The 8th International Conference on Jets, Wakes and Separated Flows, ICJWSF-2024
September 23-25, 2024, Firenze, Italy

Reduction of Two-Dimensional Cavity Flow Oscillations at Supersonic Speed by curving its Rear Face

Soumya R. Nanda[1,2], S. K. Karthick[1,3] Sudip Das[1,4] and Jacob Cohen[1]

1: Faculty of Aerospace Eng., Technion-Israel Inst. of Technology, Haifa-3200003, Israel
2: Dept. of Aerospace Eng., Indian Inst. of Technology Kanpur, Kanpur-208016, India
3: Dept. of Mechanical and Aerospace Eng., Indian Inst. of Technology Hyderabad, Kandi-502284, India
4: Dept. of Space Eng. and Rocketry, Birla Inst. of Technology Mesra, Ranchi-835215, India

[1] Corresponding author: soumyananda224@gmail.com

Abstract

The present study investigates the effect of a geometric change to the cavity rear face from vertical (VRF) to circular (CRF) or elliptic (ERF) shape in supersonic flows. The experiments are carried out in a hypersonic Ludwieg tunnel at a freestream design Mach number of $M_\infty = 6.0$. The almost two-dimensional (2D) cavity (width-to-depth ratio of 10), having a length-to-depth ratio of 3.575 is placed on a 2D symmetric wedge having a half inclination angle of $20.5°$, so the Mach number approaching the cavity is 3.32, and the Reynolds number, based on the depth Re_D of the cavity is varied between $51,500$ - $74,000$. Using Planar Laser Rayleigh Scattering (PLRS), and unsteady pressure measurements, it is demonstrated, experimentally and also numerically that similar to previous findings reported in transonic flow [1, 2], compared to a VRF cavity, this technique immensely reduces and may even eliminate the self-excited strong cavity flow oscillations (Rossiter's modes).

Keyword: *Supersonic cavity, Hypersonic Ludwieg tunnel , Rossiter modes.*

1. Introduction

Cavity flow application spans the entire range of Mach numbers, starting from subsonic, transonic, supersonic to hypersonic flows. Specific examples include flows in landing gears of aircrafts, store separation from internal cavity, isolator flow control in scramjet intakes and cavity flame holder in combustion chambers. Cavity flows are categorized as open or closed based on their length-to-depth (L/D) ratio. In open cavity flows with L/D ratios less than 10, strong pressure oscillations are created. These produce severe fluctuating pressures as well as noise levels in the vicinity of the cavity which could be detrimental to the structure housing the cavity and its integrity. Research has been carried out to understand these unsteady pressure characteristics, and towards control of such loads by implementing various passive and active controlling techniques [3]. When the freestream flow separates from the leading edge (LE) of cavity, a shear layer is formed, which bridges the entire cavity length. Upon impingement on the rear face of the cavity, in the vicinity of its trailing edge (TE), an acoustic field is formed that propagates upstream and excites the shear layer formation at the LE and induces a Kelvin-Helmholtz type of instability which grows during convection towards the TE to form an array of vortices. After impacting on the rear face, acoustic waves are regenerated which closes a feedback loop and provides self-sustained pressure oscillations. These resonance oscillations can be determined by phase relation across the feedback loop that provides constructive reinforcement of the waves. The spectrum of the pressure fluctuations inside the cavity is composed of broadband noise and narrow-band tones. The source of broadband is due to the free-stream and the shear layer. The resonance frequencies (tones) were first provided by Rossiter[4] who developed a semi-empirical formula. The feedback mechanism was termed shear layer mode by [5], as the disturbances in the shear layer compare well with predictions based on linear stability analysis of the Kelvin-Helmholtz mode. Furthermore, their Direct Numerical Simulation results show a transition from a shear-layer mode, primarily for shorter cavities and lower Mach numbers, to a wake mode for longer cavities and higher Mach numbers, characterized instead by a large-scale vortex shedding with Strouhal number independent of Mach number.

Passive and active flow control techniques have been attempted to destroy the feedback loop. Some examples include the use of vortex generators, sawtooth spoilers [6], stepped leading edge [7], geometric ramp trailing edge [8], leading edge serrations [9], and passive resonant absorbers [10]. These devices report tonal attenuation of at most 20dB and reduce broadband levels in terms of overall sound pressure level (OASPL) to 7dB. All these reductions are a function of Mach and Reynolds numbers.

