Numerical Study of Shock-Associated Noise in Axisymmetric Supersonic Jet

H. Li, Y. Luo and S. H. Zhang

Abstract Near field screech tone analysis of a typical underexpanded low supersonic circular jet issuing from sonic nozzle have been carried out numerically through solving axisymmetric Navier-Stokes equations directly. Screech tones's spectral information and the dynamic evolution of their corresponding flow structures and acoustic field are presented. Numerical results indicate that axisymmetric A_1 mode and A_2 mode screech tones are generated at the trailing edges of fourth and third shock-cell respectively. It is also found that screech tone's generation is associated with the compressive regions outside jet shear layer closely.

Keywords Axisymmetric supersonic jet · Screech tone · Shock cell DNS

1 Introduction

Most high-speed jet accompanying propulsion systems produces intense radiated jet noise. As well known, imperfectly expanded supersonic jet noise consists of three principal components: turbulent mixing noise, broadband shock-associated noise, and screech tones [8]. The turbulent mixing noise is directly associated with large-scale structures or instability waves in the shear layer; whereas, the broadband shock-associated noise and screech tones are associated with the interaction of these instability waves with the shock cell structures in the jet core. Specially, Powell's pioneering work [3, 4] indicated that screech tone is produced by a self-sustained

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feedback loop. Since then, lots of investigations on screech tone has been conducted via experiments and numerical approaches. Raman [7] provided a concise historical perspective and summary of process in jet screech research during almost 50 years from Powell's discovery. Good understanding of screech generation mechanism and prediction of screech frequency and amplitude are necessary in order to suppress screech tones without performance loss. It is well known that at low supersonic jet Mach numbers axisymmetric mode is the dominant screech mode. The objective of this paper is to examine where and how the screech tones of axisymmetric mode generate in typical low supersonic underexpanded jets.

2 Computational Details

Underexpanded supersonic circular cold jets are studied by direct numerical simulation using fifth order WENO scheme [1] for the axisymmetric Navier-Stokes equations in generalized curvilinear coordinate system. The jet is assumed to be supplied by a convergent nozzle whose designed Mach number is therefore equal to 1. The thickness of nozzle is $0.4D$ and $0.2D$ (where D is nozzle diameter) and the fully expanded jet Mach number is 1.19. The full computational domain is taken from $-5D$ to $40D$ in the streamwise direction and from $0D$ to $18D$ in the radial direction. Beyond the streamwise location of $15D$ and radial location of $6D$, grid cells are stretched and serve as sponge zones. Thompson's characteristic farfield boundary conditions are applied at left boundary and upper boundary regions. At the downstream boundary region, the non-reflecting outflow boundary condition is implemented. At the nozzle exit, the inflow plane is recessed by six cells so as not to numerically restrict or influence the feeback loop. The flow variables on the inflow plane are taken to be uniform corresponding to those at the exit of sonic nozzle. All nondimensional variables ar given as follows:

$$\rho_e = \frac{\gamma(\gamma+1)p_e}{2T_r},\ p_e = \frac{2}{\gamma}\left[\frac{2+(\gamma-1)M_j^2}{\gamma+1}\right]^{\gamma/\gamma-1},\ u_e = \left(\frac{2T_r}{\gamma+1}\right)^{1/2},\ v_e = 0 \quad (1)$$

where γ is equal to 1.4 and T_r is the reservoir temperature. For cold jet assumption, T_r is set to 1. Initially, the whole computational domain except nozzle inlet is set to ambient flow conditions as below:

$$\rho = 1,\ u = 0,\ v = 0,\ p = \gamma^{-1} \quad (2)$$

The unsteady flowfield containing sound waves are obtained and the generation mechanism of axisymmetric mode jet screech tone is investigated.

3 Results and Discussion

3.1 Shock-Cell Structure and Mean Velocity Profiles

A comparison of the present numerical schlieren and experimental schlieren photograph [5] show good agreement in shock cell structures (see Fig. 1). It is observed that the first two shock cells appear to be sharp and clear since the nearby shear layer instability wave is too weak to significantly affect the shock cells. However, when shear layer instability wave reaches the third and fourth shock cells, it has gained sufficient energy through streamwise growth. It interacts with the third and forth shock cells, which result in their deformation and produce screech tones. Figure 2 presents the comparison of our simulated time-averaged density along jet axis with Gao and Li's axisymmetric URANS result [2] and Panda and Seasholtz's experimental result [6]. It is shown that the first four shock cells agree well with the URANS result in both position and amplitude but there are deviations in the rest shock-cells. This is because that URANS method is more dissipative than present method and corresponding grid is more coarser than present grid. Both the present result and Li and Gao's axisymmetric URANS result have discrepancy with the experimental data behind the third shock cell. It results from excessive dissipation of numerical algorithm in the region before the eighth shock cell and axisymmetric N-S equations in the downstream region.

3.2 Screech Tone's Frequency and Sound Pressure Level

The time history of pressure signal is recorded at the selected monitor in the flowfield and later post-processing is to obtain spectral information using Fast Fourier Transformation techniques. Figure 3 displays the sound signal's spectral informations (frequency and SPL) of monitor located at the nozzle exit lip wall. The SPL shows that there are four spikes in the frequency spectrum range of larger than 5000 Hz. The two correspond to screech frequencies of 6567 Hz (128 dB, A_1 mode) and 8637 Hz (123 dB, A_2 mode), while the rest two correspond to frequencies of 12,087 Hz (125 dB, B mode harmonic) and 14310 Hz (123 dB, A_0 mode).

