The 14th Asia Congress of Fluid Mechanics - 14ACFM
October 15 - 19, 2013; Hanoi and Halong, Vietnam

Characterization of Strut-mounted 'Through Cavity' for Scramjet Applications

(Tahzeeb Hassan Danish*, Sathiyamoorthy K*, Pratheesh Kumar P, Manjunath P)

thdanish@nal.res.in, sathy_cim@nal.res.in

Abstract

In a Scramjet combustor, since the flow is supersonic, the residence time available is of the order of 1 millisecond. So the available time for fuel-air mixing, atomization, vaporization and combustion is very low. Wall mounted cavity has proven to be a capable candidate for fuel air mixing and flame stabilization for scramjet. Because of inherent advantages like symmetric flow, avoidance of base wall cooling, symmetric fuelling feasibility etc exploration of strut-mounted 'through cavity' has been done. It is a novel configuration formed in the space between two struts immersed in a supersonic flow in tandem. . Two variants of the cavity, formed by using rectangular and ramp strut as the rear strut and plug nozzle acts as the forward strut, have been used. Experimental characterization is carried out by unsteady pressure measurement inside the cavity for different aspect ratios.

Keywords: Scramjet, Strut-mounted through cavity

Introduction

Scramjet engines are the most promising candidates for future air breathing propulsion system. Air flow at supersonic speed in scramjet combustor chamber results in very low residence time of the order of 1 millisecond. So the available time for fuel-air mixing, atomization, vaporization and combustion is very low. Hydrocarbons used as fuel for their high energy content and ease to handle have certain amount of vaporization and ignition delay. So flame holding becomes a difficult task. One candidate for such a case of harsh environment is the properly designed cavity in the flow field. Figure 1 shows a typical wall mounted cavity.

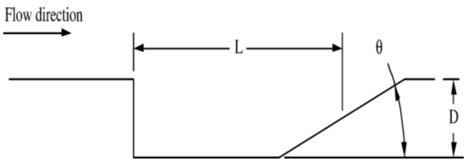

Figure 1. A typical wall mounted cavity

Flow field in the scramjet cavity flame holder is described by following features as depicted in Figure 2.

a) Oblique shock wave series at the front edge.
b) Shear layer starting at the leading edge.
c) Impact shock wave at the rear wall.
d) Expansion wave or bow shock at the rear edge. [1]

.

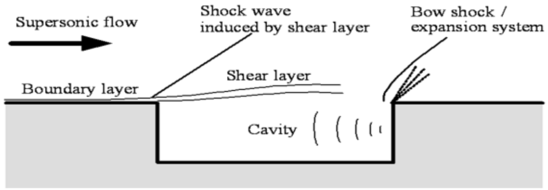

Figure 2. Flow field in a cavity, [2]

The cavity pressure fluctuation consists both of broadband small amplitude pressure fluctuation typical of turbulent shear layer as well as discrete resonance whose frequency, amplitude and harmonic properties depend on the cavity geometry and external flow conditions. The unsteady motion of the shear layer above the cavity is the paramount mechanism for cavity oscillation and results in mass addition and removal at the cavity trailing edge. The shear layer impinging on the rear wall causes free stream flow to enter the cavity. As a result of the impingement, the cavity pressure increases and creates an acoustic wave (compression wave), which propagates upstream at the local sound speed and impacts the front wall the acoustic wave on reflection from the front wall of the cavity induces small vortices, which grow as they are convected downstream towards the trailing edge of the cavity. Because of the instabilities, the shear layer deflects upward and downward resulting in a shock / impingement event on the rear wall of the cavity. [4], [5]

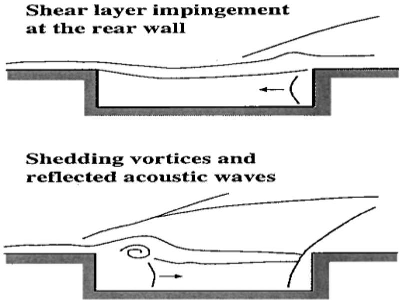

Figure 3. Typical longitudnal cavity oscillations, [4]

