Passive flow control in confined supersonic cavities of varying impinging shock strengths

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ABSTRACT A numerical investigation is conducted into how a front wall sub-cavity affects the flow field in restricted supersonic cavities. The shock pressure impinging on the shear layer varies in strength within the cavities. Flow physics is analyzed and understood through the use of numerical schlieren and spectral analysis.

1 INTRODUCTION

Confined cavities find use in the aerospace sector for propulsion systems, thermal management in spacecraft and aircraft, and the accommodation of fuel tanks and payloads[1],[2]. These cavity flows are influenced by the freestream's velocity as well as the cavities' length-to-depth ratio. The cavities are categorized into three types based on the length-to-depth ratio (L/D) and the static pressure distribution on the cavity floor: transitional cavities ($10< L/D < 13$), deep or open cavities ($L/D \leq 10$), shallow or closed cavities($L/D \geq 13$) [3]. Open cavities have a characteristic auditory signature, but closed cavities usually don't have any [4]. This signature includes discrete tones known as the Rossiter modes, which are typically caused by the vortex-vortex,vortex-wall, vortex-shear layer, shock-shear layer, shear-wall, or any similar interactions. It also includes low-energy broadband noise contributed by the free stream, the shear layer, turbulent fluctuations, and the shear layer. Open cavities' self-sustaining oscillations frequently result in extremely erratic flow characteristics. The shear layer impinges on the trailing edge after separating from the leading edge. As a result, pressure waves are created here that move upstream and excite the shear layer. This creates a strong hydrodynamic and acoustic coupling which results in a feedback loop [5]. Controlling the acoustics inside the cavities is crucial to prevent structural collapse, as the oscillations inside them are an undesired feature. Confined cavities introduce an additional flow feature due to the formation of alternate expansion and compression waves. A shock wave is created at the top wall as a result of the free jet's deflection, and it interacts with the shear layer. The reflection between the top wall and the shear layer gives rise to a shock train, augmenting the flow physics of the cavities. Comprehending the confined cavity flow physics is crucial for their extensive utilization and the creation of efficient flow control methods to enhance designs.

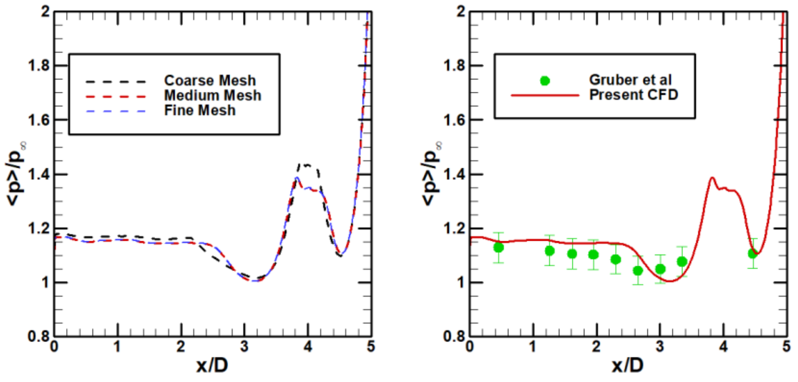
2 PROBLEM STATEMENT AND NUMERICAL METHODOLOGY

The present numerical study actively investigates how the impinging shock affects the flow of a confined open cavity with an L/D ratio of 3. Subsequently, we add a front wall sub-cavity to the baseline cavity so that we can examine a passive flow control method. We maintain the freestream Mach number constant at 1.71 during the investigation. By changing the deflection angle, the impinging shock's strength can be changed. Alterations to the strength of the impinging shock are achieved by adjusting the deflection angle. We take into account three distinct angles: 3.6°, 8.2°, and 13.78°. Within the OpenFoam framework, our simulations make use of the finite volume density-based solver, rhoEnergyFoam [6]. The convective terms are discretized using the Advection Upstream Splitting Scheme (AUSM), and time integration is conducted using the third-order four-stage Runge-Kutta method. The solver actively solves the Unsteady Reynolds-Averaged Navier-Stokes Equations (URANS) coupled with the $k - \omega$ SST (Shear Stress Transport) turbulence model.

We evaluate the solver and perform the grid independence analysis using the flow conditions from Gruber's [7] experiments. Figure 1a shows that the medium and fine mesh yield similar results. For economical usage of resources, we use the medium mesh for further study. The present simulation shows a good match with Gruber's (figure1b). The marginal mismatch in the outcome can be explained by ruling out the effects of three-dimensionality and by the ±5% differences in the sensors used in the trials.

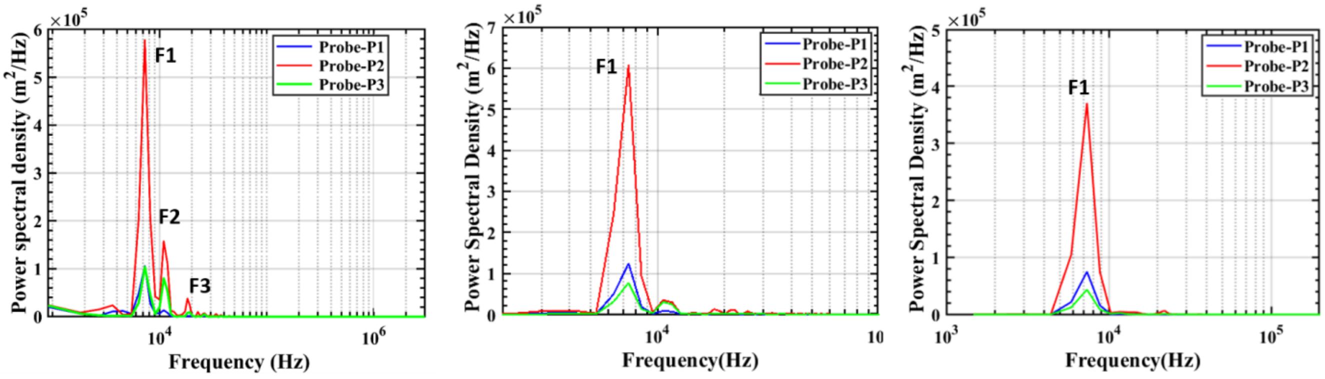
3 RESULTS

As previously said in the article, we collect the pressure fluctuation signal via monitoring stations or probes positioned at the midpoints of the cavity's front wall, aft wall, and base, as previously described in the article. This data is collected at a sampling rate of 0.5 GHz, corresponding to a lag of 2e-09 s between each time step. The chosen sampling frequency exceeds the frequencies of interest, meeting the requirements of the Nyquist criteria and ensuring adequate resolution across a wide range of frequencies. Subsequently, we perform the Power Spectral Density analysis (PSD) to ascertain its frequency content. Figure 2 a shows that the fundamental frequency (F1) in case of the deflection of 3.6°is 7.9 kHz whereas in cases of the deflection angle of 8.2°and 13.78°are 7.2kHz and 7 kHz respectively (figure 2 b and c). This observation infers that increasing the strength of the shock reduces the fundamental frequency of oscillations. We shall perform the flow-field visualization to further analyze this observation.



a) b)

Figure 1. Validation of the present work against the experiments of Gruber et al.[8] .



a) b) c)

Figure 2. Power Spectral Density vs Frequency of the cavity configuration with the deflection angle of a) 3.6°,b) 8.2° and c) 13.78°.

To comprehend the impact of passive flow control on the cavity flow, we will include a front wall sub-cavity in each of the three layouts, with a length of 0.2 times the cavity's length.

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