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Fast Track Communication

Noise control of subsonic cavity flows using plasma actuated receptive channels

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Abstract

We introduce a passive receptive rectangular channel at the trailing edge of an open rectangular cavity to reduce the acoustic tones generated due to coherent shear layer impingement. The channel is numerically tested at Mach 0.3 using an unsteady three-dimensional large eddy simulation. Results show reduction in pressure fluctuations in the cavity due to which sound pressure levels are suppressed. Two linear dielectric barrier discharge plasma actuators are placed inside the channel to enhance the flow through it. Specifically, acoustic suppression of 7 dB was obtained for Mach 0.3 flow with the plasma actuated channel. Also, the drag coefficient for the cavity reduced by over three folds for the channel and over eight folds for the plasma actuated channel. Such a channel can be useful in noise and drag reduction for various applications, including weapons bay, landing gear and branched piping systems.

Keywords: plasma actuation, noise control, cavity flow, drag reduction

(Some figures may appear in colour only in the online journal)

Flow over an open cavity generates acoustic tones caused by pressure oscillations generated from impinging shear layers. Free shear layers in an open cavity become unstable and create large vortical structures, which impinge on the trailing edge and produce periodic acoustic waves. These waves propagate upstream and perturb the shear layer at the leading edge causing instability. Thus, the downstream travelling vortices and the upstream travelling acoustic waves form a closed path, which leads to resonance in the open cavity.

Acoustic resonance in cavities has a variety of applications. On one hand, it is beneficial in generating music in wind instruments and whistles, but on the other hand it is detrimental for applications such as landing gear and weapons bay in aircrafts where high sound pressure levels can damage the fragile parts. In this letter, we introduce a passive as well as active flow control method that responds to the surrounding flow to reduce the detrimental effects of acoustic waves in an open cavity.

In general, flow control methods can be classified into passive and active control. Passive control, such as control via geometric modification does not use external energy/momentum source to control the flow. However, active control uses external energy/momentum source like mechanical or electrical input to control the flow. Examples of passive control methods include rigid fences, spoilers, ramps and passive bleed systems. Spoilers have been tested on aircraft prototypes, such as B-1, B-47 and F-111. Rossiter [1] used a guillotine-type spoiler at the leading edge to alter the boundary layer. Heller and Bliss [2] investigated different geometric configurations for the trailing edge showing successful acoustic suppression using a slant aft wall with vortex tabs or with a flap. However, extensive study on trailing edge geometric modification is yet to be explored.

Active control methods generally involve mass injection, high frequency pulsing rods, piezoelectric flaps and plasma actuators. Yugulis *et al* [3] studied the effect of arc filament plasma actuators at the leading edge of the cavity for high subsonic flows showing reductions up to 23 dB. Thus effects of plasma actuators need to be further investigated. A detailed review of active control methods can be found in Cattafesta *et al* [4].

