Cavity Flow Control by High Frequency Forcing

Mariano Martinez, Lukas Vesely, Christian Haigermoser, Michele Onorato

Dipartimento di Ingegneria Aeronautica e Spaziale, Politecnico di Torino, Italy
E-mail: *mariano.martinez@polito.it, lukas.vesely@polito.it,*
christian.haigermoser@polito.it, michele.onorato@polito.it

Keywords: Cavity flows, flow control, rod in crossflow.

SUMMARY. It has been shown that high frequency external excitation can lead to the suppression of the cavity flow resonance. However, there is a lack of clear understanding of the physics driving the suppression mechanism. In the present paper results from PIV measurements are presented in the case of external forcing represented by the disturbances induced by the Von Karman vortices emitted by a cylindrical rod, positioned transversally, at the cavity leading edge. The effectiveness of this control strategy is demonstrated for the geometry and the flow conditions of the present experiment.

In order to give a contribution to the understanding of the involved mechanisms in the suppression of the cavity flow resonance by high frequency forcing, velocity frequency spectra along the cavity mouth are shown and discussed. It is suggested that the cavity flow resonance suppression is a result of the fact that the high frequency forcing influences the shear layer towards a condition of less instability.

1 INTRODUCTION

Open cavities are present in a number of transport systems, including aircraft landing gear wheel wells, car sun roofs and the gap between train wagons. Their common feature is to be characterized by highly unsteady flows, leading to dynamical load increase and aero-acoustic sound emission.

A significant contribution to explain the unsteadiness of flows over rectangular cavities, leading to resonance phenomena, was given by Rossiter [1]. He identified an acoustic feedback mechanism for certain cavities and flow regimes. This feedback mechanism can be described as follows: A vortex is shed from the cavity leading edge and is convected downstream until it impinges onto the forward facing step, causing an acoustic pressure wave, which travels upstream and triggers Kelvin-Helmholtz instabilities in the shear layer, leading to the shedding of a new vortex. Rossiter developed an empirical formula to predict the resulting self-sustained oscillation frequencies, which is based on previous studies on edge tones (e.g. Powell [2, 3]):

$$St = \frac{fL}{U_e} = \frac{n-a}{M+\frac{1}{k}}$$

Where St is the Strouhal number, f is the frequency, L is the cavity length, U_e is the free-stream velocity, n is the integer mode number, M is the Mach number, k and a are respectively the average convection speed of the vortical disturbances in the shear layer and a phase delay. Typically $1/k = 1.75$ and a = 0.25.The Rossiter model and its further developments (see

Rockwell and Naudascher [4]) predict hence the dominant frequencies of the cavity acoustic feedback mechanism, when the flow is in the shear layer regime.

The problem of suppressing Rossiter flow oscillations over open cavities has generated in the years significant interest, and many flow control strategies, both active and passive, have been tested. An exhaustive review can be found in the paper of Roweley and Williams [5]. A control method must operate in disrupting any one of the events in the feedback loop described by Rossiter. The traditional methods are to use devises empirically designed that are passive in nature and consequently unable to adjust to changing operating conditions. To overcome this disadvantage, active control techniques have been developed, either open-loop or closed-loop devises, that have the potential to provide reliable control over a wide range of operating conditions. However, it must be expected that such active control methods, particularly the much more efficient closed-loop devices, imply much higher complexity and costs with respect to simple passive control methods. Recently, interest has been aroused in a new technique involving high frequency external forcing, that seems to combine the best aspects of passive and active control, namely simple design geometry and wide operating range of effectiveness respectively [6].

It has been shown in a number of previous experiments that exciting the shear layer developing from the cavity leading edge with a forcing frequency, being at least one order of magnitude higher than the most dominant instability frequency present in the baseline flow, the Rossiter resonating feedback loop may be completely suppressed [6]. However despite all reported results, documenting the effectiveness of the high frequency forcing method, there is still a lack of clear understanding of the physics leading to the suppression mechanism [5, 6, 7, 8]. Most of the published results refer to experiments performed forcing the cavity shear layer by the Von Karman vortices shaded from a rod in crossflow placed in the boundary layer at the cavity leading edge. Early results are mentioned and discussed in the review paper of Cattafesta et al. [9]. McGrath and Shaw [10] were the first to show the effectiveness of this technique in producing substantial reductions of both the acoustic tones and the broadband sound level emitted by a cavity, over a wide Reynolds number range. They attributed the potential mechanism to the interaction of the shed vortices by the actuator with the cavity shear layer instabilities. Later, Shaw [11] testing various cylinder diameter at a fixed height found that the suppression improved as the cylinder diameter was increased. He discussed also another potential mechanism due to reduced cavity shear layer growth rates as a consequence of the bounder layer thickening. Various aspects of the cylindrical road in crossflow were investigated by Stanek et al. [12]. They found that an optimal size of the cylinder diameter is equal to 2/3 the boundary layer thickness and they argued that their results demonstrate that the suppression mechanism was positively due to the high frequency rod shedding. A possible different mechanism is mentioned in the review paper of Cattafesta et al. [9], according to which (see ref. [13] and[14]) the cylinder lifts the cavity shear layer and causes the impingement region to be altered, affecting the acoustic strength source.

