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# Aft wall offset effects on open cavities in confined supersonic flow

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ABSTRACT

The effect of aft wall offset in open cavities in a Mach 1.71 flow is investigated experimentally. Two different rectangular cavities with length to depth ratios of 2 and 3 are investigated to validate the effects over the range of the open cavities. Three different offsets of 0%, 5% and 10% are selected for exploring the effects of aft wall offset in cavity flow fields. For investigating the flow physics, unsteady pressure measurements and schlieren flow visualisation techniques are employed. All the cases tested, exhibited the characteristic cavity flow features. Schlieren flow visualisation clearly indicated the presence of shear layer and other shock features that are associated with the cavity flow field. Statistical analysis techniques viz. Fast Fourier Transforms, correlation, coherence and spectrogram are utilised for analysing the unsteady pressure data. Experimental results confirmed the reduction in tonal amplitude in offset cavities for both the length to depth ratios. The 10% offset case provided the maximum reduction in both the length to depth ratio, 2 as well as length to depth ratio, 3 cavity. Spectrogram studies indicated the presence of temporal mode switching in the higher offset value cases. Higher number of modes are also noted to be excited for the offset cases as evident from the spectrogram. From the correlation plot, the existence of the acoustic wave inside the cavity for all the cases is deduced. The maximum OASPL and static pressure values are observed at the aft wall.



## 1. Introduction

Supersonic flow past cavities has been extensively studied for past few several decades, with the earliest of works being reported by Krishnamurthy [1] and Roshko [2] in the mid-1950's. The flow over cavities are commonly encountered in aircraft bomb-bays, wheel wells and the optical windows. Cavity flow physics also generated considerable interest among the academic and scientific community owing to their potential use in the scramjet combustors for mixing enhancement and stable flame holding. Albeit being a simple geometry the cavity flow field is relatively complex. Earlier studies have indicated that flow over cavities generate self-sustained oscillations, giving rise to high amplitude tones which can have detrimental effects on the structure of the aircraft. Whereas it is desirable to completely eliminate the pressure oscillations in external flow, the major focus is to control the pressure oscillations in confined flow for their potential use in combustors.

Krishnamurthy [1] is the first to investigate on the features associated with flow field over a cavity. He found that cavities that are cut on acoustic surfaces give rise to acoustic radiation. He also deduced on the basis of his experiments that there exists a minimum length below which no oscillations would be generated for a given Mach number and $L/D$ ratio. Roshko [2] in his study worked on cavities in the $L/D$ range of 1–62.5. The formation of a single vortex by the $L/D = 1$ cavity is reported by him. Zhang and Edwards [3] classified the cavities as "Shallow" and "Deep" based on the type of acoustic oscillations exhibited by them. It is observed by them that transverse modes of oscillations are predominant in "Deep" cavities ($L/D \leqslant 1$) whereas the corresponding mode of oscillation for "Shallow" cavity ($L/D > 2$) is the longitudinal mode. Charwat et al. [4] further classified the cavity flows into "Closed" and "Open" cavities based on the interaction of the shear layer with the floor of the cavity or aft-wall respectively. In the review paper by Naudascher and Rockwell [5] the cavity flows are further classified as fluid-dynamic, fluid-resonant and fluid-elastic based on the nature of the cavity oscillations.

Rossiter [6] proposed the basic mechanism responsible for generation of cavity flow oscillations. A semi-empirical relation for determining the modal frequencies in terms of the Strouhal number is suggested by him. The resulting expression which is referred to as the "Rossiter's formula" works well in the low subsonic and transonic regimes. According to the Rossiter model, the cavity oscillations occur due to the periodic shedding of vortices from the cavity leading edge and their subsequent interaction with the

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**Nomenclature**

| | | | |
|---|---|---|---|
| $a$ | speed of sound (m/s) | $p$ | pressure (Pa) |
| $\alpha$ | time delay for acoustic wave generation (s) | PSD | Power Spectral Density |
| $D$ | depth of cavity (mm) | $r$ | recovery factor for temperature inside cavity |
| $f$ | frequency (Hz) | SPL | Sound Pressure Level (dB) |
| $\gamma$ | ratio of specific heat | $St$ | Strouhal number |
| $K$ | ratio of vortex convection speed to free stream speed ($U_c/U_\infty$) | $T$ | temperature (K) |
| $L$ | length of the cavity (mm) | $U_\infty$ | free stream velocity (m/s) |
| $M_\infty$ | free stream Mach number | $X/L$ | non-dimensional distance from the leading edge of cavity |
| $n$ | mode number | $\rho$ | density (kg/m$^3$) |

cavity trailing edge. Heller et al. [7,8] improved the "Rossiter formula" and proposed the modified Rossiter's formula for applications involving supersonic flows. They also proposed a modified mechanism for cavity oscillations whereby the impingement of the oscillating shear layer and subsequent mass addition/removal from the cavity aft wall is considered responsible for the cavity oscillations. It is also concluded by them that a stable and non-oscillatory flow over a cavity is impossible without geometry modification. Apart from the above mechanisms certain other mechanisms for cavity oscillations are also proposed on the basis of the experimental and computational studies, and various studies have been carried out to comprehensively understand the flow physics associated with the cavity flows [9–16].

