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Study of the unsteady pressure oscillations induced by rectangular cavities in a supersonic flow field

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Abstract

The complex, unsteady, self-sustained pressure oscillations induced by supersonic flow past a rectangular cavity is investigated using numerical simulations. The present numerical study is performed using a parallel, multiblock solver for the two-dimensional, compressible Navier-Stokes equations. Open cavities with length-to-depth (L / D) ratio in the range 0.5 – 3.3 are considered. This paper sheds light on the cavity physics, cavity oscillatory mechanism, and the organisation of vortical structures inside the cavity. The vortex shedding phenomenon, the shear layer impingement event at the aft wall and the movement of the acoustic/compression wave within the cavity are well predicted. The vortical structures and the source of the acoustic disturbances are found to be located near the aft wall of the cavity. With the increase in the cavity length, strong recompression of the flow near the aft wall leading to a sudden jump in the cavity form drag is observed. The estimated cavity tones are in good agreement with the available semi-empirical relation. Multiple peaks are noticed in deep and long cavities. For the present free-stream Mach number 1.71, it is observed that around L/D=2.0, the cavity oscillatory mechanism changes from the transverse to longitudinal oscillatory mode. The effects of this transition on various fluid dynamics and acoustic properties are also discussed.

Key words: Multi-Block methods, cavity flows, and unsteady compressible flows.

Introduction

Supersonic flow over cavities generates complex unsteady flow fields. Multiple peaks of comparable strengths characterize the frequency spectra of the self-sustained pressure oscillations associated with the cavity. These cavity-induced fluctuations may cause damaging effects in the structural members of an aircraft. However, an oscillatory cavity flow field can enhance the mixing of fuel-air streams in a supersonic combustor. The cavity oscillatory mechanism can be either in transverse or in longitudinal modes.

Implementation

The flow domain is decomposed in to four blocks. In each block highly refined orthogonal structured grids are generated. Single cell overlapping strategy is used along the block interfaces. The minimum grid spacing employed along the streamwise and wall normal directions are 0.0066H and 0.0007H respectively. (H is the channel height). Typical grid sizes used in the blocks are upstream – 102 X 101, above cavity – 202 X 101, downstream – 101 X 101, inside cavity – 201 X 101. The approaching boundary layer is turbulent in nature with a displacement thickness of 0.3 mm. Reynolds number based on the channel height and inflow properties is 2.06 X 10 ^ 6. No turbulence model is adopted in the present study.

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Results

Flow inside the cavity is subsonic and the flow above the cavity top edge, i.e., the undulated shear layer is complex. In transverse oscillations a single big vortex occupies the cavity volume, in longitudinal mode two counter rotating vortices are located inside the cavity. In deep cavity two or more vortices are located inside the cavity along the top portion and floor region respectively. Flapping motion of the free shear layer leading to compression/expansion event at the aft lip of the cavity is observed. The transition of the cavity oscillations from transverse to longitudinal mode is noticed around L/D ratio 2. This transition is found to produce strong re-compression of the fluid near the downstream part of the cavity resulting in sudden jump in the cavity form drag.

The evolution of the cavity flow field with time is shown in Fig 13 a - 13 f., for illustrative purpose cavity with L/D 3 is used.

- Figure 13 a shows the convection of the shed vortex from the leading edge of the cavity
- This vortex grows in size, as it is convected (Fig 13 b).
- It impinges on the aft wall and an upstream moving acoustic/pressure pulse is generated (Fig 13 c).
- The trailing edge vortex grows in size. The upstream propagating wave gets reflected from the fore wall (Fig 13 d).
- The reflected wave moves towards the trailing edge of the cavity. The next shed vortex is about to mix with the sitting vortex.
- The shear layer deflects downward (Fig 13 e).
- The acoustic wave is reflected from the aft wall and moves upstream. The shed vortex mixes with the trailing edge vortex (Fig 13 f).

References:

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- D.Rockwell and E.Naudascher, Review-self sustaining oscillations of flow past cavities, Transactions of the ASME, Vol. 100 ; P 152-165, 1978

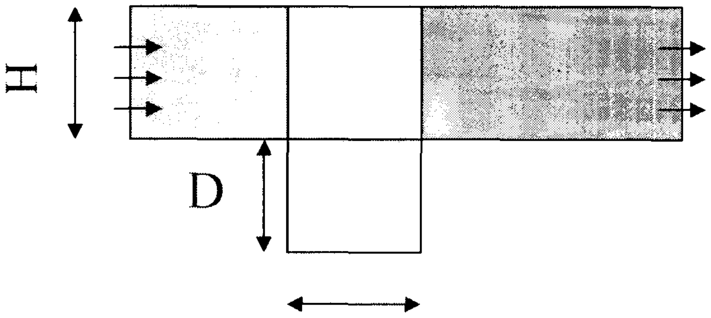


Figure 1: Outline of the decomposed cavity domain (4 Blocks)

