Selectivity of plasma actuators in a boundary layer transition control applications

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Abstract. The paper describes the results of the study of broadband velocity pulsations, induced by dielectric barrier discharge plasma actuator in the 2D subsonic boundary layer, and their role in a boundary layer excitation. The origin of the velocity pulsations is the stochastic dynamics of microdischarges. The presented data include the parametric study of the disturbances power on the supply voltage characteristics and their structure. Also, the preliminary study of the role of the broadband disturbances in the Tollmien-Schlichting wave excitation was performed.

1. Introduction

Plasma actuators are recently studied as a disturbances source in active boundary layer control applications [1,2]. The strategies tested include the natural instability wave cancellation [3,4] or hindering the growth of the least stable mode due to its nonlinear interaction with the discharge-induced suboptimal disturbances [5-7]. One of the key barriers for plasma actuators application as a disturbance source in boundary layer transition control is their limited selectivity. The latter can be formulated in terms of signal-to-noise ratio, where the signal is associated with the boundary layer mode, introduced by the controller. The problem of the selectivity is the most critical, when the actuator induces the suboptimal disturbances, since the unwanted excitation of the least stable mode by the stochastic forcing is possible. Recent application of plasma actuators 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 excitation of travelling modes. When the desired forcing lies around the stability curve minimum, the stochastic processes in actuator can manifest themselves in the asymptotic region as a stochastic wavepackets of the least stable mode. This can potentially limit the minimum disturbance level in the wave cancellation methods.

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 [8,9]. 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. Microdischarges position and starting phase are controlled by a number of volume and surface
processes sometimes referred as "discharge memory" [10]. Each MD individually creates a hydrodynamic effect on the flow, and both the instantaneous electric force field and heat release are assumed to be three-dimensional [11,12]. The wandering of the microdischarges leads to the low-frequency modulation of the forcing at a given position, 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 [13]. It has been shown that low-frequency velocity pulsations correlate with the discharge optical emission, i.e. they are indeed caused by stochastic microdischarges dynamics in sDBD. The typical amplitude of the disturbances was found to be as high as 1.5% \( U \) (\( U \) – freestream velocity) at the external flow velocity of 30 m/s. It was obtained that at \( Re_\delta^* \approx 1000 \) the disturbances decay downstream at least in the observation region of 100 \( \delta^* \), where \( \delta^* \) is boundary layer displacement thickness.

The recent paper is devoted to the parametric study of broadband velocity pulsations, induced by sDBD actuator in the 2D boundary layer, and to the preliminary analysis of the boundary layer forcing mechanism. Results presented include the parametric analysis of the effect of the supply voltage characteristics on the broadband spectra. This part is followed by the experimental study of evolution of the tonal (2D) and broadband components of the disturbances in the boundary layer, that is, estimation of the selectivity of the actuator in the problem of 2D Tollmien-Shliechting wave generation.

2. Experimental setup and measurement methods

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 30-36 m/s. The boundary layer was organized on a flat plate with an elliptical leading edge figure 1a). The plasma actuator was installed at the position 220 mm from the leading edge, with the exposed electrode edge installed at angle 90 deg to the oncoming flow. Boundary layer profile figure 2a measured slightly downstream of the actuator position is shown in figure 2 together with the Blasius fit. Displacement thickness at the actuator location was estimated to be \( \delta^* = 0.45 \) mm. The deviations from Blasius profile can be caused by the negative pressure gradient, induced by growth of the boundary layers on the wind tunnel walls, thus the boundary layer is considered more stable relative to the Blasius case. Changes in the average velocity profiles, induced by actuator operation 15 mm downstream of the discharge position at \( U = 36 \) m/s, were within 1.5% \( U \).

The discharge was created on the surface of an alumina ceramics (VK-94, \( \varepsilon = 10.4 \) ) 1 mm thick plate. The grounded electrode was covered with silicone resin to prevent the discharge formation inside the model. The exposed electrode was made of 20 \( \mu \)m thick aluminium foil, mounted onto a 3\( \mu \)m 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 and excluded the drift of the actuator characteristics during the run. The actuator was powered by sinusuous 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.
Figure 1. a) Experiment scheme and electrode configurations, b) Boundary layer profile.

