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Direct Numerical Simulations of Self-Sustained Oscillations in Two-Dimensional Open Cavity for Subsonic and Supersonic Flow

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Abstract. Direct numerical simulations of self-sustained oscillations in two-dimensional rectangular cavity were performed in both subsonic and supersonic flow. A fifth order weighted essentially non-oscillatory (WENO) scheme was used for the nonlinear term of the two-dimensional unsteady compressible Navier-Stokes equations. A third order Runge-Kutta method was used to discretize the time derivative. The pressure signals on the cavity wall were analyzed by the short time Fourier transform (STFT) method. The formation mechanism of the component with lower frequency for the subsonic cases was analyzed. The detailed oscillating structures in and above the cavity were identified and the interactions between different waves were discussed for both the subsonic and supersonic cases. The results show the oscillating system would finally reach to the self-sustained state. The switching phenomenon of two waves in the cavity was identified for the supersonic case. An improved model of the shock wave patterns for supersonic case was given.

AMS subject classifications: 76B10, 76D05

Key words: Cavity flow, aeroacoustics, WENO scheme.

1 Introduction

Cavity is a typical configuration of fluid mechanics. There are many complex phenomena such as resonant tones, shear layer instabilities and complex wave interactions. In supersonic problems, there are also shock waves. In recent decades, because of its important value in both theory and applications, the noise radiated by the flow past an open cavity has been an important topic in this area. A clear understanding of the fundamental mechanisms underlying cavity flow oscillations will help us to find effective strategies

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to suppress these resonant tones, which is still a challenge today. Thus, numerous researchers have made effort to identify the mechanism and develop various theoretical models on the issue [1].

The most important physical mechanism of the cavity oscillations proposed by Rossiter [2] is the flow/acoustic resonance, described as follows: (i) Kelvin-Helmholtz instability excites an unstable shear layer and generates vortex, (ii) the shear layer moves downstream and impinge on the back wall, which generates acoustic waves that propagate upwards, (iii) the acoustic waves interact with the leading edge fluids and further excite the shear layer instabilities. These mean that the cavity oscillation is self-sustained and a feedback loop exists. The idea of such a feedback loop was known earlier for edgetones in Powell's work [3,4]. Through a series of experimental tests, Krishnamurty [5] discovered that the subsonic and supersonic flows past rectangular cavities would emit a strong acoustic radiation. Rossiter [2] identified a series of oscillating modes with different discrete frequencies and gave a semi-empirical formula to predicted the resonant frequencies. And the Rossiter formula is in good agreement with experiments in subsonic and transonic flow. However, the accuracy of the resonant frequencies predict by this formula will decrease as the Mach number increases ($\mathrm{Ma}>2$) since the formula's deducing is based on constant sound speed. By taking account of higher sound speed inside the cavity at higher Mach numbers, Heller et al. [6] developed a refined formula. The new formula has little difference with Rossiter formula in low-speed flow, but fits with experiments better in high-speed case ($2<\mathrm{Ma}<3$). The feedback loop in high-speed flow is more complex and has some distinctions from the low-speed case. Heller and Bliss [7] further proposed a "two wave" cavity model to explain the oscillation process when the high-speed flow over cavities and gave a classification for the shock waves above the cavity. However, another classification of the shock waves was given by Zhang et al. [8]. The main difference of Zhang's [8] from Heller's [7] is the generation mechanism of the shock wave at the center of the cavity mouth. More recently, Li et al. [9,10] investigated the supersonic cavity flow using implicit large eddy simulations (LES). Li et al. [9,10]' results contain several primary Rossiter modes. Thus, it's difficult to identify the waves patterns from these complex results. Hence revealing the real shock waves patterns requires more meticulously studies.

Others [1,11–13] tried to find a new formula free from empirical constants. From these studies, the theoretical model that does not require empirical constants proposed by Kerschen et al. [12,13] seems promising though it requires further validations [1]. Kerschen et al. [12,13]'s model includes the scattering process at the both ends of the cavity and considers the interactions between the waves in and above the cavity. However, the final formula [12,13] neglects the effect of other waves except for the interactions between the shear layer and the upstream propagating waves. This may cause significant distinctions from the actual flow in some cases. Thus, the interactions between the shear layer, the upstream and downstream propagating waves in and above the cavity still need to be further studied, since it is important to construct the theoretical model.

In this paper, we try to identify the wave patterns in and above the cavity, and investi-