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Flow visualization in cavity with dielectric barrier discharge actuator control

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The results of hydrodynamic pressure fluctuations control by means of a dielectric barrier discharge plasma actuator in a rectangular cavity with sharp edges are presented. The study was carried out at the free flow velocity $V = 37$ m/s. The discharge was organized near the leading edge of the cavity. The average energy of the discharge pulse was 0.03 J, its duration was 1 ms, and frequency modulation was implemented at the natural cavity resonant frequencies of 500, 817, 1317 Hz and at a high frequency of 2160 Hz which did not correspond to the natural resonant pressure peak. Pressure pulsations were measured with a Kulite pressure transducer. It is established that the discharge regime affects the pressure fluctuations in the cavity. The pressure amplitude at the downstream wall of the cavity can be either increased from 117 dB to 128 dB or decreased to 110 dB if, respectively, if either the dominant or higher modes are pumped by the discharge. The PIV visualization was organized in the phase-locked mode. The pressure spectrum corresponds to the magnitude of coherent structures in the shear layer of the cavity.

Keywords: plasma actuator, cavity, active control, DBD, boundary layer, mixing layer, closed loop.

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In recent years, flows in cavities attract a great interest in connection with applied [1] and fundamental research tasks. Due to a complicated closed-loop control process, the cavity flow structure undergoes self-oscillations at a discrete set of frequencies (Rossiter modes) [2]. In the boundary layer near the cavity leading edge there arise vortical structures. They get enhanced in the shear layer and scatter from the downstream cavity wall. This gives rise to acoustic fluctuations. The acoustic fluctuations propagate upstream inside the cavity and excite the shear layer near the leading edge. This results in closing of the feedback loop. The effect of finiteness of the shear layer size and cavity depth was taken into account in [3] in determining the resonant frequencies. This natural feedback mechanism underlies the principle of active control of the cavity flow.

Processes of controlling the resonator tones have been studied for more than a half-century [4]. The most common practical application was found by passive devices designed for reducing high sound pressures [5]. However, active flow control techniques are also being widely studied and find their application niches. An incomplete list of the types of used actuators includes steady and unsteady jets [6], piezo-valves [7], liquid-based generators [8], synthetic jets [9], and also plasma actuators including those of the dielectric barrier discharge (DBD) [10].

The general approach implies modifications of the leading edge, e.g. chevrons, and also the use of vortex generators changing the shear layer stability characteristics. An alternative approach is active excitation of the shear layer in order to induce nonlinear interaction between the modes of the resonator or of the closed control loop. The last concept was implemented by using mechanical devices [7] at the Mach number $M = 0.2$. Synthetic jets with the zero mass flowrate were successfully employed with an analog feedback loop at the Mach numbers of 0.2 to 0.55 [11]. In work [12], the energy exchange between the first three cavity modes was studied; a conclusion was made that the closed-loop actuator is necessary for suppressing various instability modes.

To initiate intermode interactions in the resonator, localized plasma filaments were used in both the subsonic [13] and supersonic [14] flows. To manipulate the shear layer structure, a barrier discharge at the flow velocities of 10–20 m/s was used [15].

The objective of this study was controlling the flow by using the DBD actuator on the cavity leading edge. It seemed important to associate the reduction of the resonant pressure fluctuations with the shear layer vortical structure in the presence of the DBD ignition and free of it.

The experiments were carried out in a subsonic wind tunnel at the Joint Institute for High Temperatures (RAS). It was designed as an open loop with the compression ratio of 16:1 from the damping chamber to the test section. The maximal flow velocity in the test section may reach 70 m/s. The test section was 0.1×0.1 m in cross–section and 0.8 m in length (Fig. 1, a). The test section was fabricated from Plexiglas and had a glass panel, which allowed optical access to the chamber and, thus, general supervision of the experiment. The cavity depth was 50 mm, while its length was regulated in a wide range (0–240 mm) by displacing the diffuser plate. In order to demonstrate the maximal signal suppression in the pressure pulsation resonance peaks, the main results were obtained at the cavity length–to–depth ratio $L/W = 1.23$ (length