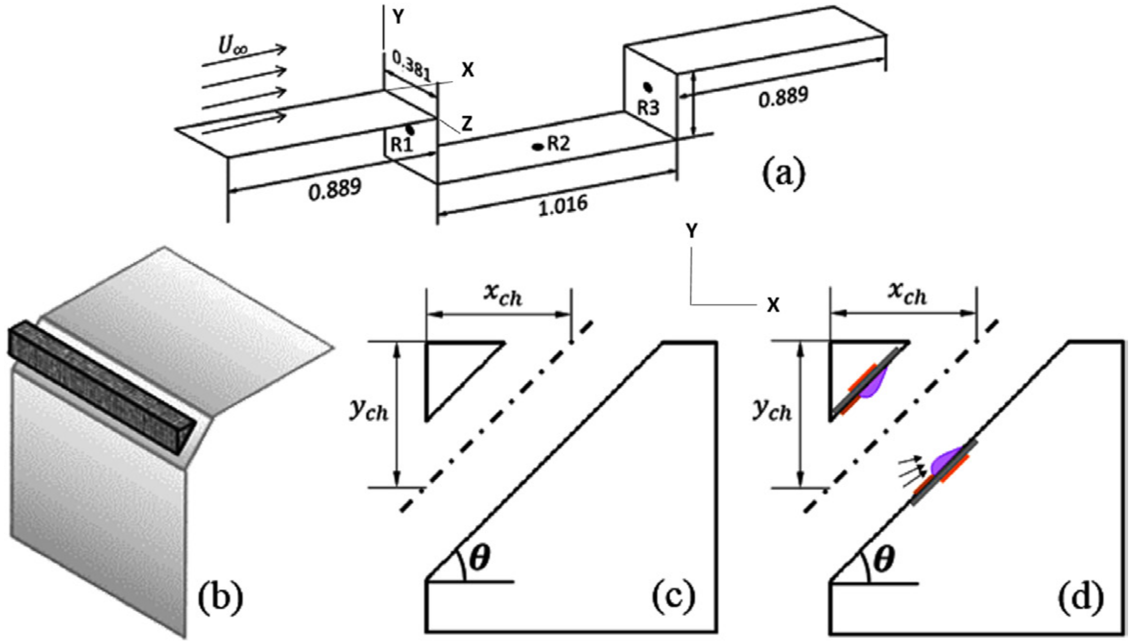

Figure 1. (*a*) Open rectangular cavity schematic and receiver locations (all dimensions are in metres). (*b*) Perspective view of the trailing edge channel. (*c*) Side view of the trailing edge channel. (*d*) Trailing edge channel with DBD actuator.

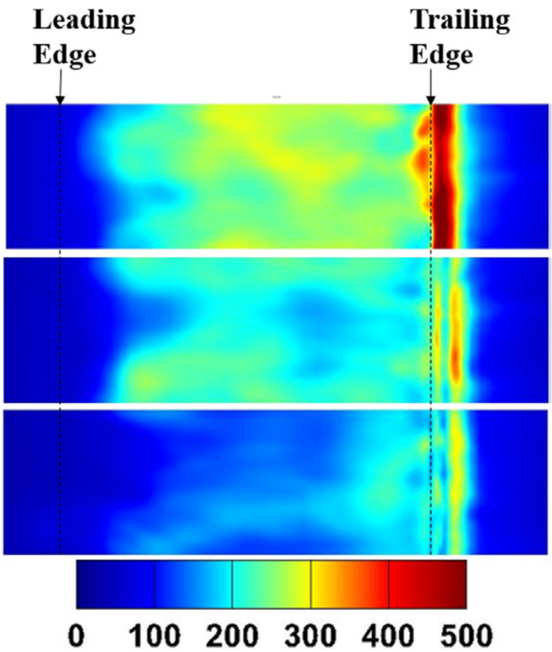

Figure 2. RMS pressure (in Pa) at $y = 0.01$m plane: (*a*) case I (top), (*b*) case II, (*c*) case III.

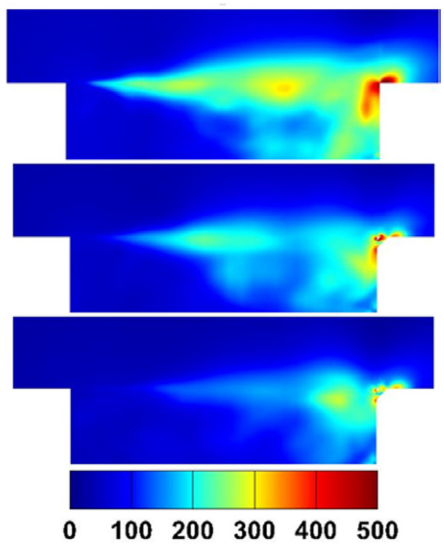

Figure 3. RMS pressure (in Pa) at centre z-plane: (*a*) case I (top), (*b*) case II, (*c*) case III.

In this letter, we introduce a receptive channel at the trailing edge and add dielectric barrier discharge actuators inside this channel to suppress the sound pressure levels. This requires minimal geometric modification. The idea is to connect the fluid between the high and low pressure regions around the trailing edge, which in turn should reduce the pressure oscillation amplitudes and thus influence the noise levels. The addition of plasma actuators will enhance the flow through the channel resulting in better flow control. We study Mach 0.3 flow over the cavity and compare the effects of channel, with and without the actuator.

The baseline cavity model shown in figure 1(*a*) is a standard open rectangular cavity. All relevant dimensions are given in the figure. The $L\,/\,D$ =4 is maintained throughout our study. Receiver 1 (leading surface), receiver 2 (bottom surface) and receiver 3 (trailing surface), drawn as black dots in figure 1(*a*), are located at (0.001, −0.127, 0.1905 m), (0.508, −0.253, 0.1905 m) and (1.015, −0.127, 0.1905 m) respectively. These are the locations where the acoustic pressure is evaluated. The passive receptive channel, shown in figures 1(*b*) and 1(*c*) is placed on the trailing edge of the cavity.

The length x_{ch} is the distance from trailing edge to the centre line of the channel. The angle θ, which the channel makes with the horizontal, is set at 45° and x_{ch} is equal to 0.0254 m. The height of the channel y_{ch} is kept constant at 0.0254 m.

