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Damping of the low veloclity streak by adaptive plasma actuator

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Abstract

The ability to control the spanwise location of the disturbance source in a boundary layer is required in a number of the transition delay applications. The redistribution of electric potential along the buried electrode allows to control the position of the microdischarges group,the latter operating as a local source of heat and 3D volume force region. The characterization of the actuator is performed in a 2D boundary layer, with a spatial resolution of the system to be as high as 0.5 mm obtained. Control of the low-velocity streak in the boundary layer is performed by an adaptive DBD plasma actuator is demonstrated in a numerical simulation.

1. Introduction

Control of the laminar-turbulent transition in the boundary layers is an important task in a number of aerodynamic applications. Formation of longitudinal structures is known to play an important role in the mechanism of transition. Streaks appear as a result of the development of algebraic instability in flows with a high level of initial turbulence, evolution of perturbations behind the distributed surface roughness, excitation of the natural modes of three-dimensional boundary layers. It is important that in the case of a low turbulence level, a laminar-turbulent transition is governed by stationary perturbations. This simplifies the use of a feedback system to suppress such disturbances. For the operation of such systems, actuators are needed that would create forcing at the desired position and amplitude, damping the disturbances existing in the boundary layer.

Plasma actuators are frequently considered for the use in the closed-loop systems for aerodynamic flow control due to their high robustness. The operation principle of plasma actuators is based on the combined effect of the volume force and heat release present in the plasma of a dielectric barrier discharge. The study of these devices covers at least last 20 years, in which they were tested in a great variety of aerodynamic tasks [1]–[3], including a laminar-turbulent transition. Efforts considering transition control by plasma actuators were mostly concentrated on the 2D boundary layers, taking into account the Tollmien-Schliehting waves as a target disturbance. The strategy of the flow control by plasma actuators usually includes either change in the base flow or the active damping of the existing disturbances in the BL. The latter approach assumes the ability to use create the three-dimensional forcing by the actuator electrode system. Works [4], [5] describe attempts to postpone the bypass transition in the boundary layer by means of plasma actuators, using the active streaks suppressing strategy. It should be noted that the works mentioned are of more academic interest, since they do not allow the position of the perturbations to be varied. The reason for this drawback lies in the design of these devices. The forcing three-dimensionality in these cases is obtained by the modification of exposed electrode, limiting the available parametric space of the system.

A three-dimensional effect on the flow can be obtained also in the case of a continuous linear electrode. This can be achieved if the discharge has a finite span across the electrode system. Inhomogenuity of the electric field along the electrode can be formed with the help of a special shape of the buried electrode. Finally, limiting the span of the discharge down to several mm requires taking into account the three-dimensional distribution of the volume force existing at the lateral edge of the discharge region. As shown in [6], even with the installation of the actuator electrode perpendicular to the oncoming flow, a pair of longitudinal vortices having a significant effect on the boundary layer originates behind the edges of the MD formation zone.

The purpose of this paper is to study the properties and application potential of a novel type of DBD actuator - "plasma panel" actuator. The principle of operation of this device is based on the localization of the discharge in a certain region on the edge of the exposed electrode by means of applying a certain potential distribution over the

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control electrode system. The work provides characterization of the actuator, estimation of the system resolution. The numerical estimations of the control of a classical object - a low-speed streak generated by a mechanical obstacle in the boundary layer is also given.

