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Computational and Experimental Investigation of Supersonic Flow and their Controls

Vasana M. Don, Eldad J. Avital, and Fariborz Motallebi

Abstract**—**Supersonic open and closed cavity flows are investigated experimentally and computationally. Free stream Mach number of two is set. Schlieren imaging is used to visualise the flow behaviour showing stark differences between open and closed. Computational Fluid Dynamics (CFD) is used to simulate open cavity of flow with aspect ratio of 4. A rear wall treatment is implemented in order to pursue a simple passive control approach.

Good qualitative agreement is achieved between the experimental flow visualisation and the CFD in terms of the expansion-shock waves system. The cavity oscillations are shown to be dominated by the first and third Rossister modes combining to high fluctuations of non-linear nature above the cavity rear edge. A simple rear wall treatment in terms of a hole shows mixed effect on the flow oscillations, RMS contours, and time history density fluctuations are given and analysed.

Keywords**—**Supersonic, Schlieren, open-cavity, flow simulation, passive control.

I. INTRODUCTION

INVESTIGATION of high speed cavity flow has received considerable interest over the years due its implications in aeronautical applications such as airborne weapon bays, landing gear and cargo bay openings. Studies in this topic have also been carried out because similar flow behaviour has also been noticed to occur at inlets and nozzles of high speed jet engines and in gas turbine blade tips, where the leakage flow through the gap between the blade and the engine wall can be reduced by a careful cavity design.

The theory of the flow oscillations in cavities has been subject to considerable research since the fifties [1, 2, 3]. Most of the research focused on low speed application but in the last two decades interest in high speed application has increased. These oscillations can lead to an increase in the drag and noise generation. The latter can reach sound pressure levels as high of 150 dB or higher [4]. All together these flow oscillations and associated noise can damage the structural integrity of the vehicle through vibration and acoustic fatigue. Furthermore the aircraft noise signature can also increase significantly [3].

Vasana M. Don from School of Engineering and Material Sciences (SEMS) of Queen Mary University of London, Mile End Road, London, E1 4NS (e-mail: v.m.don@qmul.ac.uk).

Eldad Avital from School of Engineering and Material Sciences (SEMS) of Queen Mary University of London, Mile End Road, London, E1 4NS (e-mail: e.avital@qmul.ac.uk).

Fariborz Motallebi from School of Engineering and Material Sciences (SEMS) of Queen Mary University of London, Mile End Road, London, E1 4NS (e-mail: f.motallebi@qmul.ac.uk).T. C. Author is with the Electrical Engineering Department, University of Colorado, Boulder, CO 80309 USA, on leave from the National Research Institute for Metals, Tsukuba, Japan (e-mail: author@nrim.go.jp).

The flow oscillations are caused by a feedback loop between the cavity's front and rear walls. The shear layer hitting the rear wall causes a sound wave to be generated and propagate upstream towards the front wall. At certain frequencies that sound wave will cause hydrodynamic instability in the shear layer near the front wall, which in turn will cause the shear layer to flap more and intensify the sound wave propagating upstream [3]. Such feedback mechanism exists in open cavities, i.e. the shear layer bridges over the cavity and does not touch the cavity's floor, see Fig. 1. Commonly such conditions happen for cavities of aspect ratios of length to depth of $2<L/D<8$ depending on the flow conditions [5]. Closed cavities occur at ratios of $L/D>11$ where the shear layer touches the cavity floor and the feedback loop between the two walls is disrupted, see Fig. 2. Transitional cavities occur at the intermediate aspects ratios between the open and closed cavities, where the shear layer sometimes touches the cavity floor.