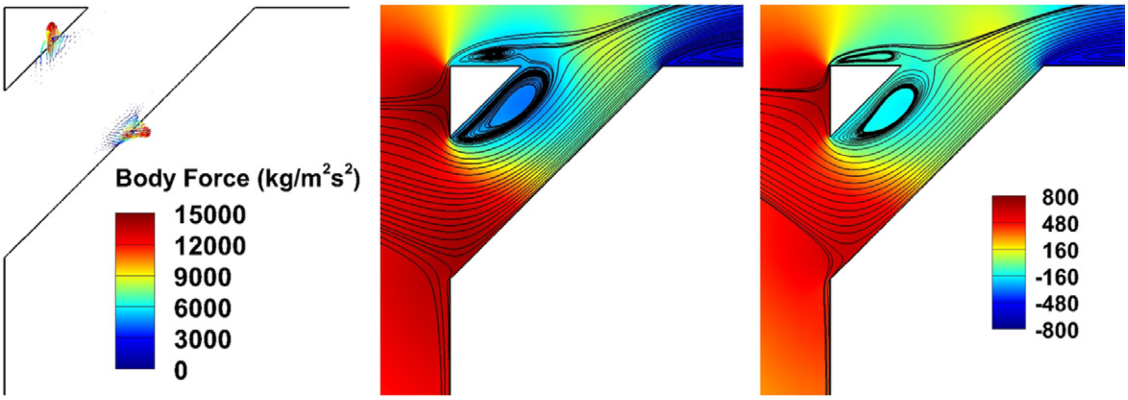

Figure 4. Time averaged static gauge pressure contour (in Pa) at centre z-plane: (a) plasma body force, (b) case II (middle), (c) case III (the black lines are surface velocity streamlines).

Figure 1(d) shows the linear plasma actuators placed inside the channel with the arrows representing the force direction. The actuator force has no variation along the spanwise direction. The body force distribution given in equations (1) and (2) is obtained using the first principles model simulation presented by Singh and Roy [5].

$$f_x = \frac{F_{x_0}}{\sqrt{F_{x_0}^2 + F_{y_0}^2}} \exp\left\{ -\left[\frac{(x-x_0)-(y-y_0)}{y-y_0+y_b} \right]^2 - \beta_x (y-y_0)^2 \right\} \quad (1)$$

$$f_y = \frac{F_{y_0}}{\sqrt{F_{x_0}^2 + F_{y_0}^2}} \exp\left\{ -\left[\frac{(x-x_0)}{y-y_0+y_b} \right]^2 - \beta_y (y-y_0)^2 \right\}, \quad (2)$$

where $F_{x_0} = 2.6$, $F_{y_0} = 2.0$, $\beta_x = 7.2 \times 10^4$, $\beta_y = 9 \times 10^5$ and $y_b = 0.00333$. x_0 and y_0 are the location of electrodes.

The domain consists of 1008 000 structured non uniform elements with a minimum y^+ of 10^{-2}. Mesh resolution study for the cavity is performed using a coarse mesh (1008 000 elements) and a fine mesh (2004 000 elements) and the coarse mesh is sufficient enough to resolve the flowfield, for which the acoustic data does not change significantly. The meshing of the channel is done using unstructured mesh which contains quadrilateral as well as triangular elements. A total of 100 000 elements is adjusted in the channel.

The numerical simulation is performed in Ansys Fluent® 14.5 using the large eddy simulation (LES) with Smagorinsky-Lilly model as the sub-grid scale model. The freestream conditions are for Mach 0.3 at a temperature of 225 K and ambient pressure of 24.95 kPa. No slip and adiabatic conditions are applied to the cavity walls. The side faces have periodic boundary conditions. Farfield conditions are used for the top boundary and the outflow is kept as non-reflecting pressure outlet. The acoustic part is solved using the Ffowcs Williams and Hawkings model [6]. All simulations are run until the sound pressure levels stop changing. The next section will discuss all the results obtained for the flow field and the acoustic data for the cavity.

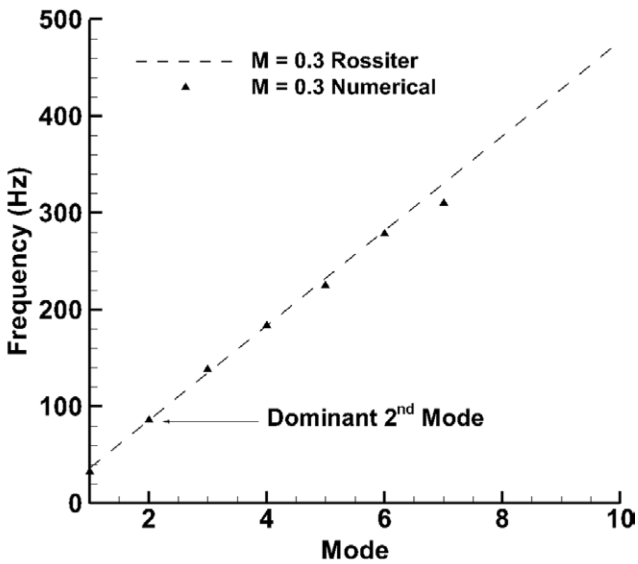

Figure 5. Comparison of different modes with Rossiter modes.