Several oscillation suppression and control mechanisms, both active and passive have also been tested and studied over several years. One of the earliest works on oscillation control is carried out by Sarohia [17] using mass injection from cavity floor. Sarno and Franke [18] tested several methods for control of oscillation; this includes static and oscillating fences, and pulsed and steady injection. Static fences are found to be most effective. Perng and Dolling [19] tested various configurations of aft wall modifications such as vented and slotted wall, beak and valley wall, and tested their effectiveness in a highly turbulent Mach 5 flow. Zhang et al. [20] computationally investigated the effect of leading edge compression ramps, expansion surfaces and mass injection in a 2D cavity. A reduction in the pressure oscillations of up to 10 dB at Mach 2.5 by mass injection is reported by them. Ukeiley et al. [21] conducted experiments to test the efficacy of two leading edge devices, namely a solid fence and a cylinder suspended in the approaching boundary layer at the leading edge of the cavity. They concluded that although the lifting of the shear layer does have an effect on the shear layer oscillations and hence on the tonal amplitudes, the mechanism responsible for lifting of shear layer is considered most important among various other factors. From their experimental study it is observed that although the solid fence is much more effective in lifting the shear layer in comparison to the cylinder, lower fluctuating pressure loads inside the cavity are observed in the case of cylinder suspended at the leading edge. It is later explained by Stanek et al. [22] that the shedding from the cylinder interacts with the cavity shear layer and is responsible for reducing the fluctuating pressures inside the cavity. Vikramaditya and Kurian [23] conducted tests on cavities with aft wall ramps. It is observed that a cavity with 45° aft wall ramp produced the maximum suppression of amplitudes. However, for the 30° and 15° aft wall ramps the pressure oscillations increased beyond the baseline case. Gruber et al. [24] in their work studied the various aft wall ramps and offsets, both computationally and experimentally to identify the best configuration for flame holding purposes. Lee et al. [25] in their study investigated both sub-cavity and triangular bump for suppression of pressure oscillations. Sub-cavity provided reduction in tonal amplitudes whereas the performance of the triangular bump in suppressing the pressure oscillations is not evident from the study. The optimal position and size of the sub-cavity is to be further evaluated. MacManus and Doran [26] proposed the cost effective passive control mechanism in the form of leading edge step that is located inside the cavity. It is observed that the tallest step provides the maximum attenuation of tonal amplitude, and this is attributed to the presence of the recirculation bubble at the top region of the step. Maurya et al. [27] in their study performed experiments on a $L/D = 3$ cavity with aft wall ramps of 90°, 60° and 30° and also with an offset of 0% and 25%. An oscillating shock train is observed by them, and it is concluded that offset aft wall is effective in eliminating the occurrence of the shock train. Reduction in tonal amplitude values are also achieved due to the aft wall ramping as reported by Vikramaditya and Kurian [23].

In summary the main focus of researchers working on cavities is predominantly on external flows only; however due to the increased interest in flame stabilization and short residence times associated with the hypersonic flight regime, the need for a mechanism to stabilize and enable combustion has motivated the research community to explore the use of cavities under such harsh conditions. Basically there are two main aspects in which the various research groups have focussed their attention: (1) use of cavity for flame holding and stabilization for supersonic combustion, and (2) cavity assisted mixing enhancement. Ben-Yakar and Hanson [28] reviewed the use of cavities for flameholding purposes in supersonic combustion. It is concluded by them that the recirculation zone of cavities is essential for flame stabilization. From their review the authors concluded that cavities reduce the induction time by providing hot pool of radicals. For Mach 8 flow, the high temperatures will cause auto-ignition of radicals, and for flows below Mach 8 the cavities are suitable choices as they facilitate higher residence time that is essential for ignition of hydrocarbon fuel. The use of the cavity TV ("Trapped Vortx") concept [29] for supersonic combustors is also discussed. Yu et al. [30] performed experiments to analyse the flame holding and mixing enhancement capabilities of open cavities. Several cavity modules which are placed just downstream of the injector ports are tested. The tests are conducted in Mach 2 flow with angled injection (45°). It is observed from the experiments that cavities with short aspect ratio ($L/D$ ratio) are good candidates for flame holding whereas those with relatively longer aspect ratios shortened the flame length. The case with the incorporation of cavity demonstrated improved performance in terms of higher stagnation pressure and temperature recovery at the exit of combustor as compared to the case with no cavities. This result indicated the enhancement in volumetric heat release. The increased uniformity in total pressure profile at the exit also indicated better mixing. However the results varied among different cavities based on the cavity shapes and their relative placement. It is concluded that positive effect of cavity enhanced combustion should be evaluated