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Studies on the Transition of the Flow Oscillations over an Axisymmetric Open Cavity Model

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Abstract

Computations and experimental validation were conducted to obtain flow field over an axisymmetric cavity with different front wall inclinations at a freestream Mach number of 2.0. Flow oscillation in and around the cavities may incur a damaging effect on the stable flight of the aircraft and store releases. Aero-acoustic from the oscillating flow induces vibration in the local bay structure and causes structural fatigue. Hence an open cavity of L/D=3 and 5 has been investigated to obtain the flow oscillation pattern and aero-acoustics. Axisymmetric simulation, three-dimensional simulations on axisymmetric bodies were carried out using FLUENT. Further analysis has been done using slanted front wall of axisymmetric cavity model. A comparison has been drawn between the oscillation level for all different cases and theirtransitions has been studied. Experiments involved schlieren, measurement of static and unsteady pressures. Qualitative flow field details obtained through experiments and computations on axisymmetric body have been validated for L/D=3 and are in good agreement. Pressure oscillations and mean surface pressure distribution on the cavity surface have been observed for each cases and the results showed that there is a sharp transition in oscillation pattern while moving from L/D=3 to 5.

Keywords: Axisymmetric cavity, pressure oscillation, aero- acoustic, Supersonic cavity, oscillating shear layer.

1. Introduction

Cavity flow has been an area of research since last four decades. Lots of researchers have invested a lot to understand the basic cavity flow physics and its unsteady behaviour. Cavity flow has found applications in weapon bay analysis, landing gear bays, flame holding devices in scramjet engines and many other aerospace applications. (Rowley et al., 2002) Flow over the cavity produces complete unstable shear layer where vortices rolls up inside it and when interacts with the rear wall of the cavity produces pressure oscillations and acoustic tones which could be either low amplitude tones or high amplitude resonating tones. (Nayyar et al., 2005) states that these oscillations and tones can produce vibrations of local bay structures and the components stored in it. Some adverse effects of cavity flow oscillations could be instrumentation failure, structural fatigue, damage to the stores, and increase in aerodynamic loading etc. It can also have detrimental effects on the stable release of weapons and their trajectories

Basic flow physics have been explained by (Dusing 1994, Yang 2010, Mohri 2011, Sridhar 2012 etc.) and they observed that flow inside the cavity can become highly unsteady and generate complex flow-fields involving shock boundary layer interactions, flow separations and reattachment phenomenon, aero-acoustics and rolling vortex structures. Cavity flow type is mainly defined by its Lengh-to-Depth(L/D) ratio, Mach number and Reynolds number. Cavities can be divided into Open (L/D<10), Transitional (10<L/D<13) and Closed (L/D>13). Shear layer spans the total length of the cavity and divide the internal subsonic flow from the external supersonic flow. (Rockwell and Naudascher, 1979) states one can identify a feedback mechanismbetween shear layer instabilities and acoustic disturbances. The instability waves produced at the upstream corner of the cavity grow as they are convected along the layer. Then they impinge on the trailing edge, resulting in the strong pressure variation. These pressure disturbances propagate upstream up to the vicinity of the separation region where they affect the instability process. Closed cavity lacks this feedback mechanism and hence there is no unsteady pressure oscillations and acoustic tones. Shear layer impinges on the cavity base giving rise to attachment and exit shock. Hence there is adverse pressure gradients existing on the cavity base. The researchers had also been conducted in controlling the cavity flow oscillation and adverse pressures using active and passive techniques. Passive techniques are simple, cheap and no external devices are required, its simply a structural modification but active controls needs external energy devices and expensive devices like sensors for controlling the flow and attenuates the acoustic tones. In the present work computations have been performed on L/D=3 and 5at Mach 2 and the effect of pressure oscillations have been shown.

2. Experiment

Experiments were performed using Supersonic wind tunnel facility available at BIT, Mesra. The test section of the tunnel is rectangular in cross section (50mm width x

100mm height). It has four windows, out of which two were used for model mounting and two windows provide optical access for flow visualization. The test section has provisions of replaceable nozzle blocks to obtain Mach numbers in the range of 1.5 to 3.0. The present tests were performed with a nozzle corresponding to a Mach number of 2.

Axisymmetric cavity models were used for the experiments corresponding to L/D of 3.Nomenclature of different walls on the cavity and the cavity geometry as shown in figure 1. The axisymmetric cavity model consists of conical fore-body having 12° semi-cone angle, Depth (D) of the cavity was maintained as 4mm and length (L) as 12mm. The maximum external diameter (D_o) of the model was 15mm. Experiments were done with front wall inclination angles (Ø)of 90°(ACØ90°), 110°(ACØ110°) and 130°(ACØ130°). Complete experimental details of static, unsteady pressure measurement and schlieren images have been reported inSinha et al (2013).

