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Interaction of exposed electrodes of a symmetric plasma actuator in a subsonic flow for controlling the lift force of the wing

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A mechanism for interaction between the exposed electrodes of a symmetric actuator and subsonic flow is proposed, which qualitatively explains the experimental data without using terms „wall jet" and „synthetic jet". The flow is thus controlled by the Coulomb force acting on the charged external flow. The flow of ions from the upstream electrode increases the velocity circulation in the space between the electrodes and at the outer boundary of the separation bubble that occurs at the downstream electrode. Application of the lift force assessment via the proposed mechanism to the experimental data shows that the optimal combination of the supply voltage period and flight time allows increasing the lift force modulus with holding constant the supply power.

Keywords: dielectric barrier discharge, symmetric actuator, synthetic jet, separation bubble.

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In recent years, significant attention has been paid to plasma actuators operating based on the dielectric barrier discharge (DBD). Gas flows are controlled by using body forces arising in the near-surface dielectric barrier discharge [1]. As the main control element, the synthetic jet arising in a stationary medium is considered [2]. Their two main disadvantages are, first, restrictions to the generated body force, which stem from the discharge physical nature and, second, low efficiency of the momentum transfer from charge carriers to neutral components of the slightly ionized medium arising in the discharge [3]. Synthetic jets created by the DBD actuators possess low velocity pressure, and asymmetric actuators have previously manifested their efficiency only in delaying the separation at the wing leading edge [4]. The potential of the symmetrical DBD actuator lies not so much in the creation of a jet perpendicular to the wing surface in the absence of external flow but in the complex interaction between the upstream and downstream electrodes. This interaction manifest itself in imparting a negative electric charge to the external flow and controlling it via the Coulomb force of the electrodes and charged surface under a sufficiently high voltage (in this study, 6−7 kV). Therewith, maintaining the discharge needs low linear power (below 100 W/m).

The main experimental data used as a basis for modeling the DBD interaction with oncoming subsonic flow were obtained on the experimental setup whose scheme is given in Fig. 1. The experimental setup consisted of a wind tunnel 110×55 mm in rectangular cross-section and 1.5 m in length equipped with a honeycomb structure for the flow laminarization with Reynolds numbers of 1000−3000, fan VENT-250L to create a flow with a velocity of up to 16 m/s, and a pair of Pitot tubes (along and across the flow) to measure the flow velocity with differential pressure gauge Testo 510. At the wind tunnel exit, a symmetrical plexiglass profile with the chord of 10 cm and span of 17 cm was installed on a lever. The symmetrical actuator was flush-mounted to the wing in the following way: to the wing profile, an encapsulated electrode made from an aluminum foil strip 50 μm thick and 28 mm wide was glued. Then a lavsan dielectric $H = 500\,\mu$m thick was glued onto the encapsulated electrode, and exposed electrodes also made from an aluminum foil strip $h = 50\,\mu$m thick and 0.5 cm wide were glued onto the dielectric. The electrode length L was 10 cm. Distance d between the exposed electrodes was equal to the encapsulated electrode width. The actuator was supplied with high sinusoidal voltage 6.5−7 kV in amplitude and 3−4 kHz in frequency. After applying high voltage, the frequency was selected so that the voltage amplitude on the actuator's exposed electrodes was maximum at a constant power-supply output power. As the high-voltage AC power supply, there was used sound generator GZ-33 combined with a transistor amplifier powered by DC power supply AKTAKOM APS 1503 and oil-filled ignition coil TU 37.466.072-96. Lift force was measured with a jewelry scale ($\delta = \pm 0.01$ g) and lever 1 : 8 on which the symmetrical profile with DBD actuator was mounted.