Resonant frequencies can be predicted using Rossiter's semi- empirical formula based on the coupling between the acoustic radiation and the vortex shedding. [5]

If shear layer spans from leading edge to all length of a cavity then it is called as open cavity. But when the cavity is long enough that shear layer attaches to the bottom wall of cavity, then it is called as a closed cavity. Closed cavity gives higher entrainment than open cavity but also imposes higher drag. Closed cavities are usually more stable than open cavities in terms of pressure oscillation. Hence open cavities are used for fuel-air mixing and closed cavities for flame stabilization. A combination of these stable and unstable cavities can be used in realization of a scramjet combustor. [4]

Cavities with lower ramp angles can be used for suppression of oscillation and entrainment control as depicted in Figure 4. Low aspect ratio cavity is more stable with a low aft-ramp angle than high aspect ratio cavity. In general, the improvement in flame holding characteristics with aft wall modification for the high aspect ratio cavity is less significant than that of low aspect ratio case. [1], [6]

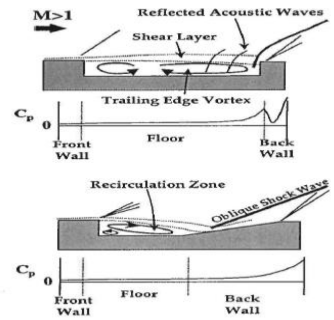

Figure 4. Change in flow field due to ramp, [4]

Because of inherent advantages like symmetric flow, avoidance of base wall cooling, symmetric fuelling feasibility etc exploration of strut-mounted 'through cavity' has been done. It is a novel configuration formed in the space between two struts immersed in a supersonic flow in tandem. A typical strut-mounted through cavity is shown in Figure 5:

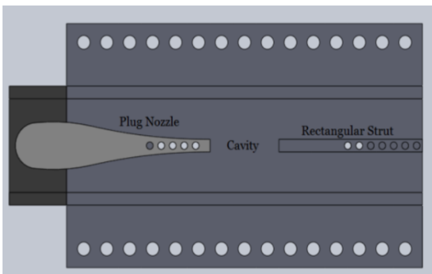

Figure 5. Test section showing strut-mounted through cavity

Experimental Details

Experimental Set-up

Tests were conducted at High Speed Combustor Test Facility, Propulsion Division, NAL, Bangalore. The air total pressure was controlled using a gate valve and a butterfly valve. A transition duct was connected to the rig (150 mm diameter) which changed the flow to 2-D rectangular (68 x 50 mm^2). It was connected to the test section which contained the Plug Contour Nozzle designed to give Mach number 2 and a rear strut. The nozzle and the strut formed a strut mounted through cavity. The cross section of the test section was 75 x 50 mm^2. Figure 6 gives a view of experimental set up.

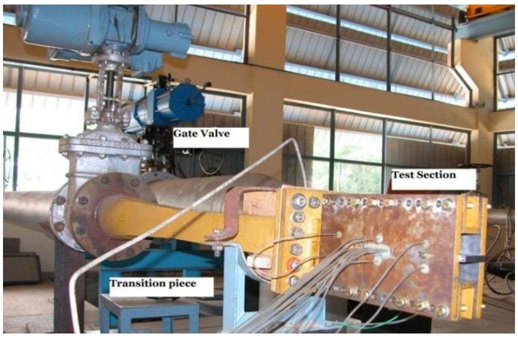

Figure 6. A view of experimental set up

The thickness of the rear strut was 10 mm. Two types of rear struts were used to make two configurations of cavity:

a) Rectangular strut having dimension of 125 x 50 x 10 mm^3 (Rectangular Cavity)

b) Rectangular strut of same dimension as a), but with aft ramp angle of 60° (Ramp Cavity)