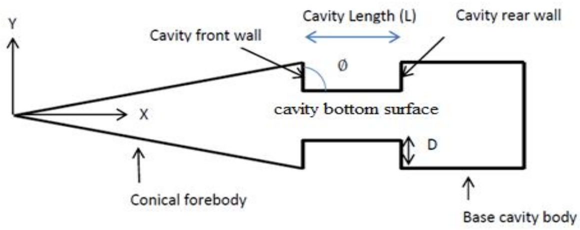


Figure 1: Cavity geometry and nomenclature (Sinha et al. 2013).

3. Computations

Unsteady axisymmetric grid has been used for performing the computations on L/D=3 and 5. Two different front wall inclination of Ø=90°, and 110°have been simulated on an axisymmetric gridfor L/D=5at an angle of attack of 0°. Simulations were made using coupled solver adopting standard k-ω turbulence model with 2^{nd} order implicit time stepping. Solution convergence was established by monitoring residuals of density, velocities, turbulent kinetic energy and monitoring few pressures at specific points on the cavity base and rear wall. Computational data for L/D=3 has been obtained from Sinha et al.(2013).

Structured grids were generated for axisymmetric domain. Figure 2 shows the axisymmetric grid for computation on cavity with L/D=5. Suitable grid clustering has been adopted in the grids to solve the flow inside the boundary layer. The converged y+ on the entire cavity wall, corresponding to the 1st cell near the cavity (0.005mm) was of the order of 2.0. Grid independent tests have been made and a final grid has been reached with cell counts of 600x150 inside the cavity. Three dimensional grid made for cavity with L/D=5, and the y+ value adopted was also 2.

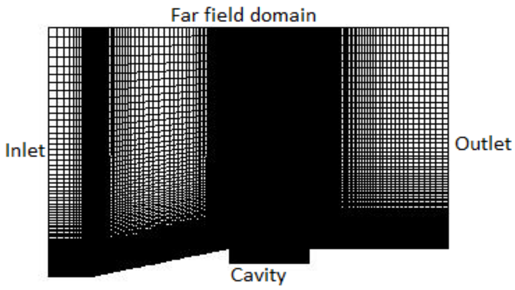
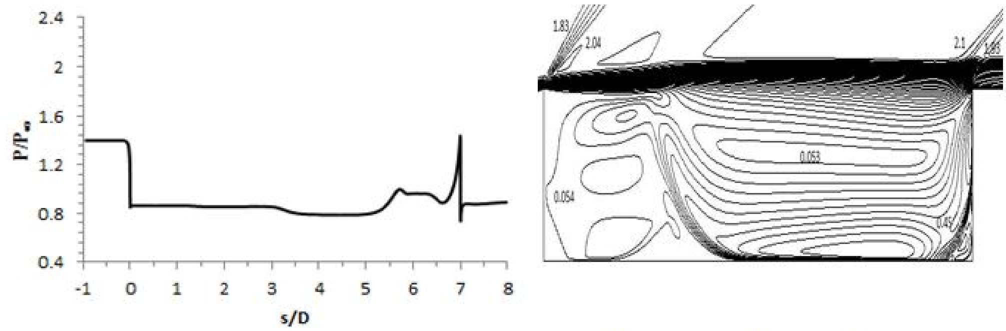


Figure 2: Axisymmetric grid for L/D=5

Grid validation has been performed based on data provided by Mohri and Hillier (2011) for L/D=1.33 and Sinha et al. (2013) for L/D=3. The validated grid has been scaled up for L/D=5 for present computations and the validated turbulence model k-ω with same unsteady parameters had been used.