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.

To analyze the correlations between the discharge intensity and the observed pulsations, discharge emission in the optical range was used as a reference signal. The image of the actuator was built on the 1mm slit by a 50 mm lens. The photomultiplier tube (PMT), installed behind the slit, collected the light from the narrow section of the exposed electrode. The whole optical system was installed on the traveling stage allowing to move it in spanwise and streamwise direction. Hotwire signal g reference signal h were Fourier transformed and a normalized cross-spectrum $C_{gh}(x,y,z)$ was calculated for each spatial position.

$$C_{gh} = \frac{\tau(g)\overline{\tau(h)}}{|\overline{\tau(h)}|}$$  

The cross-spectra was averaged over 30-100 realizations and then its real part was used to visualize the structure of the disturbances in the boundary layer.

Excitation of the Tollmien-Schlichting waves was performed by oscillating the frequency of the transistor switch near the resonance of the output circuit. This leads to the modulation of the output voltage and to the 2D forcing of the discharge.

3. Results and discussion

3.1. Structure of the broadband disturbances in the boundary layer

The analysis of the disturbances created due to the stochastic processes in sDBD actuator was performed at voltage supply parameters: frequency $f=86$ kHz, amplitude $U_a=3.2$ kV. The typical spectra of velocity pulsations at various downstream positions is shown in figure 2a. The disturbances are created in a broad frequency range from 300 to 3000Hz. Actually, the this frequency region should be even broader, since it limited by the natural disturbances in the boundary layer (at low frequencies) and disturbances decay at higher ones. As one moves downstream, the discharge-induced disturbances decay, with the decrement increasing with frequency.

Figure 2. a) Spectra of the velocity pulsations at various position downstream of the actuator. b) phase portrait of the disturbances in a near field, visualized by disturbances of longitudinal velocity around 1200 Hz. Isosurfaces levels is $\pm10^{-3}$ m/s.

The disturbances, generated by the discharge in a boundary layer, can be visualized using the correlation of the hotwire signal and the discharge optical emission. The typical disturbance portrait for the frequency around 1.2 kHz is shown in Figure 2b. One can see that the induced disturbances have a limited extent along the span. The typical transversal wavelength is evaluated in the range 3-5 mm (5-10 $\delta*$). This value was found to be nearly constant across the frequency spectra. The disturbance phase portrait is symmetrical towards the central plane and includes a single maximum
(minimum) at the central part and a pair of regions with a velocity deficit at its sides. This structure resembles a single streak, formed at the bottom of a boundary layer. The typical phase velocity of the disturbances was found to be nearly constant across the spectra in the range 300-3000 Hz. It is equal to 19 m/s (0.6 U) — the typical local velocity at the position of the maximum of the pulsations amplitude.

The streaks formation in the boundary layer is driven by the “lift up” mechanism — longitudinal momentum transport in the shear layer by longitudinal vortices. The latter are generated by the several mechanisms associated with the complex structure of the volume force in the vicinity of the microdischarge [14]. These mechanisms were previously considered during the preliminary study of the plasma-based virtual roughness for the transition control applications. The longitudinal vortices can occur due to the lateral component of the Coulomb force. The other effect is the necklace vortices formed around a small separation region, present above the exposed electrode [7]. The resulting structure formed in the boundary layer is a pair of symmetrical counter-rotating vortices, inducing a positive streak in a wake of the microdischarge group.

3.2. Effect of supply voltage parameters on the broadband spectra power

The preliminary study of the broadband spectra power as a function of supply voltage characteristics was performed, with the results plotted in Figure 3. It is shown that the power of the broadband noise increases linearly with the applied voltage as $(u')^2 \sim (U_a - U_i)$, where $U_i$ is the discharge inception voltage. Furthermore, the power of the disturbances depends on frequency as $f^{2/3}$.

