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Analysis of pressure fluctuation in transonic cavity flows using modal decomposition

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ABSTRACT

Turbulent flows at a free stream Mach number of 1.19 over an open cavity with L/D ratio of 5.0 are numerically investigated using improved delayed detached-eddy simulation based on two-equation shear stress transport model. Modal decompositions including proper orthogonal decomposition (POD) and dynamic mode decomposition (DMD) are applied to analyze the pressure fluctuations. The extracted first six POD modes possess more than 75% of the total energy and contain multiple frequencies. Their spatial structures exhibit well regular and periodic behaviors along the cavity lip line. The DMD algorithm identifies the flow structures associated with single frequencies. Major distribution area of high intensity pressure fluctuations move upstream as the mode frequency increases, and the structures with high frequencies are prone to break down near the trailing edge. The alternating pressure patterns convection process is clearly presented, and the propagation of acoustic waves validates that the acoustic waves share the same sound source but are radiated following two different paths, consistent with the feedback mechanism. In addition, the effects of free stream Reynolds number on sound pressure spectrum levels are investigated at a fixed pressure and temperature. Results show that free stream Reynolds number has no effect on the non-dimensional frequencies of the dominant modes, while the main recirculation area shrinks as Reynolds number increases. Furthermore, variations of sound pressure levels as a function of Reynolds numbers exhibit significant discrepancies for a fixed free stream pressure or temperature, indicating that the Reynolds number is not critical to the feedback tone amplitude. The enhancement of sound pressure levels mainly attributes to the increment of free flow pressure or the impingement of enlarged fluid velocity due to higher free stream temperature.

1. Introduction

High speed flows over an open cavity commonly exist in many industrial applications, such as weapon bays [1–3] and landing gear system. In the cavity flows, the shear layer oscillation and impingement on the trailing edge generate high intensity acoustic tones, causing the cavity environment extremely harsh, which challenges the surrounding structures of the cavity. Meanwhile, the multiple interactions of flow structures, such as shear layer–vortex, shear layer–wall and vortex–vortex, make it significantly difficult to clearly understand the complex fluid dynamics and its aeroacoustics.

Due to its great complexity and importance, in the past several decades, considerable research work has been devoted to this problem. Most of the numerical and experimental studies focus on the mechanism underlying pressure oscillations and the corresponding flow control strategies, bringing in plentiful achievements to enhance the comprehensions and develop more effective control devices. More detailed studies and comprehensive reviews can be referred to the literature [4–8].

In the preliminary studies, Rossiter [9,10] carried out a series of experiments on the cavity flow with the weapon bay configurations. Based on numerous tests, the author proposed a feedback loop model of vortex and acoustics disturbances, and derived a semi-empirical formula for the frequencies of high intensity tones as below:

$$f_n = \frac{U_\infty}{L} \bullet f^* = \frac{U_\infty}{L} \bullet \frac{n-\alpha}{Ma_\infty + 1/\kappa} \tag{1}$$

where f_n represents the frequency of the nth mode and f^* is the normalized. L is the cavity length, U_∞ is the free flow velocity, and Ma_∞ is the free flow Mach number. α and κ are the constants related to the cavity geometry and flow conditions, which are equal to 0.25 and 0.57, respectively. Considering the flow compressibility effects over a high Mach number range, Heller et al. [11,12] modified the original Rossiter's formula as follows:

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$$f_n = \frac{U_\infty}{L} \frac{n-\alpha}{Ma_\infty(1+\frac{\gamma-1}{2}Ma_\infty^2)^{-1/2}+1/\kappa} \quad (2)$$

To explore the effect of flow conditions, Tracy et al. [13] investigated the cavity flow at transonic and subsonic speeds, and pointed out that the flow type cannot be reliably assessed on cavity geometry alone. Ahuja et al. [14] then conducted a thorough experimental study of the influences of geometric parameters and flow conditions on pressure oscillations in cavity flows, including cavity dimensions, free stream Mach number, temperature and boundary layer. In terms of the flow control, Stanek et al. [15,16] utilized various strategies, such as powered resonance tubes, a cylindrical rod and conventional spoiler, to suppress cavity oscillations, and meanwhile tried to reveal the primary suppression mechanism of these devices.

In the past decades, considerable numerical investigations [17,18] of turbulent cavity flows were performed with the computational fluid dynamics (CFD) methods, such as Reynolds-Averaged Navier Stokes (RANS) model, Large Eddy Simulation (LES) and even Direct Numerical Simulation (DNS). Rowley et al. [19] implemented numerical simulations on cavity geometry, Mach number and Reynolds number to explore the mechanism underlying self-sustained oscillations of the laminar flow over a two-dimensional rectangular cavity. Large-eddy simulations of supersonic cavity at a free stream Mach number of 1.19 were carried out by Rizzetta et al. [20,21], and an active flow control with pulsed mass injection was investigated. Considering the computational affordability and accuracy, the hybrid RANS/LES methods are becoming more attractive for turbulent flow simulations at realistic Reynolds numbers. Hamed and Basu et al. [22–24] applied DES method based on SST model to study supersonic flow over a two-dimensional open cavity with L/D ratio of 5.0, exploring the effects of Reynolds number and sidewall boundary conditions.