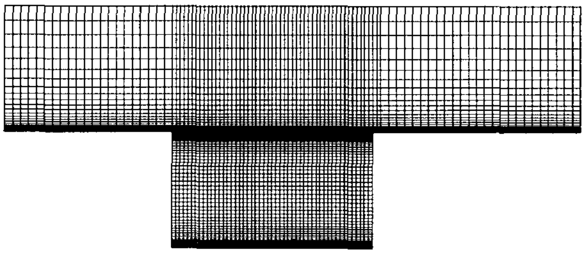


Figure 2: Enlarged view of Multi-Block structured grids in cavity domain (4 Blocks)

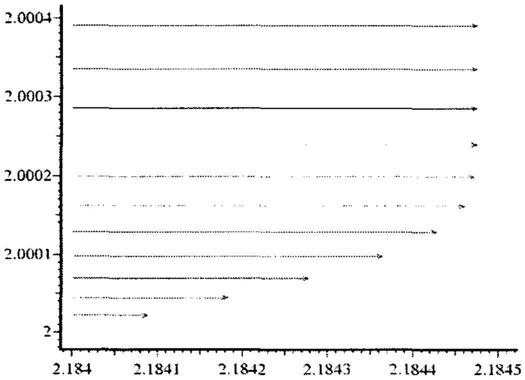
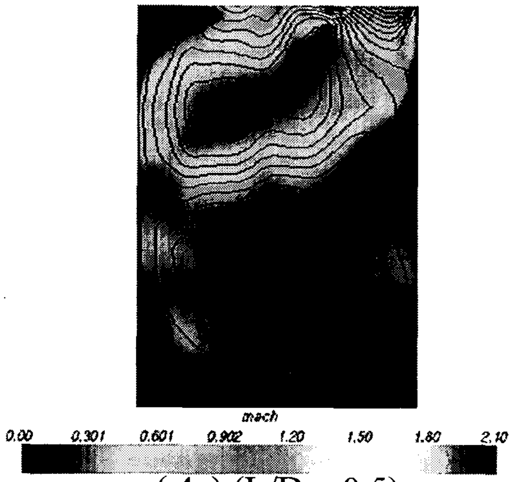
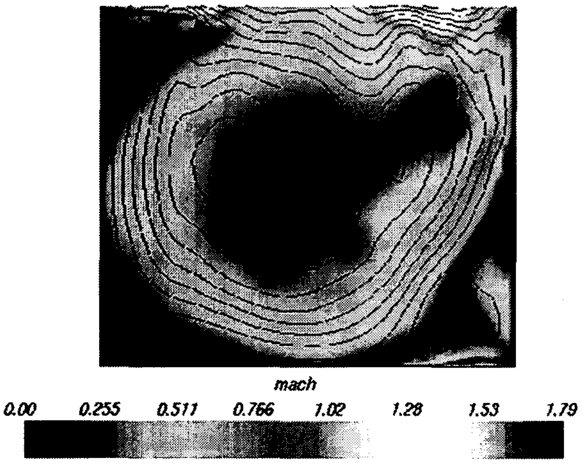


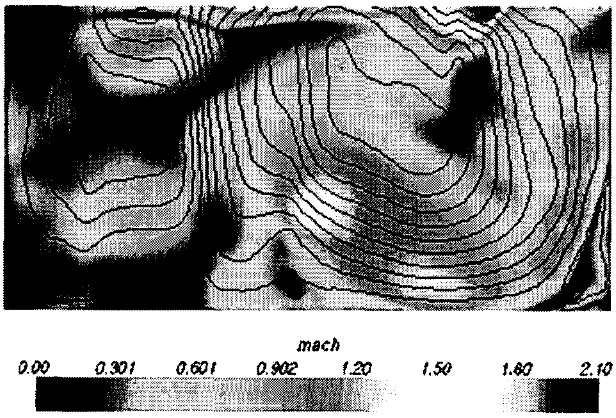
Figure 3: Enlarged view of the velocity vector plot across the boundary layer



(4a) (L/D = 0.5)



(4b) (L/D = 1)



(4c) (L/D = 2)

Figure 4 a,b,c : Iso Mach contour inside the cavity superimposed with streamlines traces

