Stochastic forcing of the 2D boundary layer by DBD plasma actuator

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Abstract. The paper describes the results of the parametric study of the broadband velocity pulsations, induced by DBD plasma actuator in 2D subsonic boundary layer. The presented data include the analysis of the disturbance growth at various pressure gradients. It is assumed that the broadband pulsations are composed of the elementary disturbances, induced by an individual microdischarges, wandering along the electrode edge. These disturbances have a streak-like structure in a near field, and evolve into a fan of packets of Tollmien-Schliechting waves as one moves downstream. The streamwise length, needed for transition to modal behavior, depends on the stability properties of the boundary layer.

sDBD surface dielectric barrier discharge
MD microdischarge
LST linear stability theory
ZPG zero pressure gradient
U freestream velocity
x,y,z streamwise, wall-normal and spanwise coordinate, relative to electrode edge
u,v,w corresponding velocity components
δ* boundary layer displacement thickness
x',y',z' coordinates, normalized to δ*
C_{gh} normalized cross-spectra magnitude
f frequency
F modulation frequency
β Hartree boundary layer parameter

1. Introduction
A limited selectivity of plasma actuators is one of the key barriers for their application as virtual roughness elements in boundary layer transition control. Recent application of these devices for the
crossflow instability control has shown that, along with the designed stationary disturbances creation, they perform a broadband unsteady forcing of the boundary layer, that leads to the unwanted excitation of traveling modes [1–3].

Typical plasma actuator consists of a pair of electrodes separated by a dielectric barrier. Plasma actuators operation is based on the Coulomb force acting upon the ions in the vicinity of the plasma formation region [4]. Dielectric barrier discharge at atmospheric pressures exists as a set of microdischarges (MDs), formed at the edge of the exposed electrode several times in a period. It is assumed that the boundary layer disturbances are formed as a result of the numerous forcing events from individual microdischarges. The wandering of the microdischarges leads to the low-frequency modulation of the forcing at a given point, and thus to the broadband excitation of the boundary layer.

Characterization of the discharge-induced disturbances in a 2D subsonic boundary layer was performed in [9]. It has been shown that low-frequency velocity pulsations correlate with the discharge optical emission. The typical amplitude of the disturbances was found to be as high as 1.5% U at the external flow velocity of 30 m/s. It was obtained that at Reδ~1000 the disturbances decay downstream at least in the observation region of 100δ. Analysis of the correlation between the discharge optical emission and hotwire measurements lets to assume that the in the near field the broadband noise of the actuator is compromised of the longitudinal streaks, induced by individual microdischarges, wandering along the electrode edge.

The general goal of this research is to study the further downstream development of the discharge-induced disturbances and to compare then with the evolution of the spanwise-coherent wave. It is a priori assumed that in the asymptotic region the broadband disturbances behaviour should change to a modal one, that is, they are to be converted in Tollmien_Schlichting waves. However, the details of disturbances evolution in the transient region and its behaviour is not quite clear.

2. Experimental details

Study of the disturbances induced in the boundary layer by sDBD plasma actuator was performed in a subsonic 2D boundary layer at a freestream flow velocity of 20.5 m/s, measured at actuator position. The boundary layer was organized on a flat plate with an elliptical leading edge (figure 1). The plasma actuator was installed at the position 180 mm from the leading edge, with the exposed electrode edge installed at angle of 90 deg to the oncoming flow. The pressure coefficient distribution was adjusted within Cp~0-0.1 m⁻¹ by small variation of the plate attack angle.

The boundary layer profiles are shown in figure 2(a). The measured data can be approximated by Falkner-Skan profiles with β~0-0.1, with an accuracy ±0.03. The evolution of the displacement thickness for two cases is shown in figure 2b. The typical Reynolds number can be estimated based on the displacement thickness as Reδ~840-1000. The displacement thickness at the actuator location was estimated to be δ*=0.52-0.6 mm. One should also note, that changes in the average velocity profiles, induced by actuator operation 15mm downstream of the discharge position, were within 1.5%U.