We have conducted the flow simulation and acoustic analysis for the baseline (case I), trailing edge channel (case II) and trailing edge channel with DBD actuator (case III). Since Fluent has been previously validated as a flow code for open rectangular cavities [7], no new validation results are presented for the flow field.

To understand the effect of the channel and the plasma actuated channel, we look into the root mean square pressure. Figure 2 shows the RMS pressure on a plane 0.264 m above the cavity floor. The addition of a trailing edge channel reduces the RMS pressure and inserting plasma actuators inside the channel further reduces it. This is due to the passage of fluid from the high pressure region before the trailing edge to the low pressure region after the trailing edge, which in turn suppresses the pressure fluctuations. Adding plasma actuator enhances this flow and creates the additional reduction.

To get a better understanding of the pressure fluctuations in the cavity, we examine the RMS pressure at the centre z-plane as depicted in figure 3. The reduction of the pressure oscillations close to the trailing edge reduces the pressure fluctuations

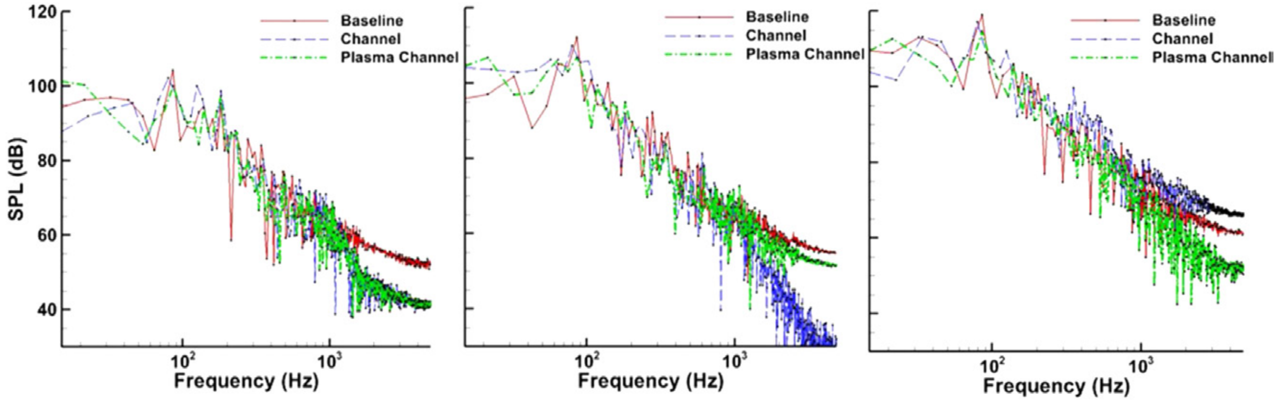

Figure 6. Sound pressure levels for $M = 0.3$: (*a*) receiver 1 (left), (*b*) receiver 2, (*c*) receiver 3.

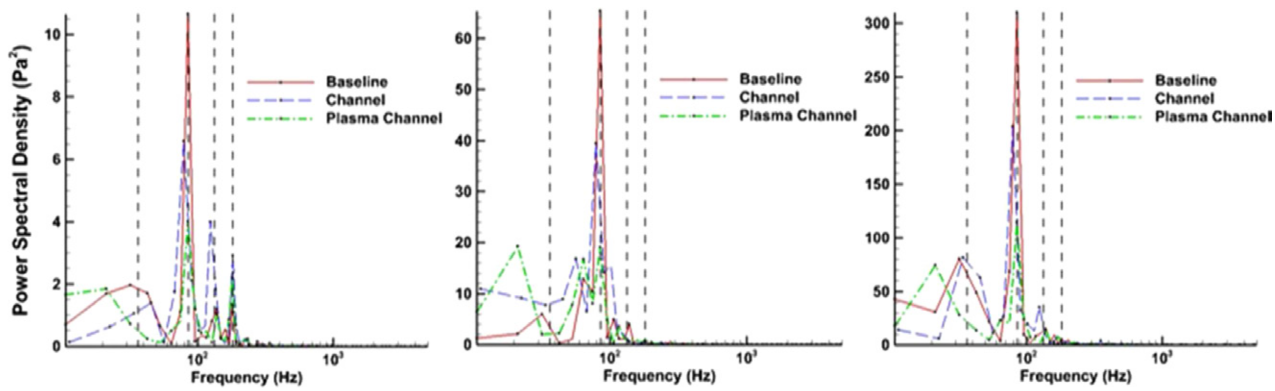

Figure 7. Power spectral density for $M = 0.3$: (*a*) receiver 1 (left), (*b*) receiver 2, (*c*) receiver 3. (Dashed vertical lines depict the Rossiter modes.)