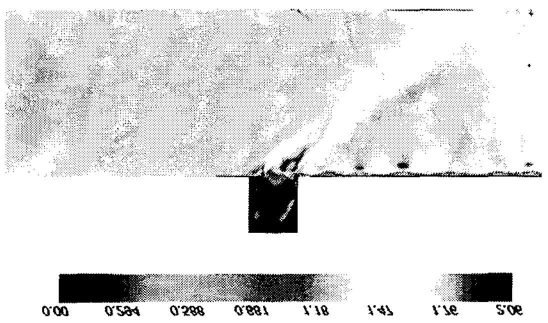


Figure 5: Iso-Mach contour (L/D = 1)

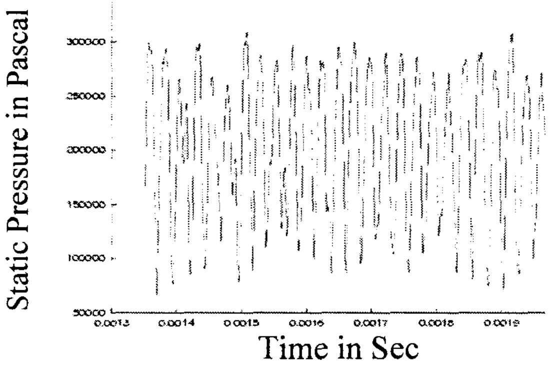


Figure 6: pressure history at the aft lip of the cavity (L/D = 1)

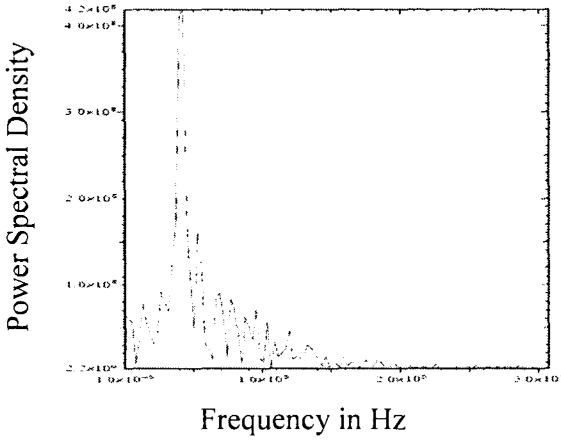


Figure 7: power spectrum (L/D = 1)

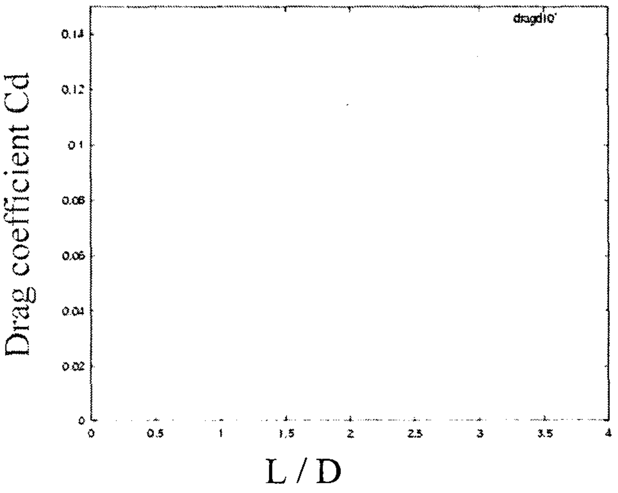


Figure 8: Cavity Form drag variation

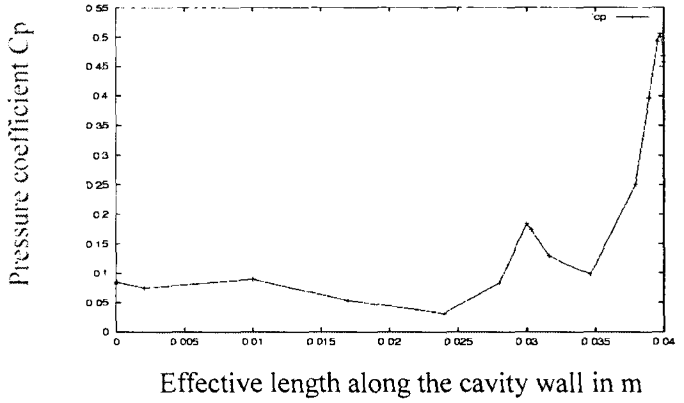


Figure 9: Cp distribution along the cavity wall L/D = 2

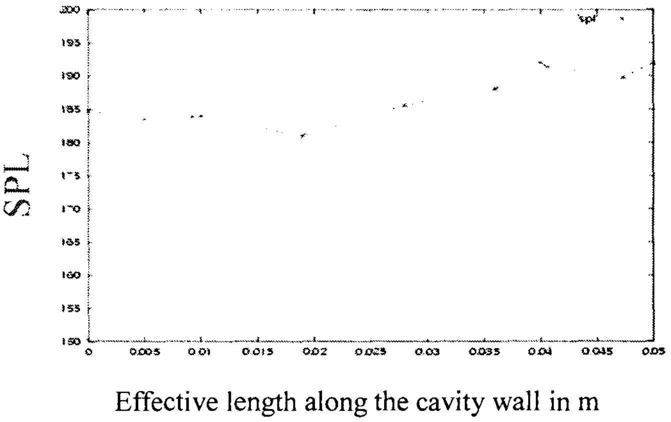


Figure 10: Acoustic Sound Pressure Level (SPL) distribution along the cavity wall L/D = 2