Mach number at leading edge of the cavity was 2.03 $\pm$ 0.02, total pressure was 7 $\pm$ 0.1 bar and total temperature at the entrance of test section was 300 *K*. Depth of the cavity is equal to half the thickness of the rectangular strut i.e. 5 mm and width of the cavity was 50 mm. Length of the cavity and hence L/D ratio (aspect ratio of the cavity) was changed by changing the position of the rear strut. Length of the cavity was varied in the steps of 10 mm from 10 to 70 mm. Thus it gave aspect ratios of 2, 4, 6, 8, 10, 12 and 14.

Measurement Plan and Data Acquisition

Static pressure measurements at the end of the transition duct and the end of plug nozzle gave the total pressure and the Mach number seen by the cavity. As the nozzle is a contour nozzle, it gives a very clean flow. Static pressure measurements were taken at one side of the cavity. On the opposite side, unsteady pressure transducers were fitted. For aspect ratios of 2, 4 and 6, only one unsteady pressure transducer was used because of space restriction. For higher aspect ratios i.e. 8, 10, 12 and 14 two unsteady pressure transducers were used. Measurement plan can be seen in Figure 7.

Unsteady pressure measurements were made using two transducers:
a)Kistler 4005BA5F with amplifier 4618A0
b) PCB 123A21
Kistler 4005BA5F with amplifier 4618A0 has a measuring range of 0-5 bar, natural frequency greater than 100 kHz and sensitivity of 2 V/bar. PCB 123A21 has dynamic pressure measurement range of 250 psi, sensitivity of 20 mV/psi and resonant frequency more than 25 kHz.

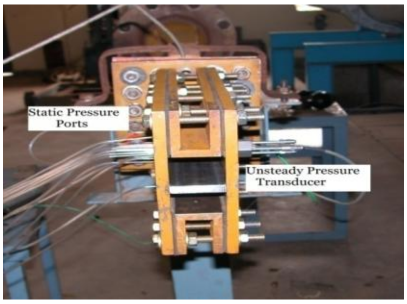

Figure 7. Test section with unsteady pressure transducer and static pressure ports

For highly accurate measurement of unsteady pressure signals, NI PXI-4472, dynamic signal acquisition module is used. Input channels incorporate integrated electronic piezoelectric (IEPE) signal conditioning. The NI PXI-4472 input channels simultaneously digitize input signals over a bandwidth from DC to 45 kHz. It has 8 input channels, 24 bit resolution, sample rate of 102.4 KS/s, voltage range sensitivity of 1.19 μV and on-board memory of 1023 samples. Signals from the unsteady pressure sensors are directly fed to NI PXI-4472 without conditioning.

Results & Discussion

During each run, approximately 8 to 10 sets 40K of voltage signals from transducers were acquired at 100 KS/s. This gave time period of 0.4 second and bin size of 2.5 Hz. Fast Fourier Transform (FFT) is performed on the pressure signals obtained by dividing the voltage signal to the sensitivity of the unsteady transducer. Single sided FFT plots Power Spectral Density (PSD) Vs Frequency, for different aspect ratios for rectangular and ramp cavity were made.

Rectangular Cavity

As the aspect ratio increases from 2 to 14 for rectangular strut, the dominant frequency decreases almost inversely to the aspect ratio. For aspect ratio of 2 and 4, the peaks are very clear at high frequencies and pressure oscillation gets strengthened as aspect ratio increases from 2 to 4. For aspect ratio of 6, there is no clear dominant frequency and the magnitude of pressure fluctuation is also very small compared to that in the aspect ratios of 2 and 4. For L/D of 8, a distinct peak at lower frequency is observed along with other modes. Strength of the pressure fluctuation is high compared to aspect ratios of 2 and 4. Aspect ratio of 6 appears to be the transition from transverse mode of oscillation (in the aspect ratios of 2 and 4) to longitudnal mode (Aspect ratio 8 and above). Also for L/D of 10, a low dominating frequency is observed having strength of pressure fluctuation comparable to that in aspect ratio of 2. For L/D of 12 and 14, very low frequency but high magnitude pressure oscillations are observed, whose maximum value is around 1.5 psi for L/D of 12 and 3.8 psi for L/D of 14. FFT plots for Rectangular cavity are shown in Figure 8 and Figure 9.