These results allow formulation of some recommendations concerning the design and powering of the actuator. The usual assumption made is that the supply voltage carrier frequency should be much higher than the typical receptivity band of the controlled boundary layer. Still, the increase of the frequency requires the reduction of the operation voltage to maintain the forcing amplitude and prevent the discharge constriction. The total disturbance induced in a boundary layer due to voltage modulation is created as a result of superposition of forcing from numerous microdischarges. Voltage decrease leads to a small number of microdischarges per period. The induced thrust of the actuator is known to increase with voltage faster than linearly [2]. This means that that actuator selectivity (or signal-to-noise ration of the created disturbances) will be higher at high voltage-low frequency operation, and thus operation voltage should be kept well above the inception one, thus limiting the driving frequency.

![Figure 3](image.png)

**Figure 3.** Effect of the supply voltage parameters on the total amplitude of the broadband noise: a) at natural parametric space, b) in reduced parametric space.
3.3. Selectivity of the DBD plasma actuator in Tollmien-Schlichting wave excitation

Excitation of the straight TS waves by plasma actuator was demonstrated in several works [3,4], however, the issue of signal-to noise ratio has never been addressed in detail. In the 2D case, the stochastic behavior of the microdischarges induces some streak-like disturbances in the actuator near field. These disturbances are composed of a number of modes for any given wavenumber. Due to the dispersion (various increment), only the wavepackets, grouped around a least stable mode, will survive as the disturbance propagates downstream. The overall amplitude of the broadband spectra should then decrease until only the TS wave will remain in the asymptotic region. The “signal-to noise” ratio in the far field will be determined by the stochastic TS wave amplitude.

In our experiments, the TS wave was excited via modulation of the supply voltage. The test wave was induced at F=760 Hz ($\omega^*=0.07$) and F=1340 Hz ($\omega^*=0.13$) (Figure 4a). The peaks corresponded to the typical amplitude below 0.1%, assuming that the disturbances propagation occurs in a linear regime. The peaks are associated with the 2D forcing of the boundary layer and are assumed to correspond to a TS wave in the region far enough from the actuator.

The comparison of the downstream evolution of broadband disturbances and TS wave is shown in Fig.4b. At both frequencies the tonal disturbances decay in the boundary layer. It can be seen that at higher tested frequency, the TS wave and the broadband pulsations have the same decay rate. For the lower tested frequency, the discharge-induced broadband pulsations have a lower decay rate that possibly means that in this region the nonmodal disturbances still prevail.

The amplitude of the tonal disturbances was varied to find a typically attainable signal-to-noise ratio at a given supply voltage characteristics and actuator construction. It is shown that the typical signal-to noise ratio in a narrow spectral region can be as high as 500. It is assumed, that for higher values of $U/U_i$ this value can be substantially improved.

![Figure 4](image-url)

**Figure 4.** a) Spectra of the disturbances in the case of the tonal excitation of the boundary layer, b) downstream evolution of the disturbances.

4. Conclusions

Dielectric barrier discharge, operating in the low velocity boundary layer, generates velocity pulsations in broad frequency range. The analysis of the correlations between the velocity pulsations and discharge optical emission reveals that the typical spanwise scale of the corresponding structures in the near field is within 3-5 mm. It is assumed that the structure appears to be a sum of nonmodal disturbances (unsteady streaks) and the Tollmien-Schlichting waves. The comparison of the streamwise evolution for tonal (TS waves) and broadband disturbances shows that the role of the latter increases at one moves downstream into the far field. It is shown that in the near field, the contribution of the streaks seems to be higher for the lower frequencies. The typical S/N ratio in the near field was found to be as high as 500 for a studied actuator geometry and supply voltage characteristics. It is
shown that the power of the broadband pulsations increases linearly with discharge overvoltage; it increases with the driving frequency as $f^{2/3}$. Since the averaged actuator thrust increases faster than linearly with overvoltage, the S/N ratio of the actuator can be increased if one uses the low frequency-high voltage DBD operation mode, when a large number of microdischarges generations is obtained over a single half-period of driving voltage.

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