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Numerical Investigation of the Coherent Structures and Sound Properties in Sonic Coaxial Jets

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Abstract. Numerical investigation of the underexpanded sonic coaxial jets is carried out using large eddy simulation for three typical inner nozzle lip-thicknesses. Various fundamental mechanisms dictating the flow phenomena including shock structure, shear layer evolution and sound production are investigated. It is found that the inner nozzle lip induces a recirculation zone between inner and outer jets, which significantly influences the behaviors of shock structures and shear layers. The sound properties of the coaxial jets are further analyzed in detail. As the inner lip-thickness increases, the helical screech mode switches to an axisymmetric one and high-frequency screech also occurs with an oscillation frequency of recirculation zone. Based on the temporal Fourier transform and correlation analysis, the primary sources of low- and high-frequency screeches are associated with the downstream shock cells in the jet column and the secondary shock structures in the outer annular jet, respectively. The proper orthogonal decomposition analysis reveals that the dominant structures constructed by the most energetic modes shift from the downstream shock cells region to the upstream secondary shock region as the lip-thickness increases. The results obtained in this study provide physical insight into the understanding of the mechanisms relevant to the coherent structures and sound properties in sonic coaxial jets.

AMS subject classifications: 76Q05, 76F65, 76F70
Key words: Large eddy simulation, coaxial jet, screech, turbulent flow.

1 Introduction

The underexpanded dual coaxial jets have attracted much attention because of the extensive fundamentals and applications, such as to enhance the fuel/air mixing in combustion chamber [1] and to reduce the exhaust jet noise [2]. Numerous studies have focused

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on the evolution processes of low-speed coaxial jets [3, 4], but the flow characteristics of high-speed jets which contain complicated shock structures and their interacting with vortical structures are lack of detailed study.

Some flow behaviors of the coaxial jets were investigated to indicate that the shock structures are strongly dependent on the pressure ratio of the secondary annular stream [5, 6]. The presence of secondary flow was found to confine the primary flow and to generate stronger compression-expansion regions [7]. The supersonic dual coaxial jets lead to a considerable increase in the shear-layer growth [8]. Some experiments about underexpanded sonic coaxial jets were carried out [9–11] to deal with the influences of nozzle-lip thickness, secondary stream thickness, swirling and nozzle pressure ratio on the near-field structures. Recently, a large eddy simulation (LES) was performed to investigate the flow features of a supersonic jet with and without steady micro-jet injection [12]. The mean flow pattern showed that a secondary shock cell is attached to the nozzle exit lip and is formed due to pressure mismatch between the supersonic region upstream of the nozzle exit and the ambient.

The production of screech by supersonic jets is a typical problem. Based on the investigation of a single supersonic jet noise, the noise comprises three basic components including the turbulent mixing noise, the broadband shock-associated noise, and the screech tones [13]. Screech tones were also studied experimentally [14–16]. According to the different instability modes, four discrete frequency stages were identified [14]. The investigation on the oscillation of shock waves in screeching underexpanded circular jets indicated that the mode of shock motion is the same as that of the emitted screech tone [17]. Based on the analysis of helical screech mode, it was found that the effective sound source constantly rotates around the jet axis at the rear of the third shock cell [18]. Moreover, the flapping and helical screech modes from an underexpanded supersonic circular jet was also studied numerically [19]. Recently, a proper orthogonal decomposition was used to extract the dominant coherent structures of the jet and to investigate the sound production of the screech [20], indicating that the sources of the screech are mostly located at the high-speed side of the shear layer in an area extending from the second to the fourth shock cells.

Understanding the screech characteristics of coaxial jets is of interest in fundamental and application. The effects of supersonic coaxial jet on its noise were studied experimentally to reveal that the external stream reduces jet noise and minimum noise conditions exist [21]. The further investigation considered the effects of the velocity ratio, the density ratio and the area ratio independently [22]. Moreover, the screech can be enhanced by flight at high fully expanded Mach number and several mode switchings were identified as the flight velocity was increased [23].

The nozzle lip-thickness plays an important role in the sound field of a high-speed jet. Based on the analysis of jet acoustics and shock-cell structures, it was found that the lip-thickness induces a large sinuous oscillation in jet shear flow and increases the screech sound pressure level [16]. Moreover, the numerical simulation on the axisymmetric jet screech modes showed that the nozzle lip-thickness has an influence on screech intensity