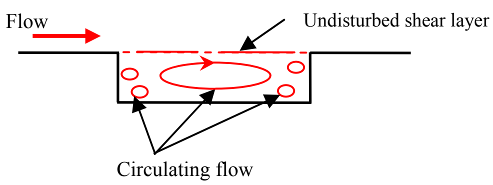

Fig. 1 Illustration of an open-cavity

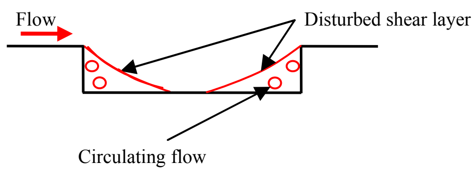

Fig. 2 Illustration of a closed-cavity

At low speed the acoustic wave can propagate within and outside of the cavity. Suponitsky *et al.* [6] showed it causes an absolute instability mechanism in the shear layer which was called the 'shear mode' for 3D flow fluctuations [7]. At supersonic speed the upstream propagating acoustic wave is limited to the shear layer and within the cavity, nevertheless intense flow oscillations were observed experimentally and computationally [8, 9, 10].

Estimate of the frequencies of the shear layer oscillations can be pursued by the semi-empirical formula of Rossister, which was later modified to include transonic and supersonic incoming Mach numbers [8], yielding,

$$St_m = \frac{f_m L}{U_\infty} = \frac{m-\alpha}{\dfrac{M_\infty}{\sqrt{1+\dfrac{\gamma-1}{2}M_\infty}}+\dfrac{1}{\kappa}} \quad (1)$$

St stands for the Strouhal number, f for the frequency, U∞ for the free stream velocity, M∞ for the free stream Mach number and γ is the heat capacity ratio. The empirical constants of α and k are 0.25 and 0.57 respectively. m is the mode number. This approximation was found to yield reasonable accuracy when compared with experiments and flow simulations [6, 8, 11, 12].

Suppression of cavity flow-induced oscillations is of great interest. Supontisky *et al*. [6] applied a simple open loop active control approach for a simulated low speed open cavity. Steady fluidic injection into cavity was achieved through the front cavity wall and steady fluidic suction through the rear cavity wall. It was shown that at sufficient levels of fluidic flow flux, the instability mechanism of the shear layer changed from absolute to convective, reducing significantly the shear layer oscillations. Open loop control was also applied for supersonic cavities [9] where closed loop control was also assessed.

Passive control is also of significant interest as it offers simplicity and reduced burden of maintenance. Various ideas have been investigated with some success, from front wall treatment of a wire obstacle to treatment of the cavity's floor and a slanted rear wall. In this paper we present a study of a supersonic rectangular cavity using experimental and computational means. The aim is to investigate the underlying physics of this cavity, where the feedback mechanism is restricted to the shear layer and within the cavity and the form of the near field sound field. A simple method of the cavity's rear wall treatment as a passive control method is also assessed.

Next we present the formulation of the problem, results analysis and conclusions.

II. Problem Formulation

A basic rectangular cavity subject to an incoming supersonic flow of Mach number of 2 is considered. A wide range of length to depth, L/D, ratios from open to closed cavity flows is considered in this project, but for this paper we present mainly our results for an open cavity.

The Schlieren experimental technique was used to produce flow visualisation of flow around the cavity. A simple z-type system with parabolic mirrors of a focal length of 2m was used. The cavity was generated by an axisymmetric opening in a circular rod similar to Mohri & Hiller [10], where the length of the cavity was adjustable to yield a range of L/D ratios, 2<L/D<16. The rod was placed in the supersonic wind tunnel of Queen Mary University of London having a work section of about 10 cm over 15 cm.

Computational Fluid Dynamics (CFD) simulations were also pursued using our in-house Large Eddy Simulation (LES) code. This code was already used successfully to simulate high subsonic open cavity flow [11] and supersonic mixing layers [13]. The code is based on a finite difference formulation and rectangular grid. Flux splitting in form of TVD and WENO schemes are used to compute the convective terms, where the Van Leer and Superbee flux splitters are used for the second order TVD computations [14] and a 5th order scheme for the WENO computation. A fourth order central finite difference scheme is used for the diffusion term. The time marching is achieved using a second order Runge Kutta method.

