of \( C_x \) and \( C_y \) are summarized in Table 1 as functions of the supplied energy \( \Delta E \) for \( \alpha = 0^\circ \) and \( \alpha = 2^\circ \) (\( C_x \) – drag coefficient, \( C_y \)– lift 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.

For the comparison, Table 2 gives the values of \( C_x \) and \( C_y \) for various attack angles \( \alpha \) without energy supply. As can be seen, an increase in \( \alpha \) (within indicated limits) leads to an increase in both lift and drag of the airfoil.
Table 2. The aerodynamic characteristics for various attack angles $\alpha$

<table>
<thead>
<tr>
<th>$\alpha$ (deg.)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_x \cdot 10$</td>
<td>0.5330</td>
<td>0.7153</td>
<td>0.9556</td>
<td>1.2290</td>
</tr>
<tr>
<td>$C_y$</td>
<td>0.2793</td>
<td>0.5025</td>
<td>0.6753</td>
<td>0.8154</td>
</tr>
</tbody>
</table>

Figure 1 shows the wing polars calculated with energy supply for the different fixed angles of attack (curve 1-4) and polar (without energy supply) for the angles of attack in Table 2 (curve 5). 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.

This behavior of the wing polar in the regimes with energy supply can be better understood using Fig. 2, which shows variation of the pressure coefficient along the wing chord for various supplied energies $\Delta E = 0$ (1, 1'), 0.0001 (2, 2'), 0.001 (3, 3'), 0.002 (4), 0.003 (5). The energy supply leads to breakage of the supersonic zone near the lower airfoil side. The closing shock wave on the lower side exhibits an upstream shift that (Fig. 2, 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. 2, right curves 1', 2', 3') and the wave drag increases. For a supplied energy above $\Delta E = 0.001$, 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). Near the zone of energy supply, the pressure profile exhibits a non-monotonic character (Fig. 2), with a pressure increase in front of this zone and reduced pressure (as a result of gas expansion) inside the zone.

Experiments and CFD correlation

For experimental problem definition correlation with CFD investigation of transonic flow with compression jump we solved inversion problem. It was necessary to achieve analogy between pattern streamlining at transonic velocities with local supersonic area and shock wave propagation in the shock tube. Transition to coordinate system, at which the supersonic area undisturbed and compression jump moved with corresponding Mach number, was made for solving this inversion (see Fig. 3). This transition allowed to compare results of energy deposition influence on shock wave configuration in shock tube with CFD results of transonic streamlining.
Fig. 3. Problem definition. Crosshatched region – energy deposition region.

CFD results were compared to some experimental ones achieved after initial energy input (first period). Dimensionality was assigned for typical variables: \( l, \Delta x, \Delta y \) and \( \Delta E \). If we select typical dimension \( l = 1 \) m, other parameters in CFD would be: energy deposition length \( \Delta x = 9 \) cm, energy deposition width \( \Delta y = 0.9 \) mm. At experimental conditions \( (p_0 = 25 \text{ Tor}) \) energy magnitude \( \Delta E = 0.0015 \) was equivalent to specific energy deposition \( 0.1 \) J/cm\(^3\) and energy input period in this case was 150 \( \mu \)s.

One pulse CFD simulation was performed (see Fig. 4) in order to compare with experimental flow visualization results. Length and width were \( \Delta x = 1 \) cm and \( \Delta y = 0.5 \) mm correspondingly. Pressure was \( p_0 = 25 \) Tor and deposed energy was 0.144 J \( (\Delta E = 4.8 \) J/m\).

Different stages of shock wave – energy deposition area interaction were visualized on shadow images. As it is seen on Fig. 4, shock wave configurations on shadow images are rather similar to CFD shocks (isosurfaces of density) at corresponding moments of time. It means that discharge and CFD energy input value and area are coincided well. Energy deposition effect in wing profile flow pattern led to compression jump shifting. In experimental simulation case it led to shock wave accelerating and shifting as well. Analysis of discharge-aided energy deposition influence on initial shock wave showed, that during \( t=30-40 \) \( \mu \)s disturbed part of initial shock wave near the wall was accelerated. Shock shifting is illustrated on Fig. 5 at parameters: Mach number, \( M=2.1 \); initial pressure, \( P_0=25 \) Tor; distance between initial shock wave front and the end of the discharge gap, \( X=25 \) mm. Shadow image corresponded to moment of time \( t=39 \) \( \mu \)s (after discharge initiating) and velocity increasing achieved 150-200 m/s at shock shifting \( \Delta X=5-8 \) mm. So, during the first quarter of energy deposition period being suggested (150 \( \mu \)s), experimentally obtained shock wave shifting upstream the flow was up to 5-8 mm.
Fig. 4. CFD (left) and experimental (right) results comparison in one pulse regime. 

- a – 3 µs; b – 9 µs; c – 13 µs. Shadow images – M=2; X=1-2 cm; P₀=25 Tor. Arrows show flow and shock wave directions according to coordinate system transition.

Fig. 5. Initial shock wave accelerating after energy deposition.

1 – shock wave position at time moment t=40 µs (discharge off); 2 – shock wave position at time moment t=40 µs after discharge.
ΔX dependence on time after energy deposition is on Fig. 6. X-t diagram presents shock wave shift, shock acceleration can be observed at later stages (t<25µs) with high energy deposition density.

Conclusions

It was shown that in the case of a one-sided energy supply necessary lift force can be obtained at a significantly lower wave drag 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.

Plasma sheet discharge appeared to be effective source of pulse (pulse-periodic) flow energy supply. Its configuration and specific energy value corresponds with CFD model. From the gas dynamic point of view nanosecond localized surface discharge provides instant homogeneous energy input in near surface flow area and it is characterized by large power supply in transonic flow. Maximal specific energy was $2 \text{ J/cm}^3$ (per unit volume). Shock accelerating (shift) is a result of discharge – shock flow interaction both in experimental and CFD simulation.

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REFERENCE