2. Experiment description

2.1 Actuator design

To control the position of the MD group, DBD plasma actuator with a sectioned buried electrode was designed. Actuator schematics is given in fig.1. The discharge is initiated on the surface of the 1mm thick aluminum oxide ceramic plate. On both sides of the plate two electrodes are mounted: exposed and buried ones. Exposed electrode is made of the commercial 20 um thick alumina foil with 30 um adhesive layer. Prior to the experiments, the electrode was preconditioned by initiating the DBD at the voltage Ua~3.6-3.9 kV and frequency 65 kHz. The in-lab manufactured flat bus with the 0.7x1 mm wires, manufactured by PCB technique and covered by a layer of fiberglass, was used as a buried electrode. The insulation tests have shown that the bus withstands the voltage Ua~5kV at f=100 kHz between the individual wires. The breakdown between the wires was mostly caused by the originating of the discharge on the surface of the bus; to further increase the operation voltage and obtain higher lifetime, the bus was buried into the silicon resin during the model assembly.
The discharge position along the electrode edge was controlled by setting the appropriate potential distribution across the buried electrode sections. To set the potential of the individual section, it was connected to the middle point of the 1:2 capacitive divider, made of HV smd capacitors. The upper point of the divider was connected to the HV output, the other- to the ground. The section could also be connected to the ground using a reed switch. Therefore, in the ON state the voltage drop amplitude between the exposed electrode was equal to Ua, in the OFF state- approximately to Ua/2. Totally, 10 section were used. The voltage on the middle 8 were controlled by switches, two outer electrodes were set to Ua/2 potential. The switches were controlled by an Arduino-based micocontroller. In the text below, the configuration of the electrodes is given by a 8bit word, with "1"/"0" corresponding to OFF/ON state. The total distribution of the voltage across the control electrode hence can be described as "1 8bit 1".
The discharge was powered by the sinuous voltage with Ua~3-6 kV, f~85-87kHz. High voltage was provided by the HF transistor switch source, with resonant output circuit. The shift of the resonance frequency by the actuator load made it necessary to adjust the pumping frequency of the power source within 1% of *f*.

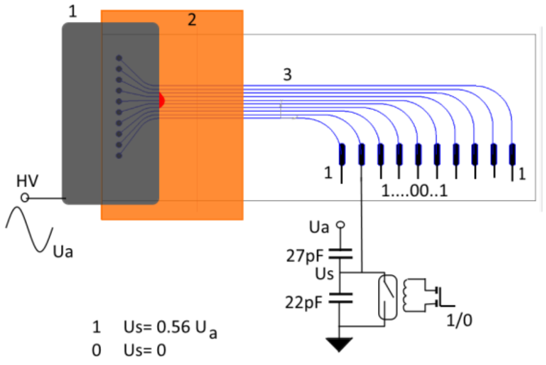

Figure 1. Plasma panel actuator schematics . 1- exposed electrode, 2- ceramics, 3- control electrodes.

1.2 Aerodynamic experiment configuration

The boundary layer experiment was designed to study the flow structure downstream of the actuator and to analyze its efficiency in controlling the amplitude of the low-velocity streak. The principal scheme of the experiment is shown in fig.2

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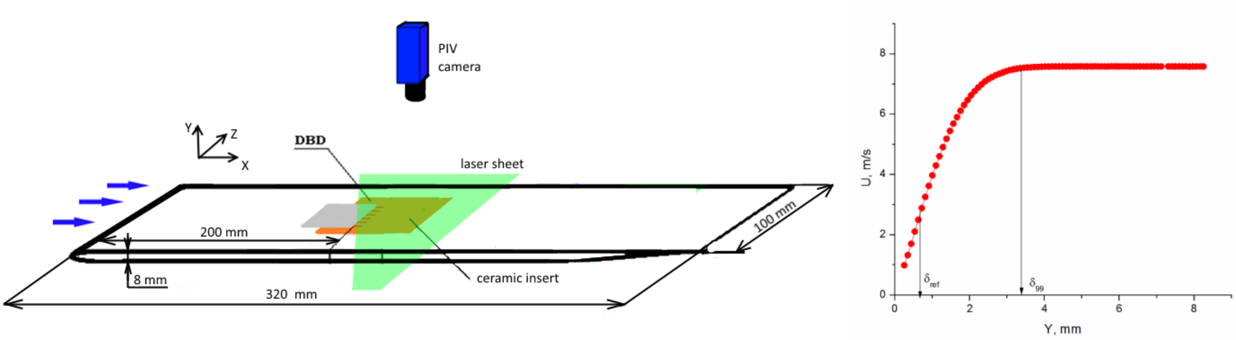

Figure 2. a)Scheme of the aerodynamic experiment, b) Boundary layer profile

Experiments were held in the wind tunnel D-2 in JIHT RAS. Oncoming flow turbulence level was as low as 0.1% for frequencies Higher than 20 Hz. Laminar boundary layer was created on a flat plate with an elliptical leading edge. The plate was installed into the test section, slightly below its middle line. Actuator was installed at the position X=200mm, its leading edge being normal to the oncoming flow. Upstream of the plasma actuator, at the positions X=150mm, the vortex generator was installed.