In the more recent review paper of Rowley and Williams [5] it is concluded that, after a number of paper on the subject, in 2006, the mechanisms for tone suppression and also broadband spectrum reduction by high-frequency actuation are still unclear, in particular a main question is whether the suppression mechanism results from unsteady (high frequency) effects, or through modifications to the mean flow. Very recently, a rather different and possible mechanism responsible for stabilizing a turbulent free shear layer by high frequency forcing is claimed by Stanek and al. [15]. As a result of a numerical study undertaken to investigate the effect of frequency of pulsed mass injection on the nature of stabilization and acoustic suppression they demonstrate the critical role of the spanwise instability to the success of the high frequency control. Their numerical simulation support the evidence that the pair of initially spanwise coherent vertical structure, emitted by pulsating jets or by a rod in crossflow, interacts and produces a violent spanwise breakdown. This process of breakdown pushes the vorticity in the direction of more random flow organization, which is responsible for the observed stabilization. Finally, on the basis of experimental measurements in the shear layer and linear stability calculations based on the experimental data, a model to explain cavity resonant acoustics suppression using high frequency excitation has been proposed by Panickar and Raman [16]. According to this model the introduced high frequency excitation into the shear layer has to be high enough to lie outside the envelope of amplified instabilities and such that a dominant part of the energy of the excited flow is contained within this frequency. This spanwise coherent, high frequency excitation, introduced at the upstream edge of the cavity, consequently, decays rapidly as it is convected downstream along the shear layer.

The object of the present measurements was to collect time and space resolved PIV data to contribute to the understanding of the mechanisms through which a circular rod, spanwise positioned at the cavity leading edge, provide the complete suppression of the Rossiter resonating feedback loop and consequently of the emitted acoustic tone. The cylinder diameter was selected in order to insure a frequency of the Von Karman vortex shedding from the cylinder one order of magnitude higher than the expected Rossiter resonance frequency.

2 EXPERIMENTAL SETUP

Planar PIV time-resolved experiments were carried out in a water tunnel, 350x350 mm^2 test section, at the Politecnico di Torino. Fig.1 shows the cavity model in the tunnel test section. The cavity depth was 10 mm, the cavity length-to-depth ratio was L/H=3. The incoming boundary layer was laminar. The experimental conditions for the baseline (non-controlled) cavity flow are listed in Table1. The ratio L/θ was 49, which is below the $L/\theta > 80$ threshold for the onset of self-sustained cavity oscillations, as determined by Gharib and Roshko [7]. θ is the momentum thickness of the boundary layer at the cavity leading edge. Despite this low L/θ ratio, self-sustained oscillations developed in the present cavity flow.

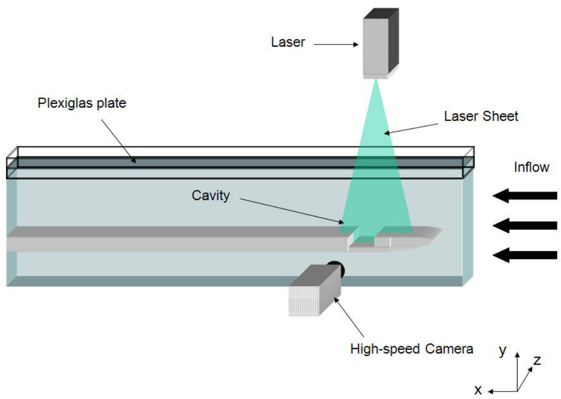

Figure 1: Experimental setup

The controlled flow experiments were carried out at similar flow conditions. The cavity upstream, external, flow velocity was Ue=0.31m/s and Re_L=9300. The cylindrical transverse rod was positioned just upstream the cavity, at the external edge of the boundary layer. The road diameter was 0.6mm. The vortex shedding frequency from the rod was one order of magnitude higher than the frequency predicted by the Rossiter formula for the baseline flow.