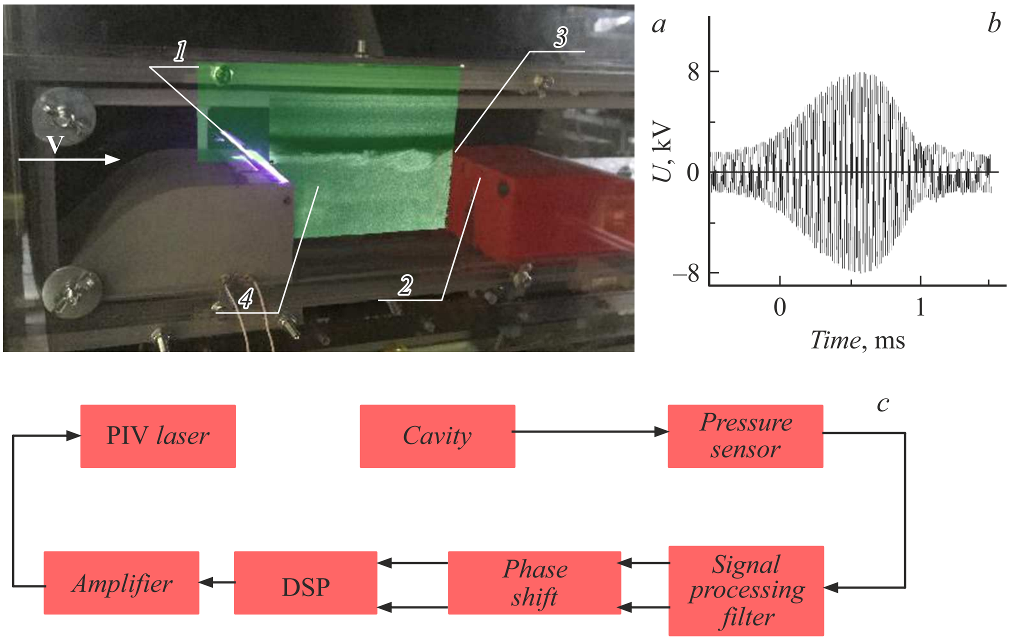

Figure 1. *a* — measurement scheme for the cavity pressure fluctuations and velocity profile by the PIV method: *1* — ceramic insert, *2* — pressure scanner, *3* — diffuser plate, *4* —laser knife; *b* — typical oscillogram of the plasma actuator voltage; *c* —schematic diagram of the frequency phase-locking loop.

$L = 61.5$ mm, depth $W = 50$ mm). Since cavities are conditionally subdivided into deep ($L/W \ll 1$) and shallow ($L/W \gg 1$), we relate the specified configuration to the transient type. The ceramic insert with aluminum electrodes was mounted flush with the flow–facing surface of the cavity leading edge. The high-voltage electrode was 85 mm long and 0.05 mm thick, the distance between the electrodes and cavity edge was 5 mm. On the inner side of the ceramic insert, the earthing electrode was mounted. It was filled with dielectric compound in order to prevent parasitic breakdown beyond the leading edge working section. The experiment was performed at the temperature of 293 K and at the atmospheric pressure. The free flow velocity was $V = 37$ m/s. The electrodes were installed at the angle of 90° to the stream.

The pressure fluctuations were measured with pressure micro-transducer Kulite XT-140(M) mounted along the cavity centerline on the cavity back wall at 2 mm from the upper edge. Then the signal was fed through an analog filter to the input of the analog-digital converter–digital signal processor–digital-analog converter (ADC–DSP–DAC) module. This module processed the signal by applying to its counts a filter with a finite pulse characteristic. The band-filtered signal was almost monochromatic and corresponded to the dominating Rossiter mode ($f = 500$ Hz) with a controllable phase delay with respect to the pressure transducer readings. The converted signal triggered the PIV system able to perform phase measurements of the excitation evolution under the resonance conditions (Fig. 1, *c*).

The discharge was initiated by a sinusoidal voltage 144 kHz in frequency and up to 8 kV in amplitude (Fig. 1, *b*). The discharge frequency modulation was tuned to the cavity eigen frequency: 500, 817 or 1317 Hz. The average discharge power was 130 W/m.

The spectrum of the pressure pulsation power is presented in Fig. 2, *a*. One can see that the cavity generates a set of acoustic tones with the maximum sound pressure of up to 120–140 dB. The lowest tone corresponds to Strouhal number

$$\mathrm{St} = \frac{fL}{V} = 0.8.$$

Under the studied conditions, the third mode appeared to be predominant; however, variations in the pressure fluctuations at the operating frequency of this actuator remained within the measurement error. Therefore, the major part of the studies was performed with controlling the first mode (500 Hz).

The cavity was excited around the first mode (in the band of 450–550 Hz). The spectrum structure around the peak is shown in detail in Fig. 2, *b*. It is clearly seen that the plasma actuator can excite the cavity with the pressure amplitude maximum increase by 10 dB in the case of resonant excitation.

It was also shown that, when the cavity is excited at a high modulation frequency, the oscillations get bound to the pump frequency. The off-resonance high-frequency (2160 Hz) discharge modulation leads to initiation of asynchronous vortex shedding from the leading edge and, thus, to the disturbance of the natural feedback loop, which finally promotes energy redistribution among the modes. Thus, the amplitude of the predominant tone decreases by 10 dB.