As only 2D computations are pursued in this study, the LES subgrid modelling was not used but instead a small artificial viscosity coefficient in the form of min(Δx,Δy)/Re_av was added to the diffusion term where 50<Re_av<100. Re_av=80 was found to be sufficient to prevent spurious oscillations without damping the flow oscillations. High grid stretching in the stream normal direction y was used to cluster grid points near the shear layer, yielding about 10 to 1 ratio between the grid spacing near the upper edge of the computational domain and in the shear layer area. A hyperbolic sin transformation was used for this purpose providing high grid resolution also inside the cavity and above the shear layer.

A no-slip boundary condition was applied to velocity field at the wall and a viscous boundary condition was applied to the pressure at the wall [14]. The wall was assumed to be adiabatic. As a pressure wave is reflected back from the cavity's rear edge it tends to thicken the incoming boundary layer as it cannot propagate upstream in the supersonic free stream. Thus this can cause an artificial shock wave near the computational domain inflow side if the inflow velocity is prescribed and an abrupt change in the boundary layer thickness occurs near the inflow side. As a result we applied non-reflecting characteristic boundary conditions on the inlet side as well as on the top side and outlet side of the computational domain. In order to enforce an inlet boundary layer profile a buffer zone approach was used near the inlet side of the computational domain. It forced gently the boundary layer profile to the desired one by adding body forces. This reduced considerably any artificial shock wave caused by the inflow condition. A turbulent boundary layer profile was specified.

III. Results & Analysis

Schlieren images are shown in Fig. 3a and b for open and closed cavities of *L*/*D*=4 and *L*/*D*=12, respectively. In both cases the flow goes from left to right. The difference in the flow behaviour is clear. The shear layer bridges the two walls in the open cavity while touching the floor of the closed cavity. As result the open cavity shows an oblique shock wave near its rear edge while the closed cavity shows on its upper side a strong normal shock wave that bends afterwards.

(a) (b)

Fig. 3 Schlieren images for open-cavity of L/D=4 (3a) and closed-cavity of L/D=12 (3b) on the right

Two-dimensional (2D) simulations were carried out for an open cavity of L/D=4 and an incoming boundary layer thickness of 0.05D. A buffer zone in a thickness of 2.8D was added in front of the inlet of the computational domain that had a length of 14D. A grid size of (151, 451) points was used in the x & y directions, respectively. The free stream velocity was normalized to one. The Reynolds number based on the cavity's depth was set to 5000 and the simulation was run until a normalized time of 30 to allow transient structures to leave the computational domain before starting to record the flow time history and accumulating statistics.

The instantaneous density fluctuations are shown in Fig. 4 for time 175 where the flow enters the domain from the left. A system of expansion and shockwaves is seen from Fig. 4. The angle of the oblique shock wave coming from the cavity's rear edge is about 33^0 and is in excellent agreement with the oblique shock wave seen in Fig. 3(a). Interestingly, the buffer zone on the left hand side of the figure did not manage to eliminate completely the compression wave caused by the interaction of the boundary layer with the inlet side of the computational domain, but it managed to reduce and smooth it considerably. Nevertheless the cavity's shear layer shows clear fluctuations that continue behaviour beyond the cavity over the rear rim. This indicates flapping on the shear layer, leading to vortices escaping from the cavity by clipping over its rear edge.

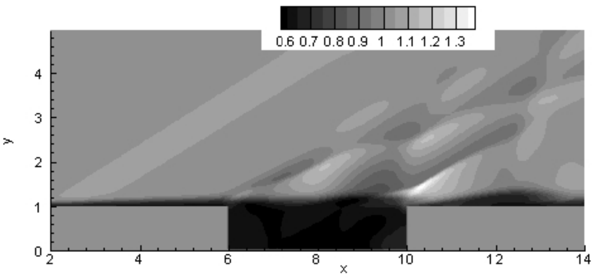

Fig. 4 Instantaneous density fluctuation contours for an open cavity of L/D=4 at time 175. The depth *D* has been normalised to one

As a comparison the same instantaneous density fluctuations are shown in Fig. 5 for a cavity of the same aspect ratio but with a rear wall treatment in a form of a square hole of D/3. The behaviour of the flow is similar to that of the cavity without a rear wall treatment. However, the rear oblique shock wave seems to penetrate deeper into the cavity at that instant of time, while the expansion zones are mildly higher near the front end of the cavity with the rear wall treatment.