L/H	*Ue*[m/s]	Re_L	L/θ	*δ/H*
3	0.26	7800	49	0.2

Table 1

PIV measurements were taken in the streamwise planes normal to the cavity floor, at the cavity mid-span. The field of view covered the whole cavity and the complete shear layerer up to the region of undisturbed external flow.

The PIV setup consisted of Spectra-Physics continuous Argon-Ion laser, with a maximum emitted beam power of 6 Watts, illuminating the measurement plane with a laser light sheet 1 mm thick. The flow was seeded with hollow glass spheres with a nominal diameter of 10 µm. The PIV images were acquired using a Dantec MK III CMOS camera with a resolution of 1280x1024 pixels and a maximum recording rate at full resolution of 1000 fps, which was the acquisition rate used in the time resolved measurements. The particle image size was approximately 3 pixels.

Two successive images were cross-correlated to obtain the velocity field using a multigrid algorithm provided by the DAVIS 7.2 software from LaVision, with an initial interrogation window size of 128x128 pixels and a final interrogation window size of 32 x32 pixels, with a 50% overlap, applying sub-pixel refinement and window deformation. One vector corresponds to the velocity in a spatial area of 0.8 x0.8 mm^2.

Statistically uncorrelated measurements were also carried out, recording only every 100th and 101st image, thus an effective acquisition rate of 10Hz was performed. The total number of acquired image pairs for the statistical analysis was 3000.

3 RESULTS AND COMMENTS

In Figs. 2(a) and 2(b) the streamlines of the mean velocity field and a color plot of the normalized velocity modulus are reported, respectively for the baseline and the controlled flows. Both flows indicate the presence of a large recirculation zone in the downstream part of the cavity and a counter-rotating smaller one in the upstream part. No appreciable differences in the mean flow configuration are evident between the baseline and the controlled flows.

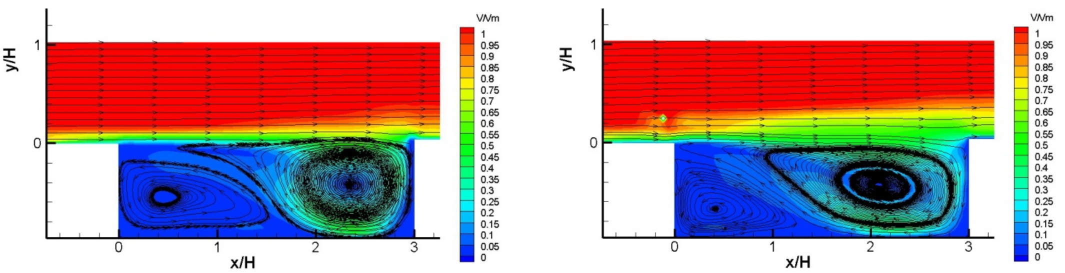

Figure 2: Mean velocity streamlines and color plot of the mean velocity modulus; (a) baseline flow, (b) controlled flow.

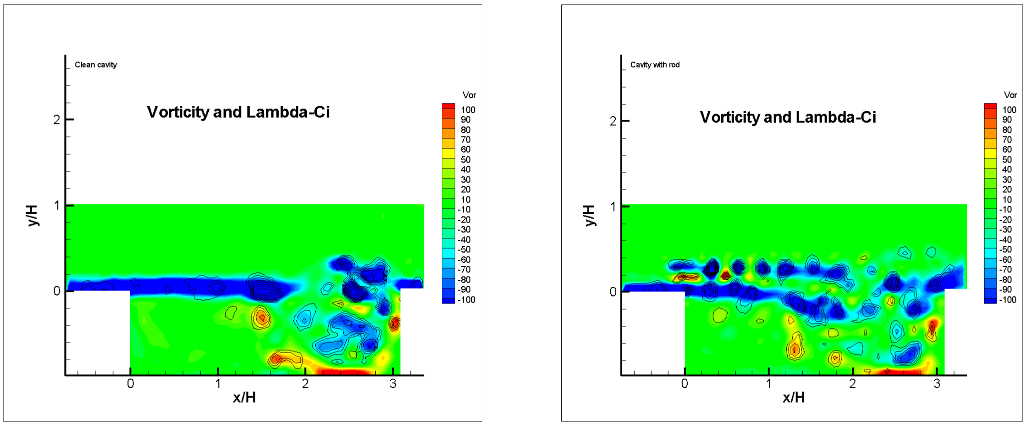

Figure 3: Instantaneous spanwise vorticity (color plot) and λci isolines; (left) baseline flow, (right) controlled flow.

