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Experimental study of influence of trailing wall geometry on cavity oscillations in supersonic flow

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ABSTRACT

An experimental study of the supersonic flow over cavities with different trailing wall geometries was carried out at a free stream Mach number of 1.63. All the cavities have same length, depth and length–depth ratio. For two pairs of cavity configurations studied the trailing wall angle is maintained the same. The study involves instantaneous shadowgraph visualization and unsteady pressure measurement. Results indicate that two cavities among those investigated are highly unstable while the others are relatively stable. For the cavities which are unstable four different type of waves are observed in the flow field. SPL and cross-correlation plots indicate high amplitude tones and the presence of forward travelling acoustic wave inside the cavity respectively in these cavities. In the case of cavities which are stable, all the four type of waves which were observed in the flow field of the cavities which are unstable could not be identified. SPL and cross-correlation plots indicate drop in the amplitude of the tones and the absence of acoustic wave inside the cavity respectively in these cavities.

1. Introduction

Flow past the cavities has been studied over a wide range of flow regimes: subsonic to hypersonic [1–3]. Regardless of its geometrical simplicity, the dynamics of the flow it generates in its vicinity is quite unique and perplexing. As of now, the basic mechanism governing such flows is known; but much of the flow physics associated with the cavity flow continues to elude the researchers. There are several parameters on which the flow field depends, a few among them are the nature of approaching boundary layer, Mach number of the flow, length-to-depth ratio (L/D) and/or length-to-width ratio (L/W) of the cavity and also to the alterations brought about in the basic cavity configuration (rectangular cavity). It is known from the earlier studies that such flows generate self-sustained oscillations producing high amplitude tones and thereby causing serious concern about the structure of aerospace vehicles. In the past, the topic of cavity flows has created deep interest due to its presence in a wide range of applications, such as bomb bays, wheel wells and slotted walls of wind tunnels. It is understood that one of the principal reasons for such complex flow field to exist in the neighbourhood of the cavity is due to the presence of subsonic recirculation zone inside the cavity. Presently, renewed interest in this area is mainly due to its efficacy in mixing enhancement and flame holding in the supersonic combustion applications. In the pioneering work, Krishnamurthy [4] reported the emission of acoustic radiation from cavities both in subsonic and supersonic flows. It was observed that the radiation became more intense and directional as the Mach number is increased. Rossiter [5] was first to propose a semi-empirical formula to predict the tonal frequency of acoustic oscillations generated by a rectangular cavity based on his feed-back model. Heller et al. [6] proposed a modified Rossiter's formula for predicting the oscillation frequencies for the shallow cavities in supersonic flows. Rockwell and Naudascher [7] in their review classified the self-sustaining oscillations generated by the rectangular cavities into (a) fluid dynamic, (b) fluid resonant, and (c) fluid elastic oscillations. Zhang and Edwards [8] observed that if the cavity L/D ratio is less than or equal to unity, the oscillations are transverse in nature, while for L/D ratio greater than two the oscillations are longitudinal. Unalmis et al. [9] investigated the shear layer–cavity acoustics coupling by testing the cavity both with and without a covering plate at Mach number 5. The cover plate isolated the cavity from the free shear layer above it. Based on the results they conclude that the coupling between the shear-layer and the cavity acoustics is reduced at high Mach numbers. They further concluded that 'closed-box acoustic' model could be used in predicting the cavity resonant frequencies at high Mach numbers. Wang et al. [10] through their numerical studies identified two modes of cavity

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Nomenclature

L	length of cavity
D	depth of the cavity
θ	angle of trailing wall with respect to horizontal
L/D	length-to-depth ratio of the cavity
R	correlation coefficient
t	time
X	distance from the leading edge of the cavity
x	location of transducer in Eq. (1)
p	fluctuating pressure
ξ	spatial separation between the transducers
τ	time delay or time lag
T	total time of signal acquisition
SPL	sound pressure level
FFT	Fast Fourier Transform
rms	root mean square