In the experiment flow structure was studied by PIV. The commercial PIV system was used, with 4M camera and 2x200mJ 532 nm laser. Laser sheet was oriented in parallel with the plate, at a distance 1.5 mm (Xδ) from the wall. The typical thickness of the laser sheet was 0.5 mm. The 32x32 interrogation windows with 50% overlap were used, providing a XXmm2 resolution. To decrease the measurement error, the initial shift of the second frame in the freestream direction with the approximate baseline pixel shift value was used prior to the processing. Average image was averaged over XX individual frames; RMS value was not more than XX for baseline case and XX for the case with plasma actuator.

Boundary layer profile in the position of plasma actuator is shown in fig.3, together with the Blasius curve. Boundary layer thickness at the actuator location was as high as δ=3.3 mm.

3 Results and discussion

3.1 Testing of the actuator

Preliminary testing of the plasma panel actuator was aimed to determine main characteristics of the system: inception voltages, resolution, forcing amplitude.

Discharge structure at various voltage distributions across the control electrode

Structure of the discharge in the plasma panel actuator was studied as a function of the voltage amplitude and voltage distribution across the sections. Discharge inception in a " wide" mode (all sections are grounded) takes place at the voltage amplitude of Ua=2.6 kV. Decrease of the discharge width below 3mm leads to the increase of the inception voltage due to the influence of the adjacent control electrodes. For the OFF state, when all control electrodes are at Ua/2 potential, the discharge is initiated at Ua=5.4 kV. The second effect, significantly affecting the actuator operation, is the dischagre constriction, taking place at certain voltage. The constricted channel is significantly longer than the diffusive discharge and is formed nearly at the center of the diffusive discharge region, irrespective to the real position of the control wires. Constriction threshold is also found to increase with the narrowing of the discharge region.

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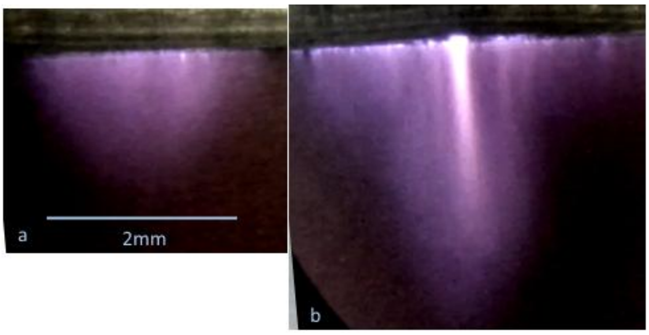

Figure 3. The discharge images. 2 mm wide configuration. Left- prior to the discharge constriction (U_a~4.6kV), right- constricted mode (U_a~5.8kV).

Velocity distribution downstream of the actuator

Velocity distribution in the boundary layer downstream of the actuator was measured in the plane y=1mm for the distances from the actuator 20-80 mm. The spanwise velocity profiles, obtained for various voltage amplitudes are given in fig.4a,b. One can see that the velocity profile for a sufficiently narrow discharge region includes a high-speed streak, surrounded by a pair of regions with a lower velocity. The amplitude of the streak increases with the amplitude of the supply voltage. Given the particular voltage amplitude, for 3 mm wide discharge, the streak amplitude is higher in comparison to the 2 mm. The HV streak width can be estimated as 3mm for w=2mm and 3.5 mm for w=3mm discharge. The width of the structure is not altered at voltage variation.
The resolution of the actuator was determined as its ability to shift the position of HS streak position in the boundary layer at the shift of voltage distributions. One can see (fig.4c) that the shift of the electrode configuration by 1 element (x1001x to x1100x) leads to the displacement of the velocity maximum by 1mm. Furthermore, transition from even to odd configuration leads to the shift of the maximum position by 0.5 mm. The latter value can be treated as the spatial resolution of the system.
The ability of the actuator to damp stationary streaks in the boundary layer requires the possibility to control the width of the generated disturbances. The spanwise distribution of the velocity in the BL downstream of the actuator at various discharge width can be seen in fig.4d. One can see, that starting from some width (4mm for given operation parameter) actuator generates a pair of streaks instead of a single plateau. This obviously is caused by the fact that a pair of longitudinal vortices, generated at the edges of the discharge region, have more effect on the velocity distribution than the ionic wind in the streamwise direction.