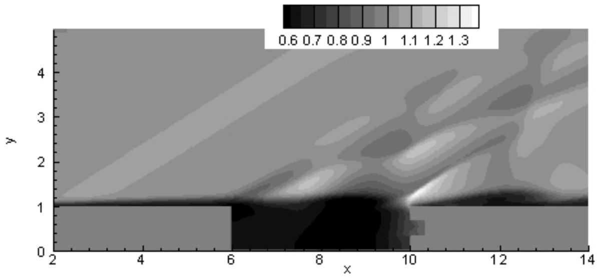

Fig. 5 Instantaneous density fluctuation contours for an open cavity with a rear wall treatment of a square hole of a length of D/3. The rest of the conditions are as in Fig. 4

The corresponding instantaneous vertical structures plotted as contours of the vorticity magnitude are shown in Fig. 6. A large vortex is seen near the cavity's rear wall in both cavities. This is similar to the finding of Suponitsky *et al.* [6] for a low speed open cavity. The hole in the cavity with the rear wall treatment intrudes a secondary vortex inside it, leading to a mild reduction in the vorticity magnitude and size of the primary vortex. Thus it is hoped that as this primary vortex clips over the cavity's rear edge, it will cause less flapping of the shear layer, reducing flow oscillations.

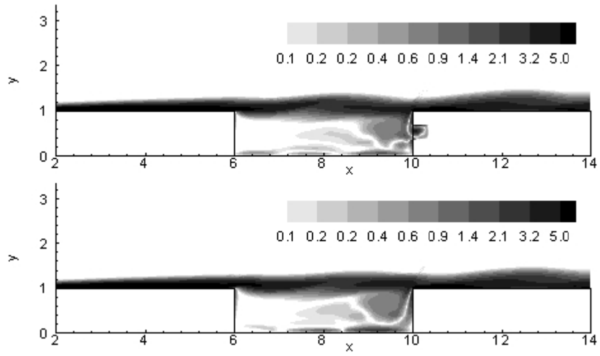

Fig. 6 Instantaneous vorticity magnitude contours for the open cavity without the rear wall treatment (6a – upper) and with the rear wall treatment (6b – lower). The rest of the conditions are as in Fig. 4

All of the contour plot results were obtained using TVD flux limiter of Van Leer.

The flapping of the shear layer can be seen through the contour plots of the streamwise flow flux ρv shown in Fig. 7 for both cavities. The changes in the sign of this term along the shear layer indicate flapping, interestingly the instantaneous flapping looks of higher magnitude for the cavity with the rear wall treatment. For both cavities there is a good correlation between those contours and the contours of the density fluctuations seen in Fig. 4 and Fig. 5.

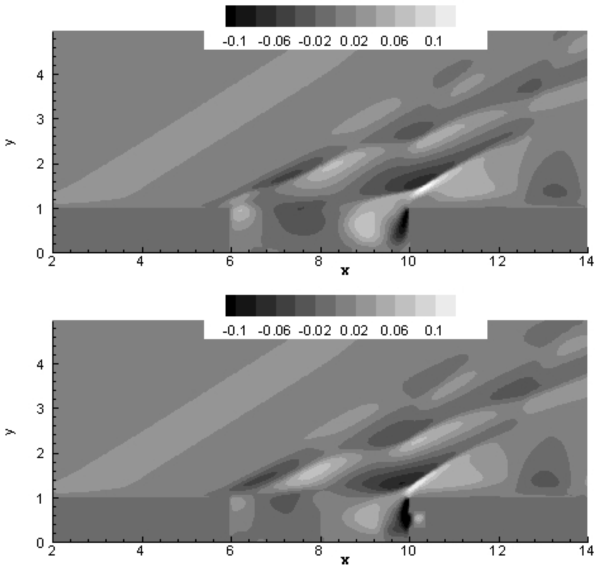

Fig. 7 Instantaneous contours of the stream normal flux of ρv for the open cavity without the rear wall treatment (7a – upper) and with the rear wall treatment (7b – lower). The rest of the conditions are as in Fig. 4

