Influence of the surface DBD parameters on the streaks development in the boundary layer

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Abstract. The effect of the filamentary barrier discharge parameters on the boundary layer streaks generation and instability was studied. The streaks are formed near the constricted discharge channels due to vortices formation driven by spanwise Coulomb volume force. The secondary instability of the streaky structures can lead to the laminar-turbulent transition of the boundary layer. This work demonstrates that supply voltage parameters affect the period of the constricted channels and thus the streaks transversal period within the boundary layer. For the various streaks periods, different modes of streak instability are shown to dominate.

1. Introduction
Plasma actuators are studied as a candidate for flow control in various applications [1–3]. One of the first and still most known results is the separation control near the wing leading edge or bluff body by dielectric barrier discharge actuator. Since the local Re number is relatively low in these works, at least in the wind tunnel tests, the flow separation is strongly affected by the position, where the boundary layer transits to the turbulent state.

The effect of the barrier discharge on the 2D boundary layer transition was studied in detail during the last decades. It was shown that velocity profile modifications by ionic wind can have a dramatic effect on the disturbances evolution in the boundary layer. Most recent studies reveal that discharge inhomogeneity can determine the structure of the boundary layer downstream of the actuators and thus affect its stability.

The increase of the power input in the discharge leads to discharge filamentation (constriction). It was shown that filamentary discharge can drive a fast transition to turbulence in the boundary layer [4]. The lateral component of the body force present near the filaments leads to the longitudinal vortices formation in the boundary layer. Momentum transport in the vortices causes the formation of the alternating regions of velocity defect and excess in the boundary layer – so-called streaks. If velocity modulation in the streaks exceeds 10-15% of external flow velocity, they become unstable. Inviscid streaks instability has two modes, namely symmetric (varicose) mode and antisymmetric (sinuous) [5][6]. For the conditions studied in [4] the sinuous mode has the maximal amplification ratio and finally drives the boundary layer to a turbulent state.

The parametric dependency of this mechanism on the discharge parameters is still lacking. It is known that streaks instability is strongly affected by the detailed shape of the mean flow distortion [5]. The latter is obviously determined by the boundary layer streaks period and amplitude. On the other hand, variation of the discharge parameters, i.e. the constriction voltage, changes the period of the filaments [7]. The main goal of this work is to analyze how the changes in the “primitive” discharge
powering characteristics: voltage and frequency affect the streaks period and the properties of the governing instability mode.

2. Experimental details

Experiments were carried in the aerodynamic channel D-2 in JIHT RAS at flow velocity 9 m/s. The boundary layer was formed on the flat plate set at zero attack angle. Dimensions of the plate were 320x100x10 mm. The plasma actuator was located at the position about 200 mm from the leading edge (figure 1), which corresponds to the Re~150k. Boundary layer displacement thickness was on the order of 1 mm. Visualization of the boundary layer streaks was performed by a particle-imaging velocimetry in the plane parallel to the plate, at the position ~1 mm from the surface. The flow was seeded in a forechamber by oil particles with dynamic relaxation time ~ 2 μs.

Secondary disturbances measurements were performed by a hotwire. Dantec hotwire probe 1 mm wide and 5 μm thick was oriented normally to the oncoming flow. The probe was operated at the overheat ratio a=0.8. Disturbance spectra were calculated based on 9k samples and averaged over 30-100 realizations.

Plasma actuator was designed in a standard 2D asymmetric configuration; 1mm thick alundum ceramics was used as a dielectric. For the study of secondary instability development, tips with a predefined period were formed on the exposed electrode. This allowed to fix the positions of the filaments and to study the detailed distribution of the pulsations amplitude over the boundary layer. The discharge was powered by alternative sinusoidal voltage with frequency 7-150 kHz and amplitude up to 10 kV.

![Figure 1. Boundary layer experiment scheme (left) and filamentary discharge image (right).]