In stationary air, operation of the symmetrical actuator causes a collision between the wall jets from each its half and formation of a synthetic jet directed perpendicular to the actuator surface (Fig. 2, *a* and *b*). Note that the main factor in the body force formation is negatively charged air ions [5]. Due to the difference in concentrations (recombination [6]), the return flow during the positive supply-voltage half-cycle is insignificant. The optimal distance between the exposed electrodes is determined by the relationship between the electric field and viscous losses

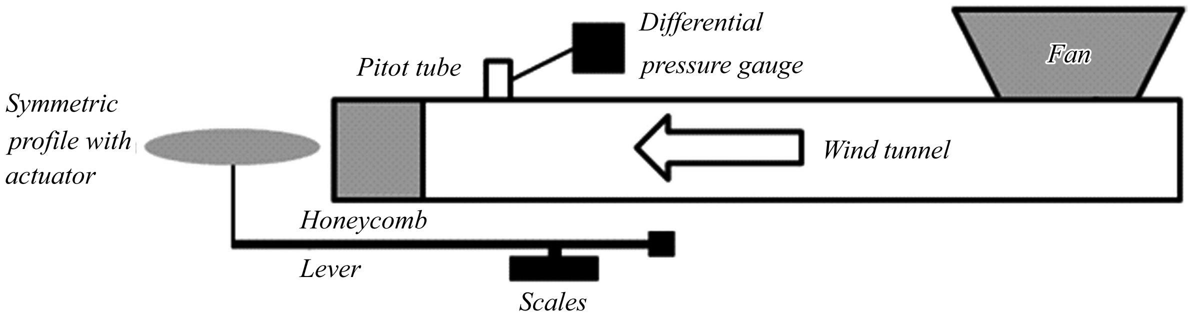

Figure 1. Schematic diagram of the experimental setup for the schlieren flow visualization. High-speed camera Video Sprint is focused on the profile, its plane of view coincides with the scheme plane.