The RMS of the density fluctuations are shown in Fig. 8. Both cavities show high RMS levels around the shear layer that intensifies near the rear edge of the cavity. The latter indicates the high amplitude flapping of the shear layer near the rear edge. There are four rays of high RMS radiating away from the shear layer in an angle similar to the expansion – shock waves system seen in Fig. 7. This indicates a dominance of low mode numbers in the shear layer oscillations. We can also see that the cavity with the rear wall treatment shows mildly lower RMS levels than the cavity with the rear wall treatment.

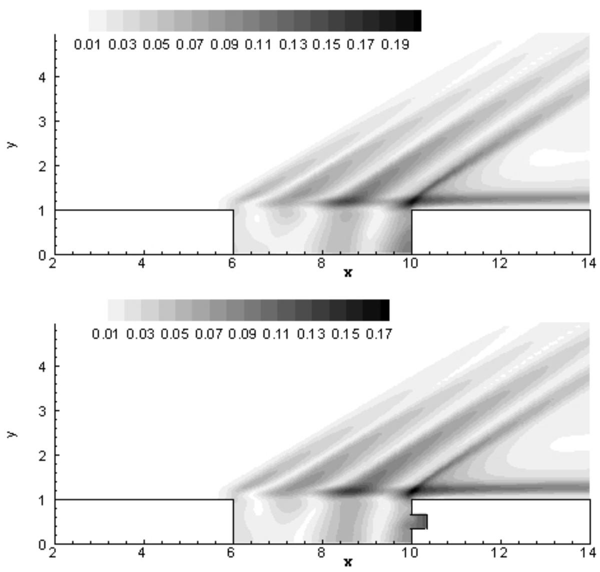

Fig. 8 RMS contours of the density fluctuations for the open cavity without the rear wall treatment (8a) and with the rear wall treatment (8b). The rest of the conditions are as in Fig. 4

The time history of the density fluctuations at the middle of the cavity but 0.5D above its shear layer are shown for both cavities in Fig. 9. Two modes of oscillations are revealed are seen after time 30. The primary oscillation has a time period of a bit less than 5 agreeing well with the time period of the third mode of Rossister mode (1). The other mode has about three times longer time period and thus agreeing fairly with Rossister first mode time period (1). The combination of the two modes leads to a continuous increase in the oscillations until the level saturates around time 150. Also one can see that the density oscillations due to the cavity with the rear wall treatment are mildly higher than those without and thus at this point of space the rear wall treatment actually did not achieve noise suppression. This corresponds to Fig. 7 showing higher density fluctuation at that point for this kind of cavity.

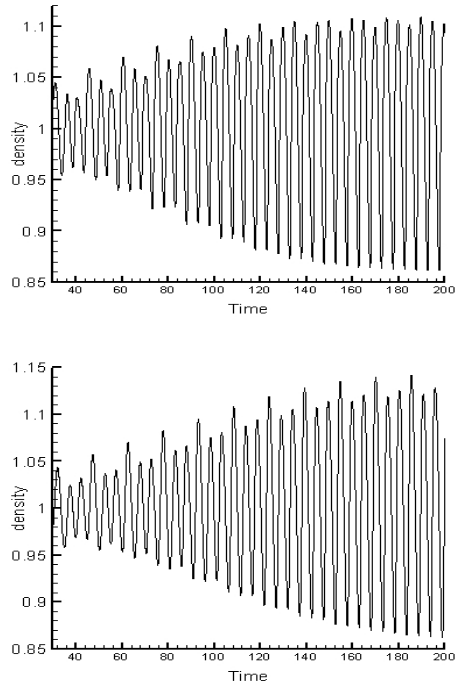

Fig. 9 Density fluctuations at (x,y) = (8,1.5)D for the open cavity without the rear wall treatment (9a) and with the rear wall treatment (9b). The rest of the conditions are as in Fig. 4