Studies have been also reported towards modification of rear face geometry of cavities. Majority of reported cases are towards changing the rear face to a ramp or wedge shape. Water tunnel experiments with three different trailing edge geometry[11] (Sharp, Nose shape and Round) of cavity with no advantage of rounding off the trailing edge is reported. Numerical simulation of flow oscillations over cavity with modifications in trailing edge geometry[12] (wedge ramps of different angles, curved ramps with different curvature and height) has been attempted. The maximum advantage of wedge angle (45°) is repoted to be 88% reduction in RMS pressure fluctuation and the maximum advantage of curving of trailing edge is reported to be 62% reduction in RMS pressure fluctuations. The frequecncy characteristics show the basic mode to increase for all the adopted cases compared to the baseline. There is no indication of any frequency palliation or energy characteristics. Variation of trailing edge ramp angles at different heights (partial ramping of rear face) has been recently investigated[13] experimentally. The influence of trailing edge flow impingement with different ramp angles and heights are discussed. The report emphasizes on the reduction on pressure drag with change in the trailing wall edge of the cavity. Change in the angle of rear edge and its influence on cavity flow dynamics at supersonic speed has been investigated by Ref[8]. With change in angles from 75° to 45° reduction in amplitude of oscillation and temporal mode shifting is reported. However further reduction in angle to 30° and 15° shows a different behaviour. Experiments in supersonic flows at $M = 2$ were carried out in [14]. They applied geometrical modifications to the rear face of the base cavity in the form of single ramp, double ramp and partial ramp circle to study their acoustic emission characteristics. Unsteady measurements indicated reduction in the peak tones, broadband levels, and coherence. Among the modified geometries, double ramp configuration significantly reduced the overall sound pressure levels and the fluctuating pressures of the order of 10 dB and 50%, respectively.

A review of cavity flow field studies and its control can be found in Ref[15], [16].

Recently, in an attempt to apply a more simplistic approach to alleviate such unwanted and inevitable loads arising due to geometry configuration, [1, 2] focused on changing the rear face geometry of the cavity for transonic cavities. It was demonstrated experimentally and numerically, that compared to a regular open rectangular cavity at a transonic Mach number of M=0.9, this technique immensely reduces and may even completely eliminate the self-excited strong cavity flow oscillations (Rossiter's modes). In the present investigation, we examine the extension of the method into the supersonic regime.

2. Experiments and DNS

The experiments were carried out in a newly constructed hypersonic Ludwieg tunnel at a freestream design Mach number of $M_\infty = 6.0$. Details of the apparatuses can be found in [17]. The almost two-dimensional (2D) cavity (width-to-depth ratio of 10) having a length-to-depth ratio of 3.575 is placed on a 2D symmetric wedge having a half inclination angle of 20.5°, so the Mach number approaching the cavity is 3.32. Based on the cavity's depth, the Reynolds number varied between $51,500$ to $74,000$. The pressure signal at the test section was found to be repeatable between the runs with a standard deviation of $\pm 2\%$, achieved during the effective run-time of $12.5\ ms$ (while flow properties remain constant). Qualitative and quantitative assessments are made using Planar Laser Rayleigh Scattering (PLRS), and unsteady pressure measurements. The cavity model used in the present study is a sting mounted type, and is designed in a modular form such as to change different parts of the cavity. The regular rectangular cavity has a vertical rear face (VRF). In the present investigation the cavity rear face geometry was changed to a circular shape (CRF) or an elliptic shape (ERF) with semi-major axis twice the cavity depth.

As the upstream approaching flow is laminar, the complementary computations are carried out without any modeling using Ansys-Fluent®. The ratio between the depth of the cavity (D) and the upstream momentum thickness (θ) of the incoming boundary layer is obtained by the DNS to be 97. Time and grid independent studies for the DNS simulations are carried out to arrive at the optimized simulation parameters.

The DNS simulations are carried out to support the experimental results and to gather more insight from the contours of vorticity and dilatation.