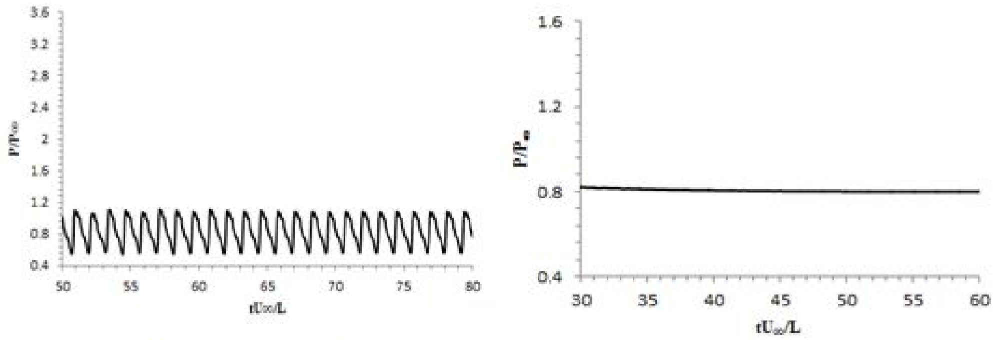
4. Results and Discussions

Simulations were initially performed to obtain the basic flow field around cavity with front wall inclination angle of $\emptyset$=90°. The instantaneous Mach contours obtained for flow inside cavity with L/D=5 is presented in figure 3(b). The dense shear layer can be seen spanning the length of the cavity and separating the external and internal flows. The surface pressure distribution, plotted in terms of P/P_∞ and s/D, where 's' is the wetted length, can be seen in figure 3(a). The mean pressure distribution is pretty smooth. Here $0<s/D<1$ is cavity front wall, $1<s/D<6$ is cavity base and $6<s/D<7$ is a cavity rear wall. Since the motive of this paper is to highlight the transition of pressure oscillations in moving from L/D=3 to 5, so flow physics has not been described explicitly here in this particular case. Pressure oscillations has been plotted in terms of non-dimensionalized pressure P/P_∞ and non-dimensionalised time of tU_∞/L.Figure 4(a,b) and figure 5(a,b) shows the comparison of the pressure oscillation level at the mid base of the cavity and on the rear wall top corner of the cavity for L/D=3 (Sinha et al.,2013) and 5 for $\emptyset$=90°. It can be seen that for L/D=5 there is almost negligible oscillations which deviates from the general notion of open cavity flow field. Figure 6(a,b) compares the effect of front wall inclination from $\emptyset$=90° to 110° on the pressure peak at the rear wall of the cavity, but the rear wall pressure distribution shows no change with inclination whereas L/D=3 showed a reduction of pressure peak upto 6 %.



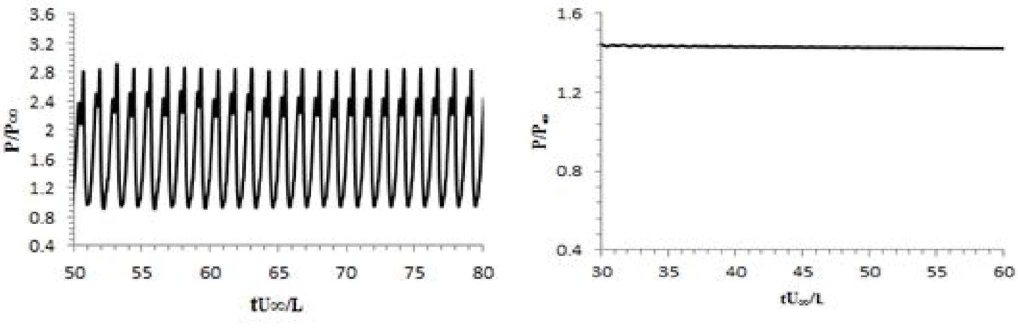
a) Mean pressure distribution b) Instantaneous Mach contour

Figure 3: Mean pressure and instantaneous mach contour for L/D=5.



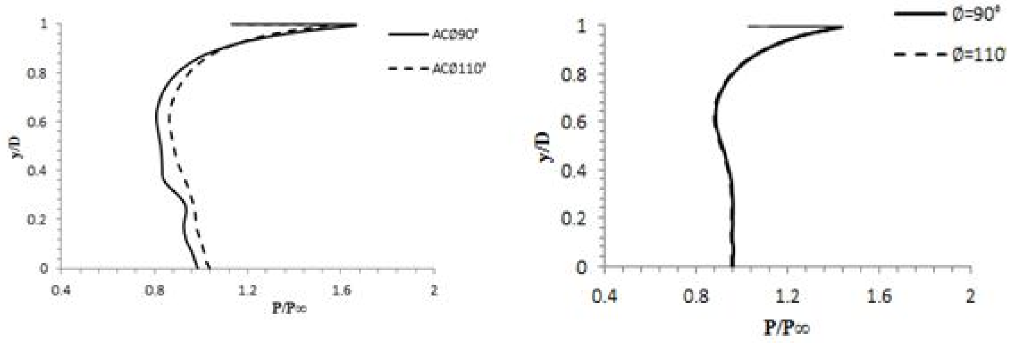
a) L/D=3 (Sinha et al., 2013) b) L/D=5

Figure 4: Comparison of pressure oscillation on mid cavity base.



a) L/D=3 (Sinha et al., 2013) b) L/D=5

Figure 5: Comparison of pressure oscillation on rear wall top corner.



a) L/D=3, (Sinha et al., 2013) b) L/D=5

Figure 6: Comparison of effectiveness of front inclination angle in peak pressure reduction.

5. Conclusion

Computational study has been carried out to understand the basic cavity flow features around Axisymmetric open cavity at Mach 2.Studies were made with change in length to depth (L/D) ratio of the cavity from 3 to 5. The front wall inclination angle of the cavity was varied and its effect on the overall flow field was investigated. The pressure fluctuations on the cavity base and rear wall seems to be completely quiet and no aero-acoustic load could be generated there which is quite ananamolous trend in an open cavity. Similarly, for L/D=5, peak pressure at the rear wall remain unaffected by the inclination of the front wall which again deviates from the perception of the effectiveness of the front wall inclination on the cavity flow control. Thus we can say that L/D=5 shows the parametric deviation in the general trends of open cavity behaviour and there is a sharptransition (reduction) in pressure oscillations from L/D=3 to 5.

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