Flow control in cavity by means of sDBD actuator

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Abstract. This paper presents results of controlling the hydrodynamic cavity pulsations by plasma sDBD actuators. The study was held at flow velocity 36 m/s. The discharge was organized near the upstream edge of cavity. The discharge pulse energy was 0.03 J. Excitation of resonant modes, whose frequency coincides with the modulation frequency of the discharge, is obtained. Also, in the case of the detuned discharge operation, locking of the cavity to the discharge modulation frequency occurs.

1. Introduction
The shallow cavity flow is a universal model flow, which is present in many practical applications. The cavity flow is characterized by a complex feedback process, which leads to self-sustaining oscillations at a discrete set of frequencies (Rossiter modes) [1]. The reason for the appearance of discrete acoustic frequencies is the resonance mechanism, which occurs when vortex structures originating at the upstream edge, are amplified in the shear layer and scattered at the lower wall, generating acoustic disturbances. Acoustic disturbances excite the shear layer, which leads to closing of a feedback loop. A more detailed study can be found in [2], where the effects of the finite dimensions of the shear layer and the depth of the cavity were taken into account when determining the resonance frequencies. Described feedback mechanism forms the basis for the active control systems development.

Control of the resonant cavity tones has a long history [3]. In practical applications, high sound pressure levels are usually reduced using passive devices [4]. Today, a variety of methods and devices for active flow control have been widely studied. An incomplete list of used actuators includes stationary and non-stationary jets, piezoelectric valves, liquid generators [5], synthetic jets, as well as plasma actuators, including DBD [6].

Flow control methods usually utilize modification of the cavity upper edge (for example, the installation of vortex generators or chevrons), or active excitation of the shear layer. The goal of active control is either nonlinear interaction of modes or feedback control. The feedback concept was implemented using mechanical devices [7] at low Mach numbers (M = 0.2). In [8], an analog feedback system was successfully used with synthetic jets at Mach numbers from 0.2 to 0.55. In [9], the energy exchange between the first three modes in cavities was investigated and it was concluded that a feedback actuator is needed to suppress a variety of instability modes.

Plasma actuators (localized arc filaments) were used in subsonic [10] and supersonic [11] flows to initiate intermode interactions in the cavity. Also, barrier discharge was used to manipulate the structure of the shear layer at flow velocities 10-20m/s [12].
Promising noise reduction technologies for cavity flow include closed loop. Most active flow control methods with automatic feedback have been successfully tested on the cavity models. However, mechanical feedback systems are limited in frequency and lifetime, with DBD actuators can be considered as an alternative. Demonstration of sDBD discharge effect on the cavity flow structure is a first step to implement close loop system at the next stage.

2. Scheme of experiment
Experimental studies of flow separation control were carried out in subsonic wind tunnel D-2 JIHT RAS. The wind tunnel had open loop design with contraction ratio 16:1 from setting chamber to working section (figure 1). Maximum flow velocity could come up to 70m/s in uncluttered working section. The test section had crosse section 0.1x0.1m, the length is 0.8m. The test section was made of plexiglass with glass insert, that allowed camera view and general control of experiment. The cavity was formed between two inserts consisting of a confuser and diffuser sections, which were made by 3D FMD printing. The cavity depth was 50mm, while length was controlled in wide range (0 – 240 mm) by shifting downstream model in the testing section. The main results were obtained at the cavity length L=120mm.

A ceramic insert with aluminium electrodes was installed flush with the streamlined surface of the cavity upstream edge. The high-voltage electrode had length 85 mm and a thickness of 0.05 mm, the distance between the electrodes and the edge was 5 mm. On the inner side of the 1mm thick alundum ceramics the grounded electrode was mounted.

The experimental conditions corresponded to the initial air temperature ~ 293 K and atmospheric pressure. The oncoming flow velocity was V=36 m/s. The electrodes were installed at 90 degree angle to the flow.

The pressure oscillations were measured by Kulite subminiature pressure transducer XT-140(M), with pressure range 1.7 Bar and natural frequency 240 kHz. Sensor diameter was 3 mm. The pressure sensor was mounted in the centerline of the cavity downstream wall 2 mm below the edge.

3. Experimental results
The discharge was excited by sinusoidal voltage with a frequency of 150 kHz and an amplitude of up to 5 kV (figure 2). The discharge modulation frequency was adjusted to the lowest natural frequency of cavity (370Hz), duty cycle was 50%. The pulse energy was 30mJ, corresponding to average power 130 W/m.

A power spectrum of the transducer pressure is shown in figure 3a. The used reference sound pressure in air is $p_0 = 20 \mu\text{Pa}$.
Figure 2. Voltage oscillograms of typical operating modes of a plasma sDBD actuator.

One can see that the cavity generates a set of acoustic tones with the maximal sound level up to 60 SPL. The lowest frequency corresponds to the Strouhal number 1.3. The dimensionless Strouhal number describing oscillating flow mechanisms was taken as:

\[
St = \frac{f_{\text{mod}}L}{V}
\]

Cavity excitation was performed around the lowest tone, in the frequency range 350-380 kHz. The detailed spectra around the peak are shown in figure 3b. One can clearly see, that plasma actuator can excite the cavity with maximal increase of pressure amplitude by 12dB at resonance.

It was also obtained that when the cavity is excited at slightly detuned frequency, locking of the oscillations to the pumping frequency occurs. Off-resonant discharge modulation near the reference dominant tone leads to redistribution of energy from 372 Hz to plasma modulation frequency, so the dominant tone amplitude decreases by 5dB.

Figure 3. Typical acoustic spectra of plasma for reference case (a), and various discharge modulation frequencies (b).
4. Summary
The flow over the shallow cavity is hydrodynamically unstable. The instability mechanism includes vortices formation near the upper edge, their amplification in the shear layer and the acoustic feedback through the cavity. Periodic discharge initiation near the upper edge can induce the organized vortical structures in the shear layer. It is demonstrated that for the studied conditions, the amplitude of such forcing was enough to excite the cavity near the lowest resonance frequency. Also, locking of the cavity oscillations to the forcing frequency was obtained in the case of detuned cavity excitation. In this case, cavity is excited at the excitation frequency, while an attenuation of the dominant mode occurs.

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