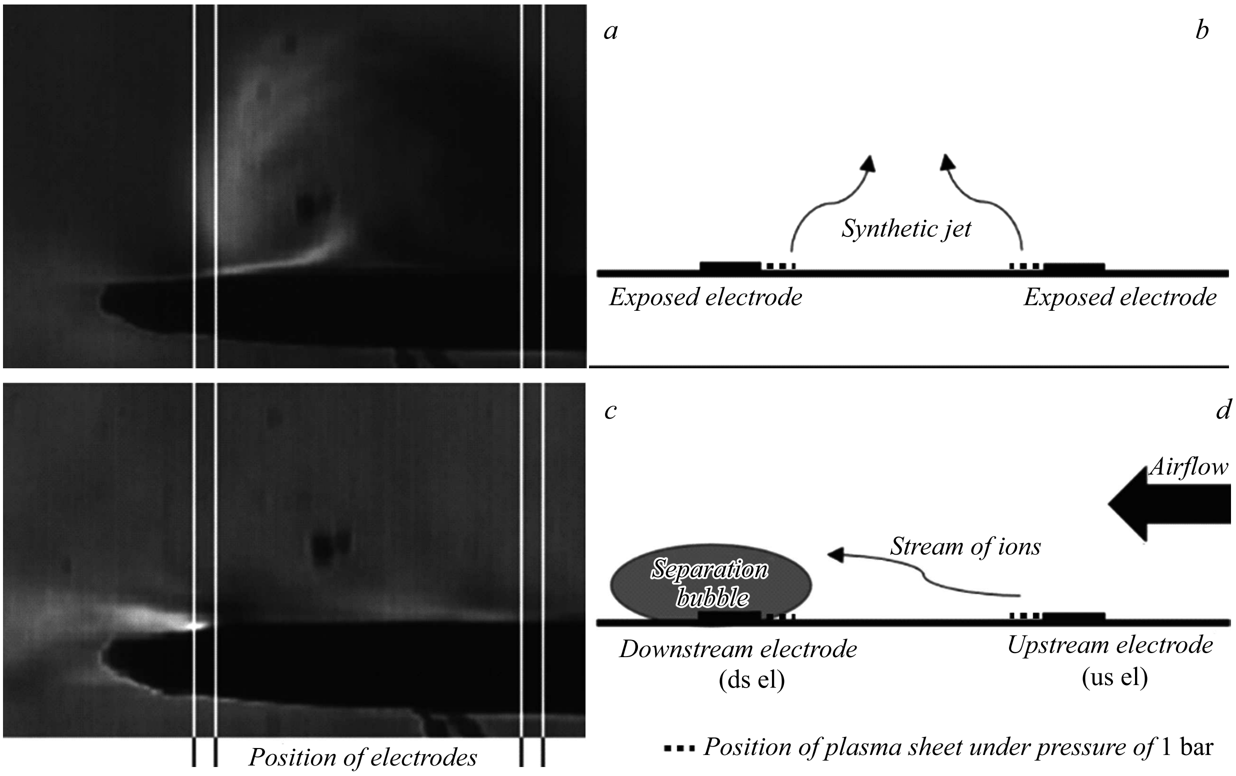

Figure 2. Shadow photographs of the synthetic jet. *a* — without the flow, *c* — in the flow, *b* — schematic diagram of the synthetic jet formation, *d* — schematic diagram of interaction between the symmetric actuator DBD and oncoming flow ($v_0 = 6$ m/s).

prior to collision of the wall jets. At the optimal distance between the exposed electrodes in the absence of oncoming flow, the total thrust of the wall jets is only 5% less than that of the synthetic jet formed by them [7]. In the oncoming flow, the roles of the upstream and downstream electrodes are significantly different. Below we consider the processes associated with the upstream (us el) and downstream (ds el) electrodes (Fig. 2, *d*).

The actuator-flow interaction produces a long separation bubble whose dimensions are determined by both the discharge's electrical characteristics and oncoming flow velocity. Consider the case when the flow separation and flow reattachment points are located on the wing surface. The flow reattachment point may also be located beyond the profile boundaries thus forming a „virtual profile“ having high aerodynamic quality at low angles of incidence. Shadow photos show that the magnitude of flow separation from the wing surface reaches the steady-state value in the same time it takes for the wall jets from each actuator half to form a synthetic jet. This time is about 0.1 s. Further the formed flow is subject in both cases to pulsations associated with the periodic impact from the DBD actuator.

The downstream electrode creates a counterflow wall jet. The vertical component of the surface charge field E_y accelerates negative ions perpendicular to the actuator surface, which leads to the flow separation upstream the ds el edge at the distance of half the plasma sheet propagation length corresponding to the maximum electron density. Since the horizontal component of the ion wind velocity pressure is an order of magnitude lower than that

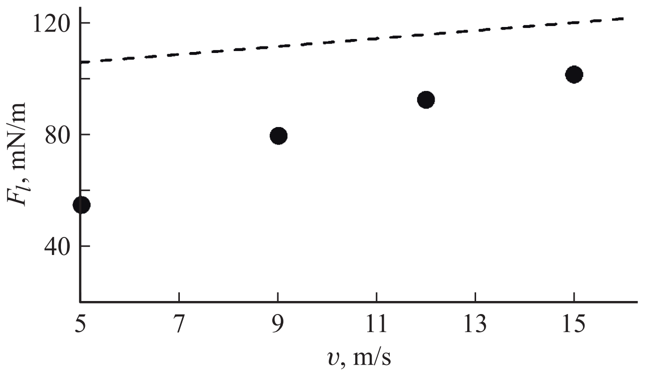

Figure 3. Lifting force generated by interaction between the symmetric actuator DBD and oncoming flow. Dots are experimental data (the synthetic jet thrust in a stationary medium: 20 mN/m, $U = 6.5$ kV, $\nu = 3.7$ kHz, $p = 1$ atm, $d = 28$ mm); the dashed line represents the upper estimate under the transit resistance condition.

of the oncoming flow, the separation is delayed over the distance of the undisturbed flow flight during a half the supply voltage period below the ds el trailing edge. Thus, a significant part of the discharge energy is not spent on increasing the circulation velocity of the segment occupied by the separation bubble as per the Joukowsky formula

$$\mathbf{F}_1 = \rho \mathbf{v}_0 \times \Gamma l,$$

where $\mathbf{F}_1$ is the lifting force of the wing segment under consideration, ρ is the air density in the undisturbed flow, $\mathbf{v}_0$ is the oncoming flow velocity, Γ is the velocity circulation, l is the separation bubble length.