oscillations, shear-layer and wake mode. They found that, as the Mach number increases the amplitude of fluctuations in the shear layer decreases. Their results also indicate that the upstream injection results in dampening the oscillations. Studies carried out previously also reported the influence of geometric changes made to the basic configuration on the flow field. Pereira and Sousa [11] experimentally studied, flow past the cavities with different downstream geometries. They employed flow visualization as well as detailed LDV measurements of the time-averaged velocity flow field and the turbulent velocity. The aim of their study was to characterize the influence of the impingement edge geometry on cavity flow field. Zhang et al. [12] computationally studied the supersonic flow past a cavity with different trailing edge modifications to investigate their influence on self-sustained oscillations at Mach 1.5. They observed that the geometrical changes reduced the flow field unsteadiness by modifying the shear layer impingement. Kuo and Huang [13] investigated the effect of sloped bottom and flow path modifier at the bottom of the cavity on the cavity oscillation, in a re-circulating water channel. It was observed that the negatively sloped bottom has the ability to suppress the oscillations. Perng and Dolling [14] in their experimental study, evaluated the effectiveness of various modifications such as slotted, vented, slant, beak and valley aft walls in suppressing the pressure oscillations generated by the high Mach number flow over a cavity. Gruber et al. [15] experimentally and computationally studied the flow field over the cavities with different aft wall angles and off-set ratios. Their study involved flow visualization and static pressure measurement in the vicinity of the cavity to identify potential configuration for flame holding. Their study was limited to cavities with small aft wall angles.

This paper presents and discusses the experimental results of supersonic flow over the cavities with same length and depth and in few cases, the cavities have similar trailing wall angle. An attempt was made to explain the contrasting behavior amongst the cavities based on the results.

2. Experimental details

2.1. Test facility and test conditions

A series of experiments were performed using a small-scale, supersonic free-jet facility. The facility was supplied with dry compressed air from the external reservoirs with a total capacity of 36 m^3 and a maximum stagnation pressure of 13.4×10^5 Pascal's (absolute). A 0.2 m diameter pipeline connects the reservoirs with the settling chamber of the free jet facility. The outlet of the settling chamber is attached with a circular-to-rectangular transition duct. A nozzle is fixed to the rectangular end of the transition duct. The top and bottom surfaces of the nozzle are converging and diverging, and the side walls are parallel to each other. The test section is attached to the free end of the nozzle. The rectangular test section is 30 mm tall and 57 mm wide and is made of perspex walls at the top and bottom and glass walls on the sides. The total length of the test section is 280 mm. Cavities are accommodated along the bottom wall of the test section. The leading edge of the cavity is 80 mm downstream of the nozzle exit. Fig. 1 shows the schematic of the test section along with the cavity. The stagnation pressure is maintained at 5.4×10^5 Pascal's (absolute), and the stagnation temperature is the ambient temperature which was 280 K in the present experiments. The approach Mach number and Reynolds number of the free stream are 1.63 ± 0.04 and 7.46 e + 07/m respectively.

2.2. Cavity models

Five different cavity configurations having same L/D ratio of 3 are used in the present study. The length (L) and depth (D) of the cavities are 60 mm and 20 mm respectively. The length of the cavities is defined as the distance from the leading edge to the mid-chord of the cavity back face [10], whereas the effective length of the cavity is defined as the distance from the leading edge to the trailing edge.

The cavities used in the experiments are either classified as C1 or C2 type. In C1 type cavity, the upper half of the trailing wall is inclined by an angle of θ degree, while the lower half is maintained normal to the flow direction. In C2 type cavity, the complete trailing wall is inclined by θ degrees up to the floor of the cavity. The schematic of the cavity configurations are shown in Fig. 2. The nomenclature of the cavities is given in Table 1. The cavities span the entire test section width.

2.3. Instantaneous shadowgraph

Instantaneous shadowgraph visualization is performed to capture the unsteady behaviour of the flow field in the vicinity of

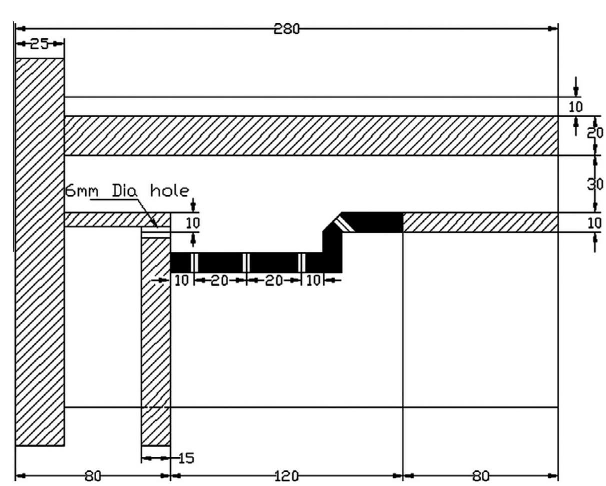

Fig. 1. Schematic of the test section along with the cavity.