A zoom view on the density fluctuations is seen in Fig. 10, showing a nearly linear fluctuations but with slight steepening, indicating mild non-linear activity. On the other hand strong non-linear fluctuations were recorded for above the rear edge of the cavity as seen in Fig. 11. A system of sharp compression followed by shallow expansion waves is seen. This is better illustrated in the zoom view of Fig. 12. This kind of density fluctuations was reported to have crackle-like features in jet noise [15]. However, unlike crackling supersonic jets, the time history here does not show any random process and the high density fluctuations indicate some movement of the shock wave. The cavity with the rear wall treatment shows a much reduced compression wave but an enlarged expansion wave, showing that this simple rear wall treatment has a moderate success in terms of reducing flow oscillations.

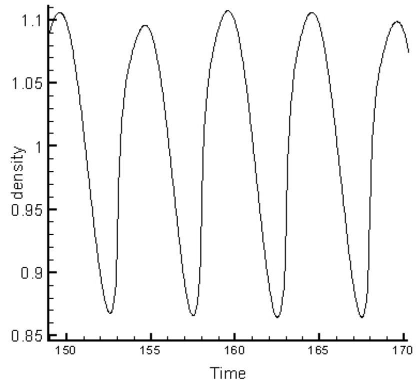

Fig. 10 Zoomed view of the density fluctuations of Fig. 9(a)

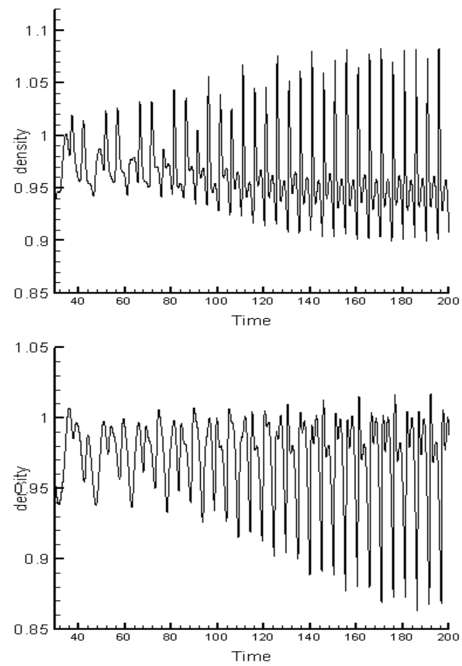

Fig. 11 Density fluctuations at (x,y) = (10,1.5)D for the open cavity without the rear wall treatment (11a) and with the rear wall treatment (11b). The rest of the conditions are as in Fig. 4

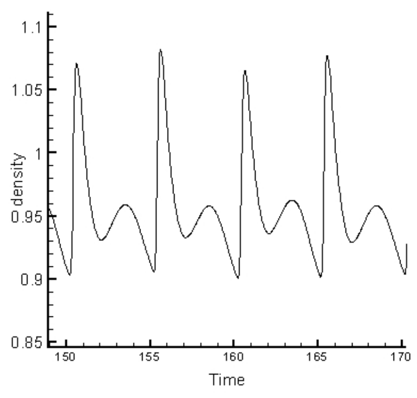

Fig. 12 Zoomed view of the density fluctuations of Fig. 11(a)

IV. Summary

Supersonic open and closed cavities were studied experimentally to show clear pattern of expansion – shock wave system and features of different flow behaviour. CFD simulations have been carried out for two supersonic open cavities one of a box configuration and aspect ratio of L/D=4 and the other with the same configuration but with a rear wall treatment of a small square hole of a length of D/3. All cavities were subject to an incoming free stream Mach number of 2 whether in the wind tunnel or in the computer simulations.