The upstream electrode creates a wall jet that is co-directed with the oncoming flow and does not create a separation bubble. However, the ion flow accelerated by upstream electrode us el significantly contributes to the process. First, it increases the velocity pressure at the bubble outer boundary during half the period of the supply voltage. As a result of the flow Coulomb repulsion from us el by the surface charge, the separation bubble height and length get increased. The flow velocity increases at the bubble upper boundary that is, in essence, a new profile boundary in the oncoming laminar flow. Thus, an increase in the circulation of the wing segment occupied by the separation bubble (near ds el) takes place. Second, there occurs an increase in the circulation of the wing segment equipped with a symmetrical DBD actuator, including the segment of the gap between the exposed electrodes (Fig. 2, *c*).

When observing the separation bubble with the aid of schlieren visualization, we can notice its pulsations $1-2$ Hz in frequency. Pulsations of this type are caused by the nonuniformity of the body force distribution over time. The sources of this are mentioned above. In the case of an asymmetric actuator, this process cannot be affected, since a single exposed electrode is considered as an independent integral system interacting with the oncoming flow. In the case of a symmetric actuator, electrode us el becomes an additional factor. The ionized flow from us el modifies the separation bubble and, provided the transit resonance conditions are met, may significantly reduce the pulsation amplitude. In this case, the portion of ionized gas that arose at us el moves downstream towards the actuator symmetry axis, the ion mobility being rapidly decreasing under the influence of ds el and surface charge it creates. If this portion arrives at the axis of symmetry at the beginning of the positive half-period, it will get additional Coulomb-force-induced acceleration under inversion of the exposed electrode polarity. When it passes above ds el, its voltage sign inverts again and accelerates the downstream portion, while upstream the growing negative potential generates a new portion of ionized inducing creation of the separation at ds el and its modification at us el.

In general, reduction of the separation bubble circulation during the positive half-period may be compensated by the ionized gas portions from us el at the optimal combination of the supply voltage period and flight time dictated by the medium density, distance between the exposed electrodes and oncoming flow velocity. In its simplest form, the transit resonance condition may be represented as equality of the supply voltage period T and ion transit time τ_i from us el to ds el through gap d:

$$\frac{1}{\nu} = T = \tau_i = \frac{d}{v_{dr}^x + v_0},$$

where ν is the supply voltage frequency, d is the distance between exposed electrodes, v_{dr}^x is the projection of the ions' average drift velocity onto the horizontal axis, v_0 is the oncoming flow velocity.

In the case of optimal combination of electrical and gas-dynamic parameters, it is possible to achieve a significant reduction in the pulsation amplitude with a simultaneous increase in the velocity circulation of the wing segment occupied by the separation bubble, i. e., to utilize for increasing the wing lifting force the entire power of the dielectric barrier discharge, except for thermal losses whose share does not exceed 20 % at the frequencies of about several kilohertz [8]. Taking into account the conditions of flight resonance, it is possible to estimate the maximum lift force increase caused by the DBD-flow interaction by the dimensional method:

$$|\Delta F_l| \leqslant \frac{4}{5} P_{dbd} \left(v_{dr}^x + v_0\right) / \left(d\nu\right)^2, \qquad (1)$$

where P_{dbd} is the power of the dielectric barrier charge [7]. Fig. 3 presents the dependence of the lift force caused by the influence of a symmetrical DBD actuator installed on a thin symmetrical profile on the oncoming flow velocity (Re $\sim$ 50 000). The line represents the estimate via relation (1) and demonstrates the lift force growth as the system approaches the transit resonance. Thus, the estimation straight line corresponding to relation (1) is an asymptote of the experimentally obtained dependence, since it reflects the maximum ability of the actuator electrical system to affect the flow around the profile as per the energy conservation law at a constant power-supply source. The energy of the low-quality [7] electric oscillatory circuit of the DBD actuator is transferred to negatively charged ions wherefrom it is transferred to neutral atoms via intermolecular collisions.

Conflict of interests

The authors declare that they have no conflict of interests.

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