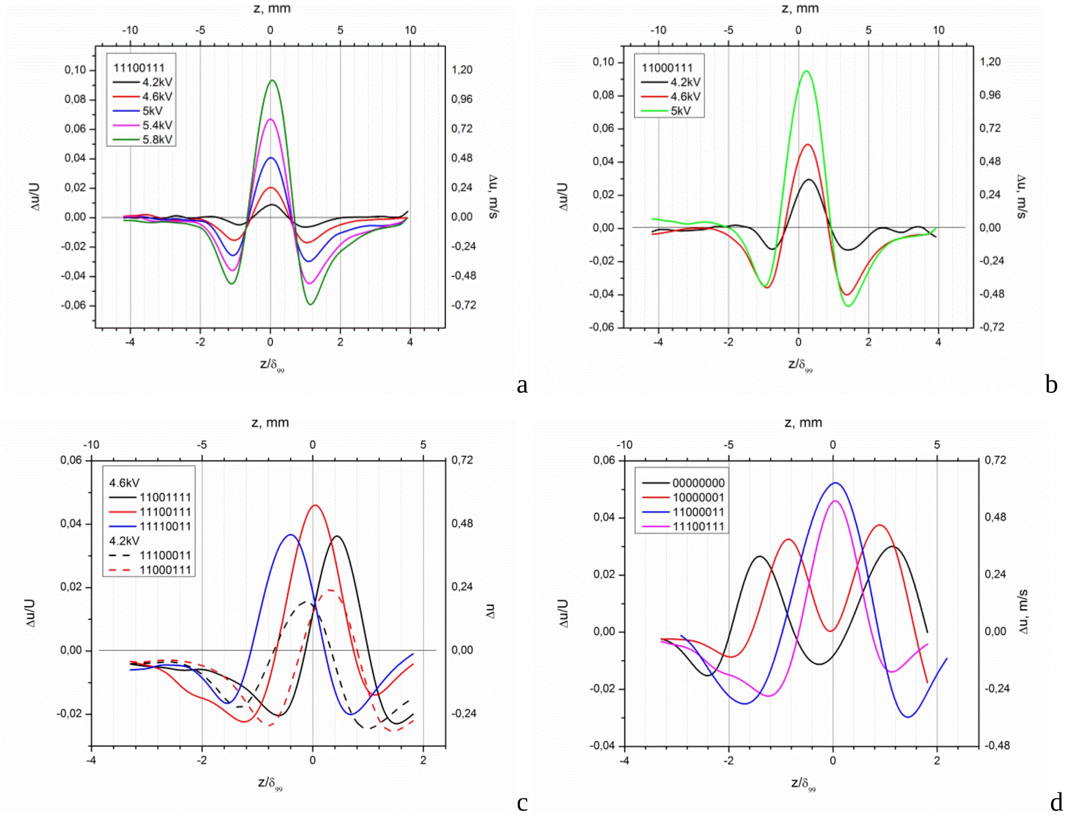

Figure 4. Velocity distribution at y=0.3δ at the position 40mm downstream of the actuator. a),b) Streak intensity as a function of voltage amplitude variation for 2mm and 3mm wide MD group. c) Effect of the voltage distribution across the sections on the streak position. d) Effect of the width of the MD group on the velocity distribution in the downstream boundary layer.

3.2 Numerical simulation of the streak damping by plasma actuator

The modeling of the streak damping by plasma actuator was performed in a commercial CFD package FlowVision. The low-velocity streak was generated in the boundary layer by a reversed wedge (fig.5). The wedge generates a pair of counter rotating vortices, transferring the momentum towards the wall. As a result, a low velocity and a pair of weaker high-velocity streaks are formed. The height of the wedge was selected to keep the vortices location inside in a boundary layer.