The simulations showed a system of expansion and shock waves around the cavity, having an inclination angle very similar to that found experimentally. Both open cavities showed a large vortex near the rear wall that clips over the rear edge causing the shear layer to flap. However, the rear wall treatment reduced somewhat the size of the vortex. Contours of RMS density indicate the dominance of low mode fluctuations in the shear layer. This was confirmed by the examining the density time history above the cavity. Non-linear fluctuations density were observed, particularly above the rear edge. This was attributed to the strong oblique shock wave emerging from the rear edge. The rear wall treatment showed mixed effect of flow oscillations suppression, reducing mildly the overall density RMS but increasing at some points the flow oscillations and reducing the compression fluctuations above the rear edge on the expense of increasing the expansion fluctuations. The latter showed crackle-like features similar in some sense to features found around supersonic jets.

It is planned to pursue 3D simulations of open cavity flows that will include turbulence development, such effect can alter the flow oscillations and will assist in designing better rear wall treatments.

References

[1] Krishnamurty, K., ‘Acoustic radiation from two-dimensional rectangular cutouts in aerodynamic surfaces’, National Advisory Committee for Aeronautics (N.A.C.A.) Technical Note 3487, 1955.
[2] Tam, C. K. W. and Block, P. J. W., ‘On the Tones and Pressure Oscillations Induced by Flow over Rectangular Cavities’, Journal of Fluid Mechanics, 89: 373-99, 1978.
[3] Rockwell, D. and Naudascher, E., ‘Self-Sustained Oscillations of Impinging Free Shear Layers’, Annual Review of Fluid Mechanics, 11: 67-94, 1979.
[4] Dellprat, N., ‘Rossiters formula- A simple spectral model for a complex amplitude modulation process?’, Physics of Fluids, 18, 7, 2006.
[5] Tracy, M. B., Plentovich, E. B., Chu, J. and Langley Research Centre, ‘Measurements of fluctuating pressure in a rectangular cavity in transonic flow at High Reynolds numbers’, National Aeronautics and Space Administration (NASA) Technical Memorandum 4363, 1992
[6] Suponitsky, V., Avital, E. and Gaster, M., ‘On three-dimensionality and control of incompressible cavity flow’, Physics of Fluid, 17, 104103, 2005.
[7] Rowley, C. W., Colonius, T. and Basu, A. J., ‘On self-sustained oscillations in two-dimensional compressible flow over rectangular cavities. Journal of Fluid Mechanics, 455: 315-346, 2002.
[8] Heller, H. H. And Bliss, D. B., ‘Aerodynamically Induced Pressure Oscillations in Cavities – Physical Mechanisms and Suppression Concepts’, Air Force Flight Dynamics Laboratory Technical Report AFFDL-TR-74-133, 1975.

[9] William, D. R., Cornelius, D. and Rowley, C. W., 'Supersonic Cavity Response to Open-Loop Forcing', Active Flow Control, 95: 230-43, 2007.
[10] Mohri, K. & Hiller, R. Computational and experimental study of supersonic flow over axisymmetric cavities. Shock Waves, 21, 175-191, 2011.
[11] Delprat, N., 'Rossiter's formula: A simple spectral model for a complex amplitude modulation process?', Fluids of Physics, 18, 2006.
[12] Williams, D. R. and Rowley, C. W., 'Recent Progress in Closed-Loop Control of Cavity Tones', AIAA paper 2006-0712, 44th Aerospace Sciences Meeting and Exhibit, Reno, Nevada, USA, 2006.
[13] Punekar J., Avital EJ and Musafir RE, Computations of Nonlinear Propagation of Sound Emitted from High Speed Mixing Layers, Open Acoustics Journal 3, 11-20, 2010.
[14] Hirsch C, Numerical computation of internal and external flows, vol. 2, Computational methods for inviscid and viscous flows, 1John Wiley & Sons 1992.
[15] Avital EJ, Musafir RE and Korakianitis T, Nonlinear Propagation of Sound Emitted by High Speed Wave Packets, Journal of Computational. Acoustics in press.