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Supersonic Cavity Flows and Their Control

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A detailed experimental study of supersonic, Mach 2, flow over a three-dimensional cavity was conducted using shadowgraph visualization, unsteady surface pressure measurements, and particle image velocimetry. Large-scale structures in the cavity shear layer and visible disturbances inside the cavity were clearly observed. A large recirculation zone and high-speed reverse flow was revealed in the cavity. In addition, supersonic microjets were used at the leading edge to suppress flow unsteadiness within the cavity. With a minimal mass flux (blowing coefficient $B_c = 0.0015$), the activation of microjets led to reductions of up to 20 dB in the amplitudes of cavity tones and of more than 9 dB in the overall sound pressure levels. The microjet injection also modified the cavity mixing layer and resulted in a significant reduction in the flow unsteadiness inside the cavity as revealed by the shadowgraphs and the velocity-field measurements.

Introduction and Background

CAVITY flow has been the subject of research since the 1950s [1]. Although geometrically simple, the fluid dynamics in such flows are rather complicated. As such, some of the basic mechanisms governing this flow, such as the feedback loop [2] discussed later, are known; however, much of the flow physics governing cavity behavior remains unclear. This topic has seen renewed interest in recent years due to the ubiquitous presence of cavity-type flows in applications, such as the control of flow over open cargo and weapon bays [3–5], and mixing control and enhancement for supersonic combustion [6,7]. High-speed cavity flow is also an ideal candidate for a benchmark problem for high-fidelity computations [8] that are attempting to simulate increasingly high Re number flows [9]. Consequently, recent studies that are mainly experimental in nature have provided valuable data primarily in the form of pressure measurements and flow visualizations, which can be used for the validation of such simulations [10].

Cavity Flows: A Brief Review

The feedback mechanism, first discussed by Krishnamurty [1] in the context of cavity flows, has been elegantly described by Rossiter [2] and is believed to be the reason of flow-induced resonance within the cavity. As the shear layer separates from the leading edge of the cavity, it starts to roll up into large-scale vortical structures due to the Kelvin–Helmholtz instability. When these structures impinge on the trailing edge of the cavity, acoustic waves are generated. These waves propagate to the leading edge within the cavity, because the free-stream flow is supersonic, to further excite the shear layer. This completes the feedback loop. Under certain conditions, when the frequency and the phase of the acoustic waves match those of the shear layer instabilities, resonance is achieved producing significant unsteady hydrodynamic and acoustic loads on the nearby surfaces. The resonance can be so intense that it can lead to significant structural fatigue in open weapon bays and landing gears, in the context of cavity flows.

Among the most distinguishing visual features of cavity flow are the waves outside the cavity that are generated by the large-scale structures in the cavity shear layer. These structures grow very rapidly due to the resonance in the cavity as a result of the flow-acoustic coupling. Krishnamurty [1] was perhaps the first to provide clear visual evidence of such waves where he observed a series of waves being swept downstream by the free-stream flow. Subsequently, Heller and Bliss [11] used water table simulation to observe wave in and outside a 2-D cavity and more recently, Heller and Delfs [12] used schlieren photography to observe waves outside a 3-D cavity. Heller and Delfs classified the waves into four categories as follows: Type 1: the upstream propagating waves above the cavity, due to the disturbances traveling upstream within the cavity. Type 2: the compression and expansion waves which occur intermittently at the leading edge. Type 3: the quasi-steady external bow shocks at the trailing edge due to the impingement of the cavity shear layer. And type 4: the weak compression waves, in the vicinity of the trailing edge. In a subsequent study, Zhang et al. [13] observed shock waves generated by large-scale structures in the shear layer of a 2-D cavity. They classified as “type 3 waves” per their nomenclature. Zhang et al. determined that the angles of these “shock” waves correspond to a Mach angle where the Mach number is essentially the difference between the free-stream Mach number and the convective Mach number of the large-scale structures. For further details regarding the nomenclature, the interested reader is referred to these papers.

In addition to flow visualizations, more quantitative measurements have been obtained for cavity flow where a large number of these studies consist of mean and unsteady surface pressure measurements. Among these some are more recent and notable: Bauer and Dix [14] conducted detailed surface pressure measurements of supersonic cavity flows over a Mach number range of 0.6–5.04; Cattafesta et al. [4] and Kegerise et al. [15] obtained fluctuating surface pressure measurements for low- to high-subsonic cavity flows with the goal of implementing active closed-loop control (more on that later). Similarly, Ukeiley and coworkers [16,17] have examined the unsteady wall pressures to better understand the cavity dynamics and subsequently to control its behavior [10]. These studies confirm the presence of high dynamic pressure loads inside the cavity where the fluctuating pressure spectra are dominated by discrete frequencies, or cavity tones. Furthermore, the results how that the frequencies of these modes are fairly accurately predicted by the well-known Rossiter’s model.

More limited attempts have been made to characterize the flow field properties for high-speed cavity flows. Ünalmis et al. [18] measured the dynamic pressure in a Mach 5 cavity flow, and visualized the cavity shear structures using a double-pulsed planar

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