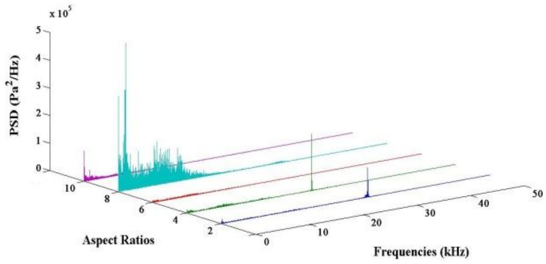

Figure 8. FFT plot Rectangular cavity at aspect ratios 2 to 10

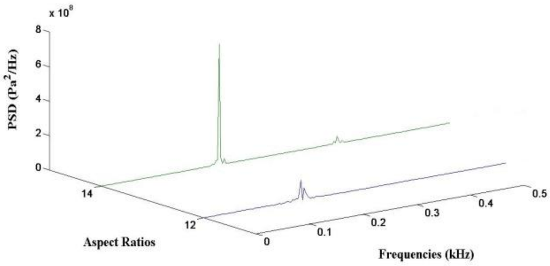

Figure 9. FFT plot Rectangular cavity at aspect ratios 12 and 14

Ramp Cavity

Dominant frequencies show a similar trend as in rectangular cavity with the increase in aspect ratios, with an exception observed for L/D of 10. By changing rectangular strut to ramp strut, the dominating frequencies are decreased. For L/D of 2 and 4, multiple peaks are observed in the case of ramp strut as compared to the only one peak in the case of rectangular cavities. The magnitude of pressure oscillation is substantially decreased for L/D of 2 and 4. PSD magnitude for L/D of 2 it is 1/18 times the value for rectangular cavity and it is 2/33 times for L/D of 4. For other aspect ratios the PSD magnitudes are of the same order for both the rectangular and ramp struts but slightly lower than rectangular cavities in general. For L/D of 6 and 10, a slight higher PSD value is observed than rectangular cavities. Hence in general, ramp cavity is suppressing the oscillation amplitude as reported in literature. FFT plots can be seen in Figure 10 and Figure 11.

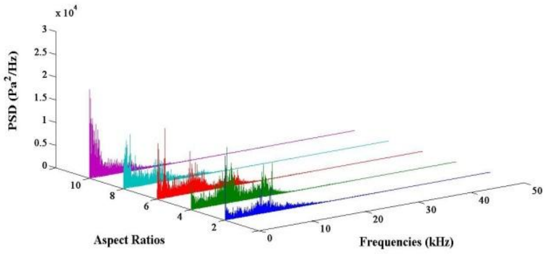

Figure 10. FFT plot Ramp cavity at aspect ratios 2 to 10

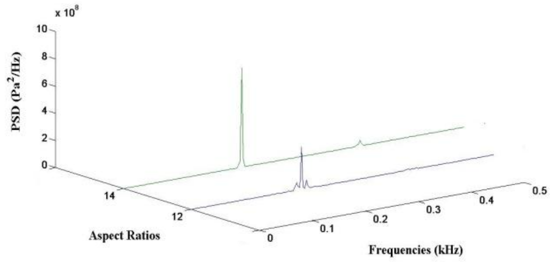

Figure 11. FFT plot Ramp cavity at aspect ratios 12 and 14

Comparison of pressure oscillation magnitude from LE to TE of the cavity

The magnitude of pressure oscillation increases along the cavity length from leading edge to the trailing edge of the cavity. This occurs because, vortices generated by reflection from leading edge of the cavity, increase in size as it goes towards the trailing edge of the cavity. So, the magnitude of pressure oscillation also increases. Figure 12 shows a comparison FFT plot for ramp strut at L/D ratio of 8, for two points close to leading and trailing edges. It can be seen that the PSD amplitude rises approximately by 10 times as we go from leading edge to the trailing edge of the cavity.