The discharge was created on the surface of an alumina ceramics (VK-94, ε=10.4) 1 mm thick plate. The grounded electrode was covered with silicone resin. The exposed electrode was made of 20μm thick aluminium foil, mounted onto a 3μm glue layer. Prior to the measurements, the actuator was operated for 30 min to stabilize the oxide layer built on the electrode. This led to the more homogeneous discharge structure [10] and excluded the drift of the actuator characteristics during the run. The actuator was powered by sinusus voltage, supplied by the resonant transistor switch power source. Operation frequency was 80-180 kHz and was stabilized by outer quartz generator with the accuracy of 10⁻³ Hz.

Hotwire measurements were made by 5 μm thick and 1.5 mm wide Dantec hotwire probe. The sensor was operated at overheat α=0.8.
In the absence of the discharge, the total $u'$ profiles in a boundary layer are determined by low frequency streaks. In the TS amplification frequency range (around 600Hz), the significant growth is seen for the ZPG case (dashed lines in figure 3(a)). For $\beta=0.08$, the selective amplification of natural disturbances is marginal (dashed lines in figure 3(b)).

3. Results and discussion

Downstream evolution of the broadband disturbances was studied as a function of pressure gradient. Experiments were held for two Hartree parameters: $\beta=0$ and 0.08. The typical spectra of the discharge-induced disturbances at various downstream positions are shown in figure 3. One can see that the discharge operation creates broadband velocity pulsations spanning from 200 Hz to at least 2 kHz. At the high frequencies, the band limit depends on the distance from the discharge.

At the position closest to the discharge, the spectra shapes for the two studied cases are similar. As one moves further downstream, the disturbances evolution depends on the boundary layer stability. For the accelerating flow, the spectra shape is conserved, and a gradual HF decay is observed downstream of the discharge. For the ZPG boundary layer, the clearly observable selective amplification of the initial disturbances in the range 400-800 Hz can be seen.

Localization of the disturbances in a boundary layer is shown in figure 4. The maximal amplitude is observed at $y^* \sim 0.9$. Although the comparison of the experimental profile to the TS wave eigenfunction for 660Hz shows the qualitative similarity, the maximum position is not predicted. This may be explained by the presence of finite-amplitude non-modal perturbations in the boundary layer. Interaction of TS wave with them in known to shift of maximum of pulsations from the wall (see [11]).
Figure 3. Spectra of the velocity pulsations. (a) $\beta=0$, (b) $\beta=0.08$.

Figure 4. Wall-normal profiles of the discharge-induced broadband and tonal and natural pulsations. (a) $\beta=0$, (b) $\beta=0.08$.

Figure 5 summarizes the growth of both the natural and discharge-induced pulsations around the frequency 660 Hz. The same plots show the development of the tonal disturbances, introduced in a boundary layer by modulation of the discharge voltage at $F=660\text{Hz}$. As the discharge amplitude is modulated across the whole electrode span, tonal pulsations are assumed to be mostly associated with a 2D wave.

One can see that the disturbances evolution depends on the boundary layer stability. For the zero pressure gradient case, all three types of disturbances grow downstream. The discharge-induced disturbances in a broadband spectra show only slightly weaker amplification rate in comparison to the natural and tonal ones.

For the more stable boundary layer at $\beta=0.08$, the disturbances in a broadband and tonal part of the spectra show completely different behavior. While both tonal and natural wave demonstrate weak amplification, the discharge-induced broadband pulsations decay. The LST estimates (solid lines in figure 5) underestimates the growth observed in experiment, most likely due to the systematic error in Hartree parameter evaluation from BL profiles.
4. Conclusion
Dielectric barrier discharge plasma actuator, operated in a continuous mode in a boundary layer, generates velocity pulsations in a broad frequency range. It was previously demonstrated that these pulsations are correlated with the individual microdischarges formation at the electrode edge, and the flow-induced structure can be interpreted as a streak, formed due to localized forcing of the boundary layer.

In the near field (within ~40δ*) from the actuator the spectra seem to be nearly flat. As one moves further downstream, the actuator induced pulsations show a selective amplification in the TS frequency band. Growth of the disturbances depends on the stability of the boundary layer. For the less stable BL, selective amplification for discharge-induced broadband pulsations is not observed in the studied region, indicating that non-modal disturbances dominate in the boundary layer further from the discharge.

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