Samples of snapshots showing the instantaneous spanwise vorticity and isolines of swirling strength λci are shown in Figs. 3(a) and 3(b), respectively for the baseline and the controlled flows. The color levels represent the magnitude of the spanwise vorticity and the isolines highlight vortices in the flow, identified by the λci criterion, where λci is the swirling strength as introduced by Zhou et al. [16]. Fig. 3(a) shows regular spacing of identified periodic vortices in the shear layer, growing downstream due to Kelvin-Helmholtz instability. Some of the vortices shed inside the shear layer impinge onto the forward facing step and it is nearly always seen that during the impingement they are divided and one part passes over the cavity trailing edge and the other part enters into the cavity. Some of the vortices overpass the cavity and some of them are entrained in the downstream recirculating zone. Fig. 3(b) and the sequence of similar snapshots evidence the Von Karman wake downstream the transversal rod and show the shear layer vortices travelling at a frequency much higher than the vortices in the baseline flow. Moreover, from Fig. 3(b) and similar snapshots it can be seen that in the case of the controlled flow, in the upstream part of the cavity mouth, the shear layer vortices are produced at a frequency equal to the Von Karman cylinder wake frequency and more downstream they appear to be weakened and to show a less spacing organization.

This different behavior is highlighted in the following Fig. 4, showing the frequency spectra of the wall normal component of the velocity, along the cavity mouth.

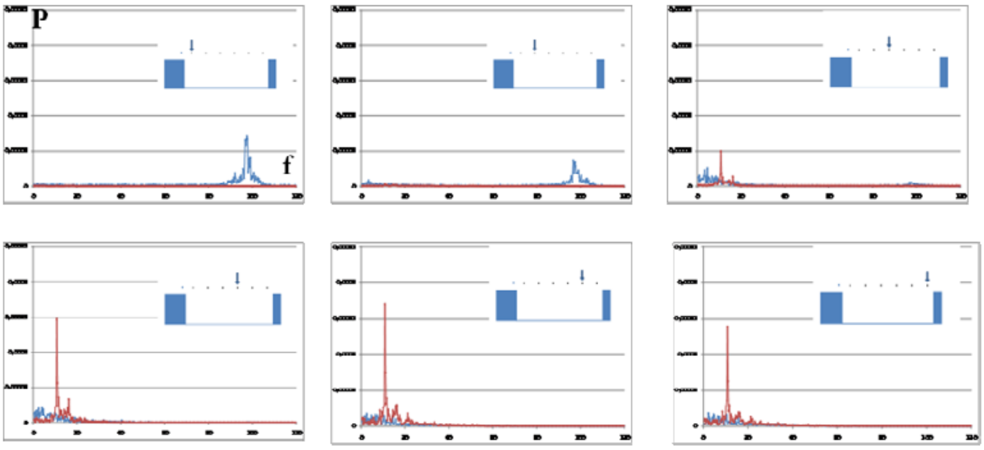

Figure 4: Spectra of the wall normal velocity component along the cavity mouth at different distances from the leading edge; red color: baseline flow, blue color: controlled flow.

The arrow in each diagram shows the reference position where the spectra were computed. In the case of the baseline flow (red color diagrams), very near the leading edge the spectrum shows a broadband nature. A peak appears in the central part of the cavity and grows in the downstream positions. This peak appears at a frequency of about 10 Hz and at a Strouhal number, based on the cavity length, St_L=1. This value corresponds to the second frequency mode predicted by the Rossiter formula. Also the third and forth Rossiter frequency modes are visible in the spectra, at much lower amplitude. From the time resolved results and the shown spectra, the self-sustained feedback loop described by Rossiter clearly takes place, leading to acoustic resonance and high amplitude tones at a well-defined frequency. This mechanism appears to be completely suppressed in the controlled flow, where (see blue color diagrams) a relatively low amplitude frequency peak is visible near the cavity leading edge and disappears going downstream. The observed low amplitude peak near the leading edge appears at a frequency of about 100 Hz, corresponding to a Strouhal number St_L=10. This is the expected Von Karman frequency of the emitted vortices from the cylindrical rod.

The scenario appearing in the case of the controlled flow is that the Kelvin-Helmholtz shear layer flow instability, leading to vortex shedding along the cavity mouth, still takes place, but not at the frequency predicted by Rossiter, but at the much higher frequency corresponding to the frequency of the Von Karman vortex shedding from the cylinder. The forcing leading to the Kelvin-Helmholtz shear layer instability in the case of the controlled flow appears to be the disturbance produced by the emitted structures from the rod and not the feedback Rossiter acoustic mechanisms. Moreover, the simple observation of the time resolved PIV images shows that the structures generated very near the leading edge in the case of the controlled flow are weakened going downstream. This suggests that the high frequency excitation introduced by the Von Karman wake at the upstream edge of the cavity decays as it is convected downstream along the shear layer. Speculatively this can be due to the fact that the shear layer appears to be much less unstable in the case of the controlled flow at the much higher frequency driven the Kelvin Helmholtz instability.