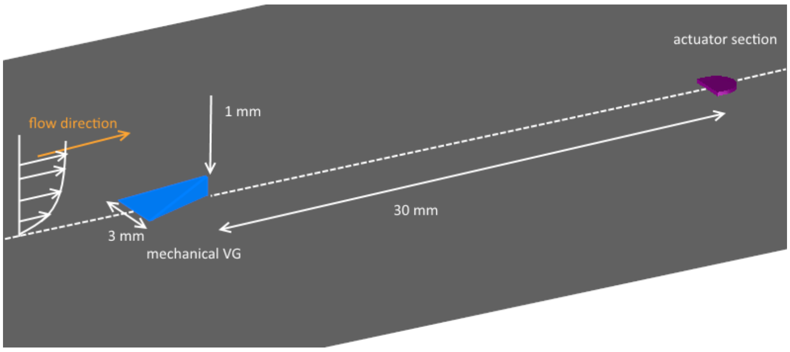

Figure 5. a) Scheme of the streak damping numerical task. b) Scheme of the actuator section equivalent model

The actuator model was used, based on quiescent flow characterization of the similar actuator [7]. The model consisted of a pair of symmetrical regions with a given component of longitudinal and tangential force components, and also a heat release density. Although the operation parameters are somehow different in this work, the qualitative demonstration of the damping process can be given.

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The damping process is illustrated in fig.6. One can see that at the actuator position the low-velocity streak with a typical width of 2mm and the amplitude of 0.15 U at 0.3δ exists when the actuator is off. As soon as the discharge is turned on, the velocity modulation downstream of the actuator decreases. Actually, in the modeled case the streak is slightly overcompensated - a resulting velocity distribution contains the central region with a positive velocity defect; anyhow this region is much wider (4mm) relatively to the non-controlled case.

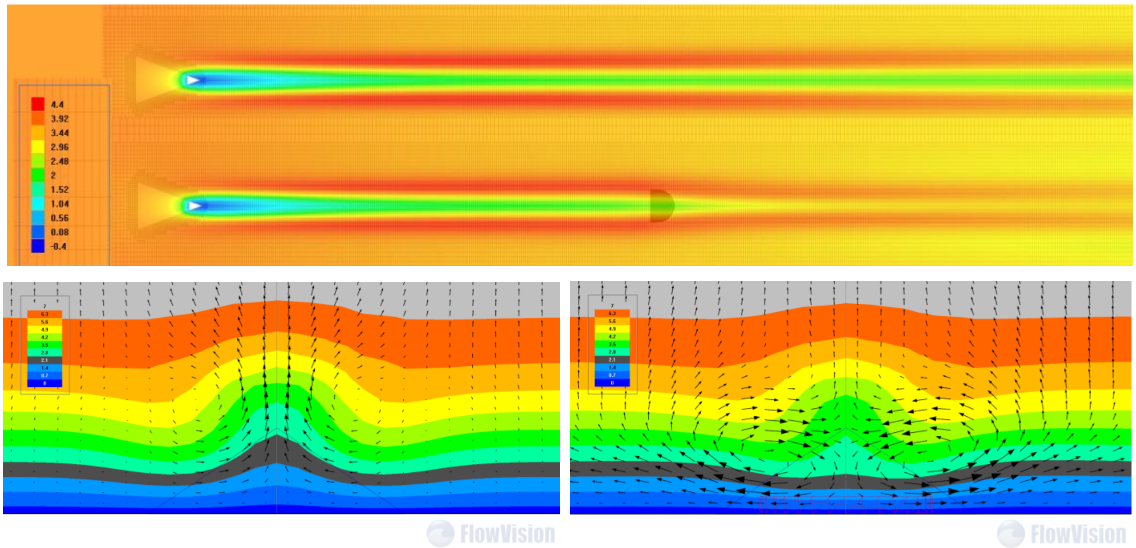

Figure 6. Numerical modeling of the single low velocity streak damping by plasma actuator. a) flow velocity at y/δ~0.3 without and with control (upper and lower case), b) cross-flow section at X=20mm downstream of the actuator. Color indicates the longitudinal velocity magnitude.

4.Conclusions

The testing of the plasma panel DBD actuator with a controllable position of the MD group is fulfilled. The actuator, being installed in a 2D boundary layer normally to the flow direction generates a pair of counter-rotating longitudinal vortices, localized at the edges of the MD group. As a result of momentum transfer in a vortex pair, a flow structure containing a high-velocity streak with a pair of surrounding low-velocity ones is formed in the boundary layer downstream of the actuator. Control of the MD position by varying the potential distribution over the buried electrode allows to control the position of the high-velocity streak with the resolution of 0.5 mm (1/2 of the control electrodes step). The effectiveness of low-velocity streak cancelation in the boundary layer at U=7m/s is demonstrated in numerical experiment.

Aknowledgements

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