3. Results and discussion

3.1. Filaments and streaks period as a function of the discharge voltage parameters

The period of the discharge channels is known to be a function of the applied voltage. The distance between the filaments immediately after the constriction onset decreases with the driving voltage frequency. Discharge filamentation occurs as soon as the dissipated power per electrode length exceeds some critical value ~ 200 W/m [4]. It is known [2,4,8] that prior to the transition onset, the dissipated power is proportional to the value \( P \sim (U-U_0)^2 f \). It means that the filamentation voltage decreases with the frequency increase. The typical distance between the filaments is determined by the extension of the charged region on the dielectric surface (discharge length), the latter being proportional to the voltage amplitude. Therefore, the distance between the filaments in sDBD decreases with the rise of the discharge driving voltage frequency. The effect of the driving frequency on the streaks separation is shown in figure 2. One can see that the streaks period increases as one drops the voltage frequency.
3.2. Streaks secondary instability

One can also obtain from figure 2 that the secondary disturbances in a boundary layer have different structure for various streaks separation. One can speculate that long-wavelength sinuous oscillations of the streaks, observed for neatly packed streaks pattern, are changed by the shorter symmetric oscillations for the wider nearly isolated streaks.

The analysis of the typical spectra of the velocity oscillations was performed for the actuator configuration with the discharge filaments, stabilized by small tips on the exposed electrode. The spectra were observed for two tips periods: 5 mm and 10 mm, roughly corresponding to the «natural discharge» cases 20 and 5 kHz.

For shorter wavelengths, $\lambda_z=5$ mm, two spectral ranges, corresponding to the lower (500-1000 Hz) and higher (1100-2300Hz) frequency pulsations are marked in the spectra (figure 3). The initial growth is obtained in the second frequency band. However, this growth stops at the position ~20mm from the discharge. More downstream, the disturbances power increases only in the lower frequency band. The studies performed in [4] for similar conditions show that the high-frequency disturbances correspond to the varicose mode, while the lower frequency pulsations are associated with the sinuous streaks oscillations. For a longer streaks pattern wavelength, a single hump at the typical frequency 300-900 Hz can be seen.

![Figure 3](image_url)  
**Figure 3.** Hotwire spectra in the filament wake at the height $y=1$ mm for the two spanwise streaks periods.

Modes attribution usually requires a decomposition of some coherent velocity data, for example, POD of PIV measurements. However, some indirect conclusions can be done from the localization of
the pulsations in the streak. Varicose and sinuous modes have different eigenvectors [5][6]: for the varicose mode, the eigenfunction has the maximal amplitude both at the sides and the top of the streak; for sinuous mode, the upper maximum is absent (figure 4a). The two modes of streaks instability can be associated with two inflection points: the wall-normal profile at the center of low-velocity streak and two inflection points in the shear region at the lateral side of the streak.

Figure 4b,c show the spectral power density distribution in the cross-flow plane. One can see that the patterns typical for the antisymmetric mode is observed only for the short streak period ($\lambda_z = 5$ mm) at a large distance from the actuator; in all other cases, the power distribution seems to be more typical for the symmetric (varicose) mode. This allows assuming the following secondary disturbances behavior for the two studied cases. In all cases, the initial instability occurs for the varicose mode due to the highly inflectional wall-normal velocity profile in the low-velocity streak. For a shorter period, the growth of this mode stops due to the gradual smoothing of the velocity profile as one moves downstream. Still, the sinuous mode, driven by inflection points in spanwise profiles, dominates in the flow starting from ~30mm. For wider streaks, the main instability is associated with the wall-normal profile inflection point, and thus the varicose mode has the maximal amplitude in a whole region. These conclusions are qualitatively consistent with the streaks snapshots for different periods of the streaky structure (figure 2).

![Figure 4](image-url)

**Figure 4.** (a) Amplitude distribution of velocity fluctuation for varicose (right) and sinuous (left) instability modes [6]. (b),(c) velocity and spectral power contours for measurement stations $x = 20$ (left) and $x = 80$ mm (right) for the streaks period 5 and 10 mm (b) and (c).
4. Conclusions
The period of the boundary layer streaks, induced by filamentary barrier discharge, depends on the discharge driving voltage characteristics. The variation of the streaks period and shape leads to the change in the governing modes of the secondary streaks instability. For short-period streaks, obtained at a high frequency of the applied voltage, the varicose mode dominates only close to the electrode, while the more downstream region is governed by the sinuous instability. The wider streaks, corresponding to the lower frequencies, are mostly subject to the varicose instability.

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