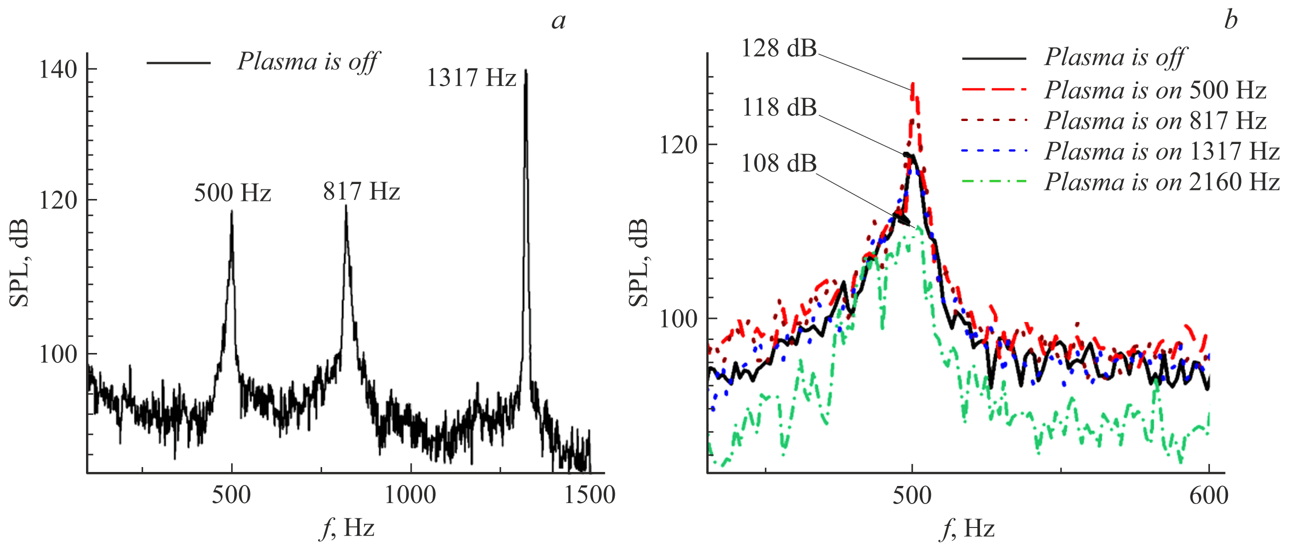

Figure 2. Typical pressure spectra for the freestream flow (a) and flow at different discharge modulation frequencies of the DBD actuator (b).

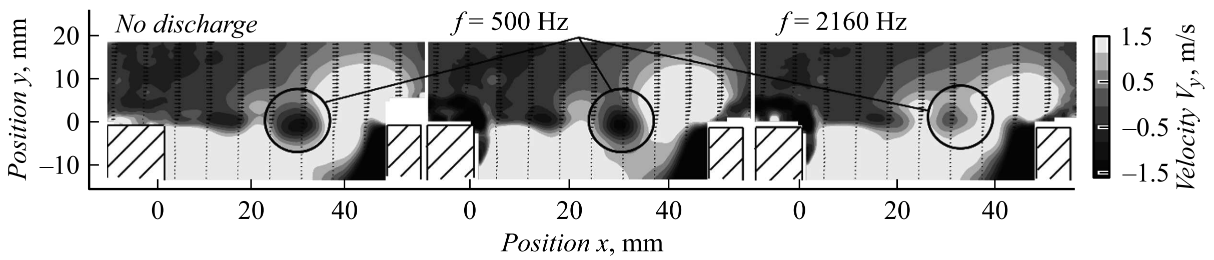

Figure 3. Visualization of the freestream flow and shear layer excitation at the frequencies of 500 and 2160 Hz.

The velocity field was investigated by using the LaVision FlowMaster PIV system described in detail in [16]. The resulting velocity field was obtained by averaging over 400 instantaneous frames. The frames were phase-locked with the filtered pressure signal (500 Hz).

The obtained flow fields presented in Fig. 3 clearly demonstrate the difference between the freestream flow (mode a) and excitation mode (mode b) as well as the suppression mode (mode c). One can see that the vortex intensity and geometry undergo changes in the wake near the downstream wall, namely, the vortex circulation and size for modes a, b, c are 368, 370, 365 m^2/s and 11, 12, 4.6 mm, respectively.

Notice that, to clarify the reasons for enhancement of the cavity pressure fluctuations at some of the actuator operating frequencies and their reduction at other frequencies, it is necessary to take into account that an important role is played by the property of selective shear-flow enhancement that makes some excitations be enhanced stronger than others. An important additional condition for occurring of high-amplitude oscillations may be best of all described in terms of an effective feedback. This feedback that is, in essence, the upstream propagation of perturbations, is enhanced due to the presence of the cavity lower edge. The pressure turbulences coming from the downstream cavity edge (or from its vicinity) give rise to vorticity fluctuations near the onset of the sensitive shear layer. In their turn, such fluctuations create additional turbulences that are later enhanced in the shear layer, and so on. To reveal the predominance of one aspect of the cavity flow excitation mechanism over others, extra investigations are needed.

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Conflict of interests

The authors declare that they have no conflict of interests.

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