3. Results

A comparison of power spectra of measured PLRS signals, obtained at the middle of the shear layer at three different cavities: VRF (vertical rear face), CRF (circular rear face), and ERF (elliptical), is presented in the top row of Fig. 1, and corresponding results obtained by the unsteady pressure sensors positioned at the center of the cavity floor are shown in the bottom row of the figure. Large amplitude discrete cavity tones are observed for VRF that match the 3rd Rossiter mode ($n = 3$). The response of CRF indicates the reduction of the tonal peak (as shown by the pressure spectra, and the existence of some relatively low-frequency background noise.). However, a clear demonstration of complete alleviation of tonal peaks (decrease of the dominant peak) and reduction in the broadband spectra is observed for the ERF case.

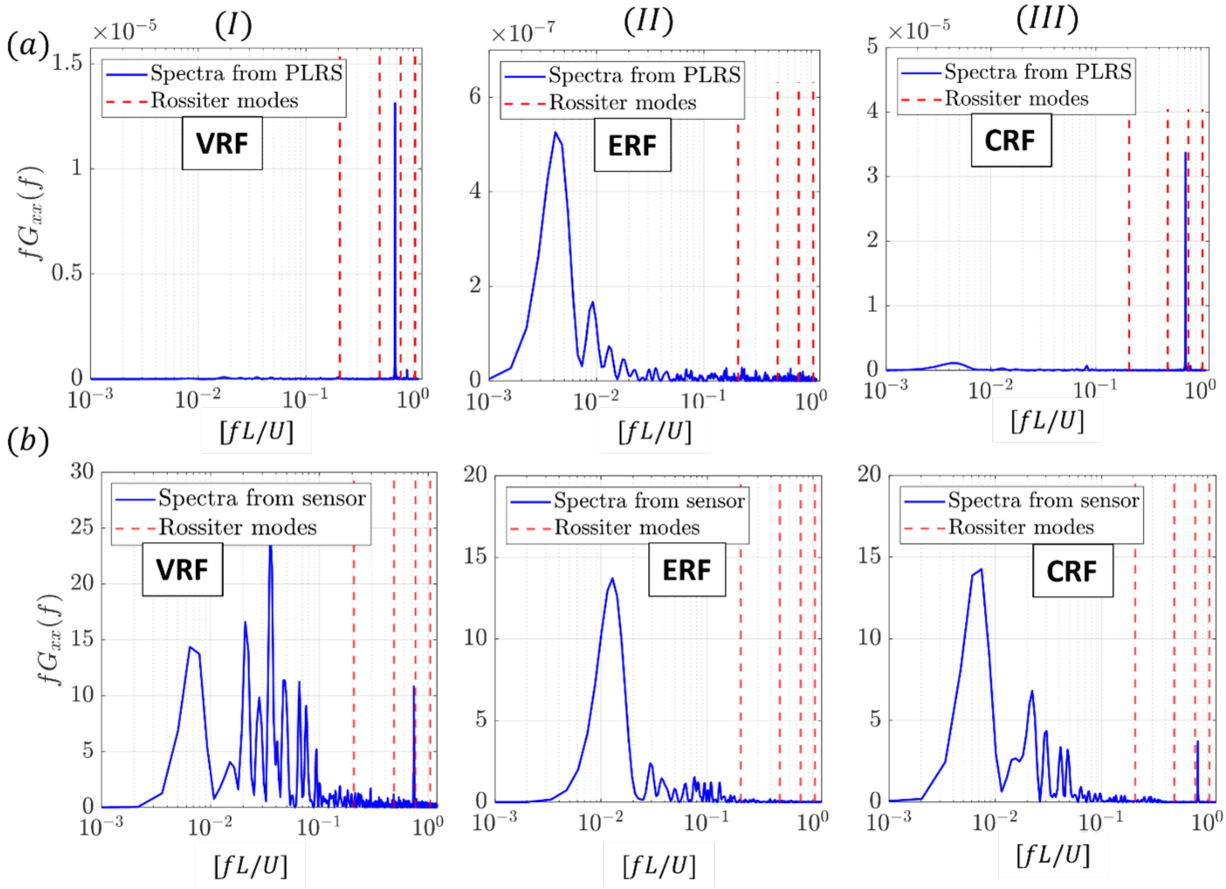

Fig. 1: Spectra obtained from (a) the PLRS signals at the shear layer and (b) from the pressure transducer at the center of the cavity bottom floor (flow conditions: $M = 3.32$,$Re_D = 74,000$).