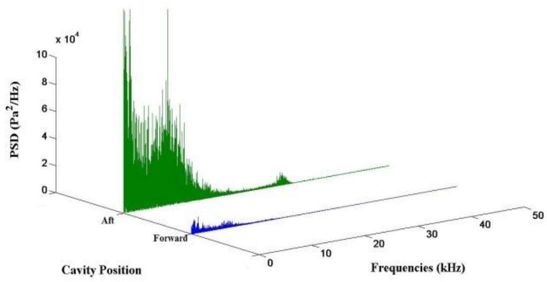

Figure 12. FFT plot of Ramp cavity at aspect ratio8 near leading and trailing edges of the cavity

Conclusions

Pressure fluctuations are observed in strut- mounted through cavities. As the aspect ratio is increased, the dominant frequencies of oscillation vary almost inversely, as depicted by Rossiter formula. Low aspect ratios of 2 and 4, show very high dominant frequencies but higher aspect ratios show lower dominant frequencies. This transition is because at low aspect ratios transverse oscillation is present and for high aspect ratios longitudinal oscillation comes into action. The amplitude of oscillation increases from leading edge to the trailing edge of the cavity. Amplitude of pressure oscillation decreases for low aspect ratios of 2 and 4, using ramp strut, but for higher aspect ratios its effect is minimal. High aspect ratios of 12 and 14, give very high pressure amplitudes but at very low frequencies in both the cases of rectangular and ramp cavities.

Acknowledgement

The authors wish to express their sincere thanks to the Director and the Head, Propulsion Division, NAL for providing all the necessary support. The authors would like to thank Mr. Srinivas J, Mr. Venu G, Mr. Jayprakash C and Mr. M Satish Kumar for their contributions in the experimental work

References

[1] Tianwen Fang, Meng Ding and Jin Zhou, (2007), "*Supersonic Flow Over Cavities*", Translated from Journal of National University of Defence Technology.

[2] Youngki Lee, Minsung Kang, Heuydong Kim and Toshiaki Setoguchi, (2008) "*Passive Control Techniques to Alleviate Supersonic Cavity Oscillation*", Journal of Propulsion and Power, Vol.24, No.4.

[3]Ming-Bo Sun, Zhen Guo Wang, Jian-Han Liang and Hui Geng, (2008) "*Flame Characteristics in Supersonic Combustor with Hydrogen Injection Upstream of Cavity Flameholder*", Journal of Propulsion and Power, Vol.24, No.4.

[4] Adela Ben-Yakar and Ronald K Hanson, (2001) "*Cavity Flameholder for Ignition and Flame Stabilization in Scramjets: An Overview*", Journal of Propulsion and Power, Vol.17, No.4.

[5] Rossiter, J. E., (1964) "*Wind-Tunnel Experiments on the Flow over Rectangular Cavities at Subsonic and Transonic Speeds,"* Aeronautical Research Council Reports and Memo. 3838.

[6] M C Mohammad Ali and Job Kurian, (2008) "*Performance of Aft-Ramp Cavities For Flame Stabilization in Supersonic Flows*", Journal of Propulsion and Power, Vol.24, No.3.

Tahzeeb Hassan Danish, Scientist, NAL Bangalore

Sathiyamoorthy K, Senior Scientist, NAL Bangalore

Pratheesh Kumar P, Technical Officer, NAL Bangalore

Manjunath P, Senior Principal Scientist, NAL Bangalore