In recent years, more advanced analysis methods stimulate the further understanding of cavity flows. Modal decomposition techniques, including Proper Orthogonal Decomposition [25,26] and Dynamic Mode Decomposition [27], are gradually popular to investigating the pressure oscillation tones in cavity flows. The POD algorithm was applied by Yilmaz et al. [28] to investigate the effect of length to depth ratio (L/D) of the cavity on the flow structures. Using DMD method, Vinha et al. [29] studied the laminar flow over an incompressible open cavity numerically and experimentally to explore the saturation process. Lee et al. [30] performed a DMD analysis to investigate the self-sustained oscillations of turbulent cavity flow, examining the influences of the cavity dimensions and incoming momentum thickness.

In spite of considerable efforts devoted to cavity flows, most of the detailed investigations focus on the incompressible cavity flows. A deep understanding of pressure fluctuation in transonic turbulent cavity flows is still necessary. Considering the complexity of cavity flows and the advantages of modal decomposition, it's meaningful to carry out a numerical investigation on the problem with the POD and DMD methods. Besides, the effect of free stream Reynolds number is still vague, especially on the feedback tone amplitude. Ahuja et al. [14] pointed out that Reynolds number had no influence on the non-dimensional frequencies of a cavity, while Tracy [13] considered that the Sound-Pressure spectrum Levels (SPL) were little affected. Similar results by Hamed et al. [23] revealed that higher SPL and finer scale structures were obtained at higher Reynolds number. Herein, the motivation of this work is to acquire a further knowledge about the pressure fluctuations in the transonic turbulent cavity flow with modal decomposition, and meanwhile make clear the effect of Reynolds number. It is expected that this study can serve as a reference for further investigation and cavity-flow oscillation control.

To achieve the objective, a numerical investigation on turbulent cavity flow [22,24] at a free stream Mach number of 1.19 with Length/Depth/Width of 5.0/1.0/1.0 is carried out in this paper. With the POD and DMD methods, detailed analysis on the pressure fluctuations is implemented and the effects of free stream Reynolds number on feedback tones are investigated.

The paper is organized as follows: Section 2 describes the details of numerical methods. The mode decomposition methods used in the present investigation, including the POD and DMD algorithms, are explained in Section 3. In Section 4, computational details are described, such as grid information, boundary conditions, algorithms and result validations. Computational results and analysis are presented in Section 5. Finally, conclusions are summarized in Section 6.

2. Numerical methods

All the computational simulations are carried out by an in-house finite volume solver developed by the authors, which has been utilized for steady and unsteady numerical simulations of turbulent flows [31,32]. The three-dimensional compressible Navier–Stokes equations are solved with finite volume method on multi-block structured data structure in an arbitrary curvilinear system. For simplicity, main algorithms of the solver are described as follows.

2.1. Improved delayed detached-eddy simulation (IDDES)

In this study, IDDES based on the two-equation shear stress transport (SST) turbulence model [33,34] is employed to predict the unsteady turbulent flows over an open cavity. The hybrid RANS–LES method was developed from the delayed detached-eddy simulation (DDES) [35], and has been successfully applied into considerable numerical simulations of unsteady turbulent flows [36,37].

The construction of two-equation SST IDDES method is implemented by modifying the dissipation-rate term of the turbulent kinetic energy transport equation. More details are described as follows:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho U_i k)}{\partial x_i} = P_k - \frac{\rho k^{3/2}}{L_{\text{hybrid}}} + \frac{\partial}{\partial x_i}\left[(\mu+\sigma_k\mu_T)\frac{\partial k}{\partial x_i}\right] \quad (3)$$

$$\frac{\partial(\rho\omega)}{\partial t} + \frac{\partial(\rho U_i \omega)}{\partial x_j} = \alpha\rho S^2 - \beta\rho\omega^2 + \frac{\partial}{\partial x_i}\left[(\mu+\sigma_\omega\mu_t)\frac{\partial \omega}{\partial x_i}\right] + 2(1-F_1)\rho\sigma_{\omega 2}\frac{1}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i} \quad (4)$$

where k is the modeled turbulent kinetic energy, and ω is the specific turbulence dissipation rate. L_{hybrid} is the length scale defined as [34]:

$$L_{\text{hybrid}} = \tilde{f}_d(1+f_e)L_{\text{RANS}} + (1-\tilde{f}_{de})L_{\text{LES}} \quad (5)$$

$$L_{\text{RANS}} = \sqrt{k}/(\beta^*\omega), \qquad L_{\text{LES}} = C_{\text{DES}}\Delta \quad (6)$$

in which L_{RANS} and L_{LES} are the length scales of RANS and LES respectively, and β^* is a constant in the SST model equals to 0.09. In SST-IDDES model, C_{DES} is a DES constant attained via the blending function $C_{\text{DES}} = 0.78F_1 + 0.61(1-F_1)$, where F_1 is defined as

$$F_1 = \tanh\left\{\left\{\min\left[\max\left(\frac{\sqrt{k}}{\beta^*\omega d}, \frac{500\mu}{d^2\rho\omega}\right), \frac{4\rho\sigma_{\omega 2}k}{CD_{k\omega}d^2}\right]\right\}^4\right\} \quad (7)$$

$$CD_{k\omega} = \max\left(\frac{2\rho\sigma_{\omega 2}}{\omega}\frac{\partial k}{\partial x_i}\frac{\partial \omega}{\partial x_i}, 10^{-10}\right) \quad (8)$$

The grid scale Δ is defined as

$$\Delta = \min\left[\max(C_w\Delta_{\max}, C_w d, \Delta_{\min}), \Delta_{\max}\right] \quad (9)$$