Afterward, the spectra obtained from the PLRS signals are compared to those obtained from the DNS, as shown in Fig. 2. Excellent agreement is observed; the single dominant frequency in the VRF case matches Rossiter's 3rd mode in both the experiment and DNS. For the ERF case the Rossiter dominant mode is practically eliminated in both cases (Note that the power of the dominant DNS mode is four orders of magnitude smaller than the corresponding VRF value. The CRF case shows a reduction in the spectra magnitude compared with the VRF magnitude, but not as much as was achieved in the ERF case.

4. Summary and conclusions

Experiments and computations were made of a regular rectangular cavity at supersonic speed. Geometric modification to the rear face of the cavity was performed by utilizing either a circular or elliptic shape. The large amplitude discrete cavity tones were observed which is due to the cavity flow feedback loop, shear layer formation and more importantly the flow impact on the rear edge of the cavity. Modification of the vertical

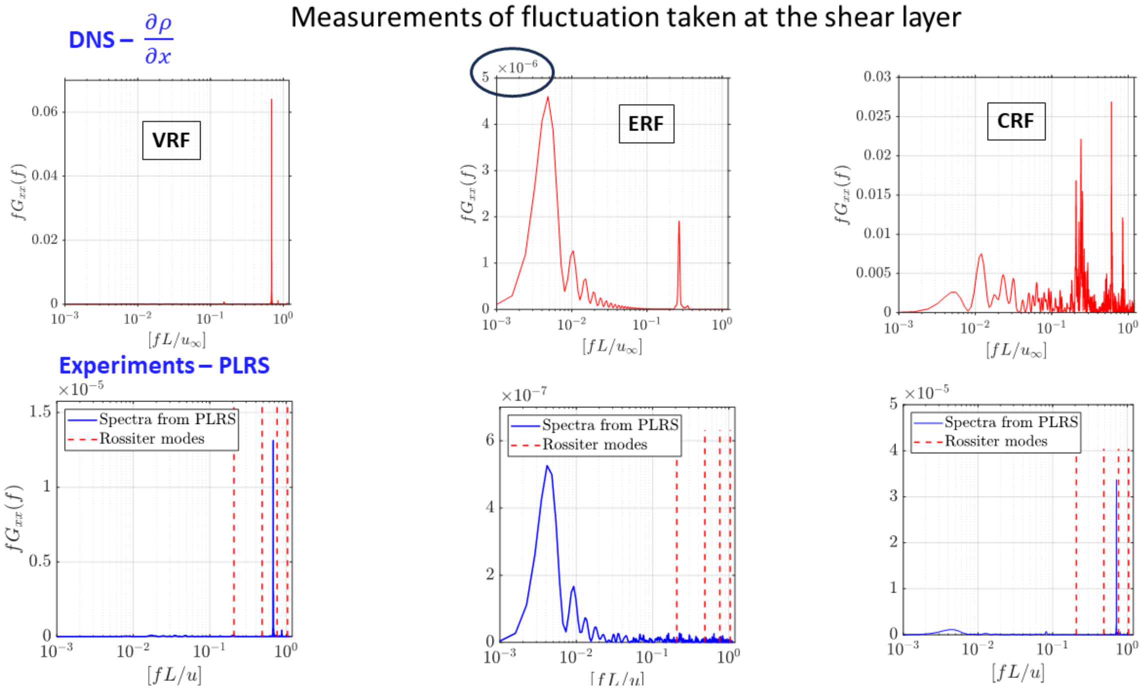

Fig. 2: Spectra obtained at the shear layer from (a) $\frac{\partial\rho}{\partial x}$ from DNS and (b) from the experimental PLRS signals (flow conditions: $M = 3.32, Re_D = 74,000$).

rear cavity shape to circular or an ellipse resulted in significant reduction or completely alleviate the cavity narrow band tones at all frequencies and reducing the broadband spectra. DNS simulations are undertaken to support the cases and more insights are being extracted from the vorticity and dilatation contours.

Acknowledgments

The authors sincerely thank Michael Dunaevsky and Oleg Kan of the Wind Tunnel Complex of Faculty of Aerospace Engineering, Technion, IIT, for extending their support in the smooth conduct of the experiments.