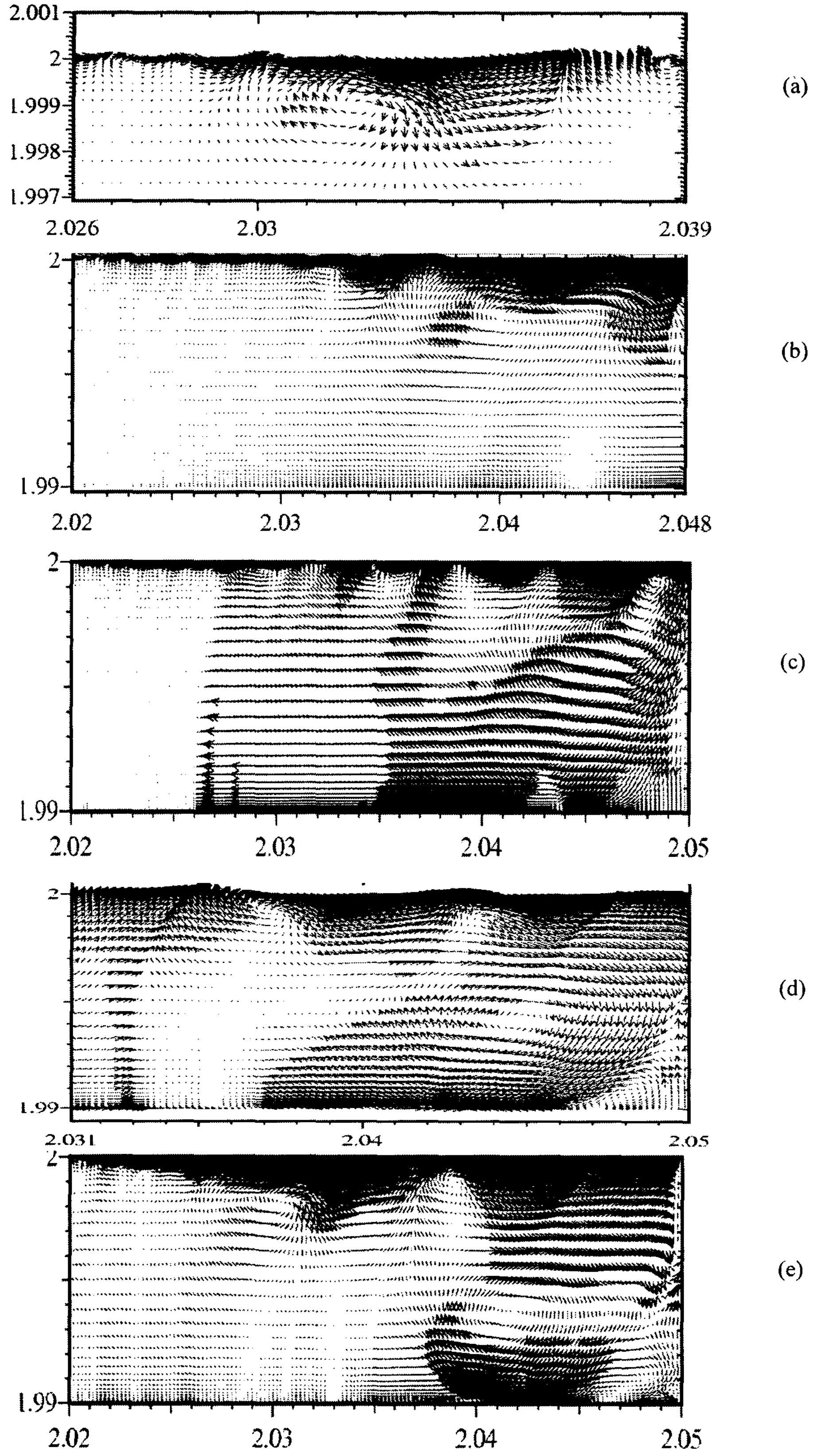


Fig 11 a-e: Velocity vector plot inside cavity showing time evolution of cavity flow features L/D = 3