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Numerical analysis of supersonic flows over an aft-ramped open-mode cavity

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ABSTRACT

The characteristics of supersonic cavity flows were investigated using large eddy simulation together with the acoustic analogy method. A fifth-order hybrid compact-weighted essentially non-oscillatory scheme was applied to calculate the convective flux, and a sixth-order compact scheme was used for the viscous flux. *Farassat's Formula* $1A$ was used to solve the Ffowcs William–Hawkings equations to obtain the far-field acoustic pressure fluctuations. The effects of cavity configuration and flow Mach number on the pressure waves generated by the interaction of shear vortices and cavity were compared. The ramped rear-step of the cavity can increase the more-organized level of flow coherent structures, and decrease the static pressure distribution on the cavity bottom-wall. The attenuation of the interactions between the shear layer vortex and the aft-ramped wall of the cavity can reduce the feedback of pressure waves upstream. The energy of the main frequency significantly decreases for the far-field acoustics in the upstream flow over the ramped rear-step cavity. Thus, the effectiveness of noise reduction by the rear-ramp is considerable for the area upstream of the cavity for the present conditions, but it is not the case opposite to and downstream of the cavity. The present conclusions are valuable for evaluating the performance of noise suppression by cavities embedded in supersonic inflows in engineering applications.

1. Introduction

Cavities are widely applied in aircrafts and spacecrafts. For example, a cavity can increase the flow residence time in the combustor of a scramjet engine and can provide a perfect reaction zone, in which the flow velocity is relatively low compared to the main flow. Therefore, the cavity is applied as a flame holder to guarantee successful ignition and reduce the ignition delay time under a wide range of operating conditions. In addition, the flow over a weapon bay of a fighter plane can also be considered as a cavity flow. Such supersonic cavity flows cover fundamental flow phenomena, such as the shedding of vortices, boundary layer separation, shear layer, linear/nonlinear acoustic waves, shock and expansion waves, and the complicated interactions among them.

In the late 1950s, people started to study cavity flows and carried out relevant experiments. Stallings and Wilcox [1] divided the supersonic cavity flow into three types according to the length-to-depth (L/D) ratio of the cavity: open ($L/D < 10$), closed ($L/D > 13$), and transitional cavity ($L/D \sim 10$–13). In an open cavity the shear layer forms at the leading edge and attaches to the rear wall of the cavity. Weak shock waves exist at the separation and reattachment points, inducing high intensity acoustic waves. A closed cavity refers to one in which the shear layer is not covering the whole cavity but is attached to the bottom wall of the cavity. Two recirculation zones are formed at the bottom wall of the cavity and no acoustic waves appear. The flow in a transitional cavity is in the intermediate state between the open and closed cavities. Tracy and Plentovich [2,3] conducted experiments to study the subsonic and transonic flows over cavities with different L/D ratios. They found that the open and transitional-open cavity flows support the tone generation for the subsonic flow as the Mach number is greater than 0.6; the cavity changes from a resonant to a non-resonant one as the L/D increases. Murray and Elliot [4] found that the two-dimensionality of a supersonic cavity flow decreases with increasing flow Mach number. Ukeiley and Murray [5–7] noted that the scale of vorticity with respect to the aft wall determines whether resonance can occur in the subsonic cavity. Handa et al. [8] experimentally studied the generation and propagation of pressure waves in supersonic cavity flows and found that there was a strong relationship between the shear-layer motion, pressure-wave generation, and pressure oscillation at the trailing edge of the cavity. Beresh et al. [9] applied experiments to study compress-

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ible flows over a rectangular cavity and explored the influence of compressibility on the turbulence properties of the cavity shear layer. These studies focused on the flow features with varying geometries in a wide range of Mach number. With the development of computational technology as well as turbulent models, an increasing number of numerical simulations have been proposed to show the refined flow structures and to analyze the physical parameters. Zhang et al. [10] numerically simulated the compressible flows over cavities with different L/D ratios by using different eddy-viscosity turbulence models. Hamed et al. [11] performed a detached eddy simulation (DES) with a shear stress transport turbulence model and found that detailed variations of sound pressure level (SPL) were well-predicted by DES. Rizzetta and Visbal [12] used large eddy simulation (LES) with the Smagorinsky model to study supersonic flows over an open cavity. Xiao et al. [13] adopted the improved–delayed–detached-eddy simulation to simulate the hypersonic cavity-induced transition flow. Kim et al. [14] investigated the unsteady flow-fields inside a supersonic cavity and found that the flow unsteadiness inside is mainly caused by the detaching and reattaching process of the shear layer. Rokita et al. [15] numerically studied the dominant flow structures in supersonic turbulent cavity flows. In summary, the above investigations are mainly focused on the flow pattern as well as its variation with the cavity geometry, i.e., the L/D ratio.