References

[1] S. Das and J. Cohen. Reducing pressure oscillations by change in rear-face geometries at subsonic and transonic speeds. *AIAA Journal*, 55(12):4401–4411, December 2017. ISSN 1533-385X. doi: 10.2514/1.j055895. URL `http://dx.doi.org/10.2514/1.J055895`.

[2] S. Das and J. Cohen. Reducing cavity flow pressure oscillations by change in rear face geometries at transonic speed. In *21st Australasian Fluid Mechanics Conference*, December 2018.

[3] Clarence W. Rowley and David R. Williams. Dynamics and control of high-reynolds-number flow over open cavities. *Annual Review of Fluid Mechanics*, 38(1):251–276, January 2006. ISSN 1545-4479. doi: 10.1146/annurev.fluid.38.050304.092057. URL `http://dx.doi.org/10.1146/annurev.fluid.38.050304.092057`.

[4] J. E. Rossiter. Wind tunnel experiments on the flow over rectangular cavities at subsonic and transonic speeds. *Aeronautical Research Council Reports and Memoranda - Technical Report*, page 3438, 1964.

[5] CLARENCE W. ROWLEY, TIM COLONIUS, and AMIT J. BASU. On self-sustained oscillations in two-dimensional compressible flow over rectangular cavities. *Journal of Fluid Mechanics*, 455: 315–346, March 2002. ISSN 1469-7645. doi: 10.1017/s0022112001007534. URL `http://dx.doi.org/10.1017/S0022112001007534`.

[6] Sally Moon, Sudhir Gai, Harald Kleine, and Andrew Neely. Supersonic flow over straight shallow cavities including leading and trailing edge modifications. In *28th AIAA Applied Aerodynamics Conference*, page 4687, 2010.

[7] David G MacManus and Diane S Doran. Passive control of transonic cavity flow. *Journal of Fluids Engineering*, 2008.

[8] NS Vikramaditya and Job Kurian. Pressure oscillations from cavities with ramp. *AIAA journal*, 47(12): 2974–2984, 2009.

[9] Sudhir L Gai, Harald Kleine, and Andrew J Neely. Supersonic flow over a shallow open rectangular cavity. *Journal of Aircraft*, 52(2):609–616, 2015.

[10] David A Roberts, David G MacManus, Rudy A Johnson, James E Grove, Trevor J Birch, and Ross A Chaplin. Passive attenuation of modal cavity aeroacoustics under supersonic and transonic conditions. *Aiaa Journal*, 53(7):1861–1877, 2015.

[11] JCF Pereira and JMM Sousa. Influence of impingement edge geometry on cavity flow oscillations. *AIAA journal*, 32(8):1737–1740, 1994.

[12] Xin Zhang, Aldo Rona, and John A Edwards. The effect of trailing edge geometry on cavity flow oscillation driven by a supersonic shear layer. *The aeronautical journal*, 102(1013):129–136, 1998.

[13] Yin Yin Pey, Leok Poh Chua, and Wei Long Siauw. Effect of trailing edge ramp on cavity flow structures and pressure drag. *International journal of heat and fluid flow*, 45:53–71, 2014.

[14] T.V. Krishna, P. Kumar, S. Das, and S.L.N. Desikan. Effect of cavity rear wall modifications on pressure fluctuations at supersonic speed. *Acta Astronautica*, 185:78–88, August 2021. ISSN 0094-5765. doi: 10.1016/j.actaastro.2021.04.030. URL `http://dx.doi.org/10.1016/j.actaastro.2021.04.030`.

[15] SJ Lawson and GN Barakos. Review of numerical simulations for high-speed, turbulent cavity flows. *Progress in Aerospace Sciences*, 47(3):186–216, 2011.

[16] Louis N Cattafesta III, Qi Song, David R Williams, Clarence W Rowley, and Farrukh S Alvi. Active control of flow-induced cavity oscillations. *Progress in Aerospace Sciences*, 44(7-8):479–502, 2008.

[17] S. K. Karthick, Soumya R. Nanda, and Jacob Cohen. Unsteadiness in hypersonic leading-edge separation. *Experiments in Fluids*, 64(1), January 2023. ISSN 1432-1114. doi: 10.1007/s00348-022-03559-7. URL `http://dx.doi.org/10.1007/s00348-022-03559-7`.