4 CONCLUSIONS

PIV results have shown the effectiveness of high frequency forcing in controlling Rossiter acoustic resonance in the cavity flow tested in the present experiment. The forcing to control the flow was the disturbance produced by the Von Karman wake downstream a rod in crossflow, at the cavity leading edge. Velocity spectra in the shear layer demonstrate the complete suppression of the Rossiter acoustic tone present in the baseline flow at the frequency of St_L=1.

The simple observation of the sequence of the PIV images shows that vortical instabilities are still present near the cavity leading edge of the controlled flow, but they are driven at a frequency corresponding to the Von Karman vortex shedding from the cylinder, being one order of magnitude higher than the Rossiter frequency. Moreover, this vortical instability generated near the leading edge, characterized by this high frequency, is seen to decay going downstream.

It has speculatively suggested that the physical mechanism leading to eliminate the growth of the vortical instabilities in the shear layer is that in the case of the controlled flow the characteristics frequency lies outside the range of the shear layer more unstable frequencies.

Future development of this work will concentrate on comparison of experimental measurements, like the one here shown, with results predicted by linear stability theory.

References

[1] Rossiter, J. E. (1964) *Wind-tunnel experiments on the flow over rectangular cavities at subsonic and transonic speeds*, Aeronautical Research Council Reports and Memoranda, No. 3438.

[2] Powell A. (1953) *On edge tones and associated phenomena*, Acustica, 3:233–243.

[3] Powell A. (1961) *On the edge tone*, J. Acoust. Soc. Amer., 33:395–409.

[4] Rockwell D. and Naudasher E. (1978) *Review–self-sustaining oscillations of flow past cavities*, J. Fluid Eng., 100:152–165.

[5] Rowley C. W. and Williams D. R. (2006) *Dynamics and control of high Reynolds number flow over open cavities*, Annual Review of Fluid mechanics, 38:251-276.

[6] Panickar P. and Raman G. (2008) *Cavity resonance suppression using high frequency excitation: The mystery of the cylinder-in-crossflow revisited*, 29th American Institute of Aeronautics and Astronautics Aeroacoustics Conference. British Columbia, Canada.

[7] Panickar P. and Raman G. (2008) *Understanding the mechanism of cavity resonance suppression using a cylindrical rod in crossflow*, American Institute of Aeronautics and Astronautics Paper AIAA 2008-54.

[8] Stanek M.J., Visbal M.R., Rizzetrta D.P., Rubin S.G., Khosla P.K. (2007) *On a mechanism of stabilizing turbulent free shear layers in cavity flows,* Computers and Fluids 36:1621-1637.

[9] Cattafesta L.N., Williams D.R., Rowley C.W., Alvi F.S. (2003) Review of active control of flow-induced cavity resonance, American Institute of Aeronautics and Astronautics Paper AIAA 2003-3567.

[10] McGrath S.F., Shaw L.L. (1996) *Active control of shallow cavity acoustic resonance*, American Institute of Aeronautics and Astronautics Paper AIAA 96-1949.

[11] Shaw L.L. (1998) *Active control for cavity acoustics*, American Institute of Aeronautics and Astronautics Paper AIAA 98-2347.

[12] Stanek M.J., Raman G., Ross J.A., Odedra J., Peto J., Alvi F., Kibens V. (2003) *High frequency acoustic suppression: The mystery of the rod-in-crossflow revealed*, American Institute of Aeronautics and Astronautics Paper AIAA 2003-0007.

[13] Ukeiley L.S., Ponton M.K., Sener J.s., Jansen B. (2002) Suppression of pressure loads in cavity flows, American Institute of Aeronautics and Astronautics Paper AIAA 2002-0661.

[14] Arunajatesan S., Shipman J.D., Sinha N. (2003) *Mechanisms in high frequency control of cavity flows*, American Institute of Aeronautics and Astronautics Paper AIAA 2003-0005.

[15] Stanek M.J., Visbal M.R., Rizzetta D.P., Rubin S.G., Khosla P.K. (2007) *On a mechanism of stabilizing turbulent free shear layers in cavity flows*, Computer and fluids 36: 1621-1637.

[16] Zhou J., Adrian R. J. (1999) S. Balachandar, T. M. Kendall *Mechanisms for generating coherent packets of hairpin vortices in channel flow*. J. Fluid Mech., 387:353-396.