Combustion stability can be realized by embedding a cavity in the scramjet combustor. Many researchers [16–22] have studied the supersonic cavity with different parameters to visualize the cavity flow field and to find out the effects of cavity on ignition, mixing, and combustion efficiency of the scramjet combustor. The achievement of flame stability in a supersonic combustor is a difficult but an interesting task. Wang et al. [19] found that a cavity with a lower rear wall will delay the occurrence of chemical reactions and form a more concentrated and intense heat release region downstream of the cavity, which will accelerate the chemical reactions and achieve a sufficient combustion. Cai et al. [21] investigated the characteristics of a stable flame by experiments and indicated that a robust and stable flame would be achieved in the combustor by applying a rear-wall-expansion cavity. Yang et al. [23] conducted both experimental and numerical studies to investigate the effect of a cavity on flame stability in a supersonic combustion, and found that flame stability was attained with the co-existence of three regions, which were identified as reacting reservoir, premixed and hydrogen-rich combustion region, and downstream combustion zone. The L/D ratio of a cavity also influences the combustion phenomena, and Mahto et al. [24] found that there is an optimal L/D ratio of a cavity in which the performance of a combustor significantly improves. Kummitha et al. [25] observed that the residence time of air in a scramjet combustor is increased and they achieved stabilized combustion owing to the cavity.

For the acoustic features of supersonic cavities, Rossiter [26] revealed the oscillation mechanism coupling vortex shedding and acoustic modes, and initially proposed a semi-empirical formula to predict the main frequencies of flow-acoustic oscillations in a cavity. The predicted mode was called the “Rossiter mode.” Then, Heller and Bliss [27] corrected Rossiter’s formula for higher velocities according to their experimental and analytical studies. Bilanin and Covert [28] suggested another analytical model to predict aero-acoustic modes. These analytical models work well under some specific conditions, but none of them is universal. Kaufman et al. [29] measured the flow field and aero-acoustic environment of a cavity at subsonic and supersonic flow conditions. They found that the SPL increases with increasing flow Reynolds number, but the modal peaks do not change. Rockwell and his coworkers [30, 31] showed that the turbulence in a separated shear layer along the mouth of a cavity and in the jet-like flow within the cavity dominates the turbulent structure of the inflow. Zhang [32] suggested that the flow oscillation and wave emission are directly caused by the shear layer deflection. Rowley and his coworkers [33, 34] applied a two-dimensional direct numerical simulation (DNS) to study the modes of oscillation and acoustic fields radiated by compressible flows over open cavities, indicating a transition from a shear-layer mode for shorter cavities and lower Mach numbers to a “wake mode” for longer cavities and higher Mach numbers. Bogey and Bailly [35], Hamed et al. [36], and Alvarez et al. [37] separately analyzed the computational methods used in three-dimensional acoustic simulation of cavity flow. Lai and Luo [38] proposed a three-dimensional hybrid LES-acoustic analogy method for predicting the noise of a subsonic open cavity. Thaker and Somandepalli [39] found that the amplitudes of pressure oscillations corresponding to shock oscillations are higher than those of the acoustic pressure inside the cavity. Yokoyama and Kato [40] numerically studied fluid–acoustic interactions in a flow over a rectangular cavity by DNS and investigated the effects of acoustic waves on the shear layer of a backstep flow. Wang et al. [41] numerically investigated the pressure oscillations in supersonic open cavity flows and studied the effects of Mach number and upstream injection. Maurya et al. [42] experimentally examined the effects of reducing the aft wall height and ramp angle on cavity oscillations. However, the dominant factors for determining pressure oscillation amplitudes are still unclear in the said research. Furthermore, the mechanisms of suppressing the pressure fluctuation and aero-acoustic noise of a cavity were explored by using porous floors and slot vents [43], leading edge oscillating flaps [44], zero-net mass injection [45], and active actuators [46,47].

The literature reveals that a majority of researchers have already focused on the study of subsonic cavity flows to determine their acoustic characteristics and on the flow dynamics as well as pressure oscillations of supersonic cavity flows [48–50]. However, only few studies of supersonic cases have been conducted to analyze the suppression of aero-acoustics by changing the configuration of cavities and the characteristics of aero-acoustics in the far-field over the cavity. Therefore, in this study the aero-acoustic characteristics of supersonic cavity flows are investigated by using an LES-acoustic analogy method. First, the LES coupled with the immersed boundary method for calculating the supersonic turbulent cavity flow and the aero-acoustic analogy for calculating the aero-acoustic pressure are introduced. The numerical procedures are validated and verified by three cases. Then, the coherent flow structures in a supersonic cavity are analyzed. Finally, the frequency spectrum analysis of the aero-acoustic pressure of the far field and SPL distributions are compared to determine the effectiveness of noise reduction using a ramped cavity. The acoustic analogy theory used in this study is the *Farassat’s Formula* 1*A* based on the Ffowcs William–Hawkings (FW–H) equation.

2. Numerical method

2.1. LES and validation

Numerical procedure for LES

The unsteady compressible LES equations for mass, momentum, and total energy, neglecting the body force and external heat source, are given by

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial \bar{\rho}\tilde{u}_i}{\partial t} + \frac{\partial(\bar{\rho}\tilde{u}_i\tilde{u}_j + \bar{p}\delta_{ij} - \bar{\tau}_{ij} + \tau_{ij}^{\mathrm{sgs}})}{\partial x_j} = 0 \tag{2}$$

$$\frac{\partial \bar{\rho}\tilde{E}}{\partial t} + \frac{\partial[(\bar{\rho}\tilde{E} + \bar{P})\tilde{u}_j - \tilde{u}_i\bar{\tau}_{ij} + \bar{q}_j + q_j^{\mathrm{sgs}}]}{\partial x_j} = 0 \tag{3}$$