near the cavity floor and the leading edge. Addition of actuators inside the channel increases the mean pressure inside the recirculation zone as depicted in figure 4. This increase in pressure is balanced by the decrease in pressure before the trailing edge which implies enhanced mixing. The applied body force generates a wall jet of $5\,\mathrm{m\,s^{-1}}$ in quiescent conditions inside the channel which is reasonable considering recently reported experiments of plasma channel flows [8, 9]. This strongly suggests that only a small momentum is required to alter the pressure in the channel. The total (viscous and pressure) drag coefficient for the case I is 0.0272, for case II is 0.0077 and for case III is 0.0033 which indicates that the geometric modification and plasma actuated channel reduces the net drag forces by over 350% and over 800%, respectively.

To validate the acoustic data of our simulation, the frequencies of different modes are compared to the resonant Rossiter frequencies [1] f_n.

$$f_n = \frac{U_\infty}{L}\frac{n-\phi}{\{1+[(\gamma-1)/2]M_\infty^2\}^{-\frac{1}{2}}+\frac{1}{K}}. \qquad (3)$$

In equation (3), different integer mode numbers are given by n, L is the streamwise cavity length, U_∞ and M_∞ are the freestream velocity and Mach number, f_n is the Rossiter frequency, ϕ is the phase lag between the downstream travelling Kelvin–Helmholtz instabilities and the upstream travelling acoustic waves and k denotes the ratio of convective speed of the shear layer instabilities and the freestream velocity. The values of $\phi = 0.25$ and $k = 0.66$ are used to calculate the frequencies. The comparison, depicted in figure 5, validates that most of the modes are captured with excellent accuracy.

The sound pressure level spectrum (reference $20\,\mu$Pa) depicted in figures 6 shows that introducing the channel suppresses the sound pressure level for a wide range of frequencies. However, the maximum suppression varies from 2 dB up to 10 dB depending on the receiver location and the mode. The best reduction is seen at receiver 3. Introducing actuators inside the channel gives further reduction in the sound pressure levels by 2 to 5 dB.

Figure 7 shows the power spectral density. The different modes are easy to discern in this figure. We can see that the addition of channel creates peaking at higher modes ($n>2$). These modes have been suppressed with the application of plasma actuator. The channel geometry with the plasma actuator has reduced the power spectral density to 1/3rd its value for the dominant second mode.

The main factor which leads to the suppression in sound pressure levels is the redistribution of high pressure region and low pressure region around the trailing edge. When a channel connects these two regions, the air flows from the high pressure to the low pressure region and reduces the pressure differential and the amplitude of pressure oscillation which directly affects the sound pressure levels. Since the flow through the channel is restricted by the recirculation bubble formed as shown in figure 4, the DBD actuators placed inside the channel removes/reduces that bubble by pulling more air from the high pressure region, allowing further reduction of the pressure oscillation. Concerning noise generated by the plasma actuators in the channel, Baird *et al* [10] showed that sound generated from plasma actuators is dominant in the first (same as the frequency of the input signal) and second mode. However, the power spectral density is two orders of magnitude lower than the power spectral density for the cavity. Thus, effect of plasma noise on the cavity tones is negligible.

In summary, introduction of a passive receptive channel placed at the trailing edge shows an appreciable effect on the acoustic tones in the cavity. The channel is found to reduce the pressure oscillations considerably. A suppression of 7 dB is obtained close to the trailing edge of the cavity using the plasma actuated channel. Frequencies higher than 1 kHz show 5 to 15 dB reduction. The power spectral density for the dominant mode is suppressed by 66% at all the receiver locations. These encouraging trends underscore a need for extending this study in the transonic and supersonic regime, where the effect of channel geometry should be significant. Investigating the effect of geometric modifications like angle of the channel and channel cross-section will give the optimal design for this passive receptive control technique. The use of the channel along with other passive or active devices should also be investigated to get better suppression of acoustic tones. Conducting experiments for this new passive receptive channel will give useful insights and help in validating our predictions.

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