3.3 Axisymmetric Mode Screech Tone's Generation Mechanism

Figures 4 and 5 present the flow structures and acoustic waves related to screech tones of A_1 mode and A_2 mode respectively. In the figures, the part with orange red color is the flow structure characterized by numerical schlieren and the gray part is

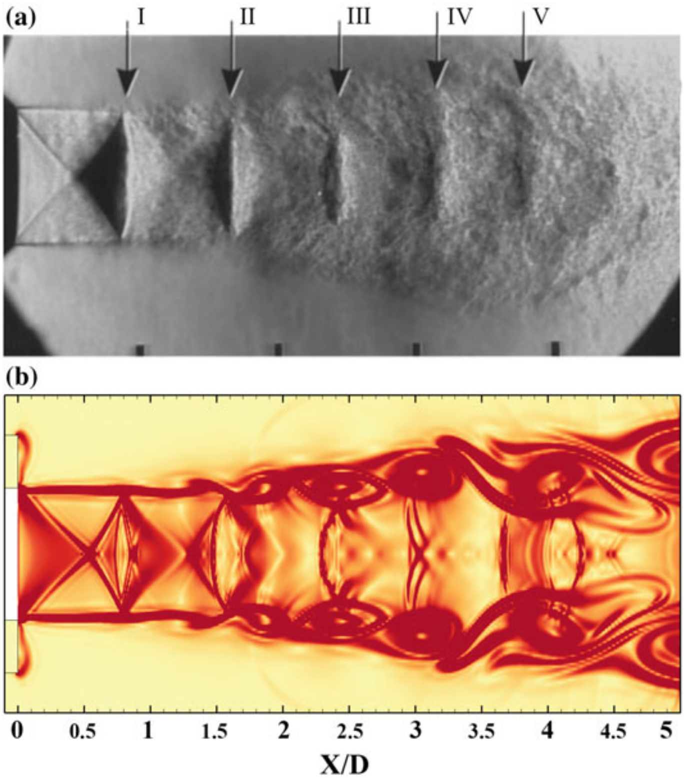
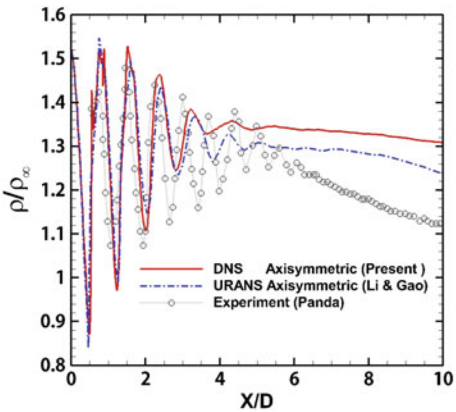


Fig. 1 Numerical schlieren (bottom) for shock cell structure of a supersonic jet at $M_j = 1.19$ and its comparison with experimental schlieren (top)

Fig. 2 The time-averaged density along the axis and its comparison with numerical and experimental results of screeching jet at $M_j = 1.19$



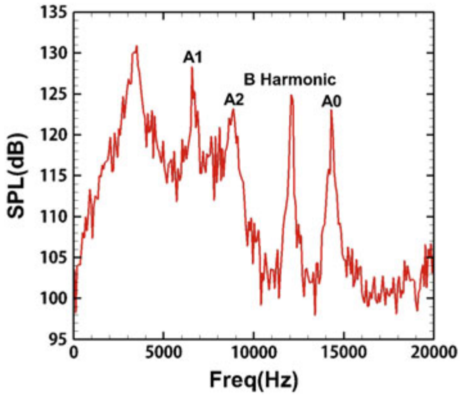


Fig. 3 Spectral analysis of sound signal at the point [0.0, 0.642] on the nozzle exit lip wall

the acoustic field characterized by dilatation. It is shown that screech tones of A_1 and A_2 modes emitted from the regions of third or fourth shock cells.

Figure 6a–f present the spatial and temporal evolution of flow structures and acoustic field corresponding to screech tone of A_2 mode in its complete cycle. At the beginning (t_0) of A_2 mode screech's period (T), a vortex saddle point in the jet shear layer is present at the third shock-cell's trailling edge (streamwise location of $x = 2.43D$ after nozzle exit), where the compressive region outside shear layer and shock tip inside shear layer are connected. As the continuous development of coherent structures in shear layer, such connection will be cut off by the vortices traveling dowstream. After that, the outside compressive region gradually stretches out a tentacle (see Fig. 6b). It will build bridge connection with upstream adjacent compressive region outside of shear layer to form an arc-shaped compressive wave (see Fig. 6c, d), which gradually grows from small to large and develops into screech tone traveling upstream finally (see Fig. 6e). At the same time, shock-tip inside shear layer will continue to interact with developing vortice moving downstream.

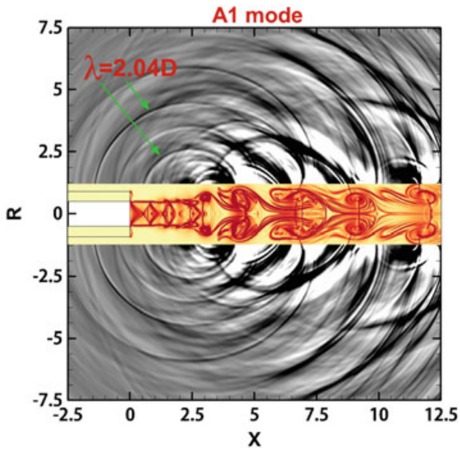


Fig. 4 Flowfield and acoustic field corresponding to the screech of A_1 mode

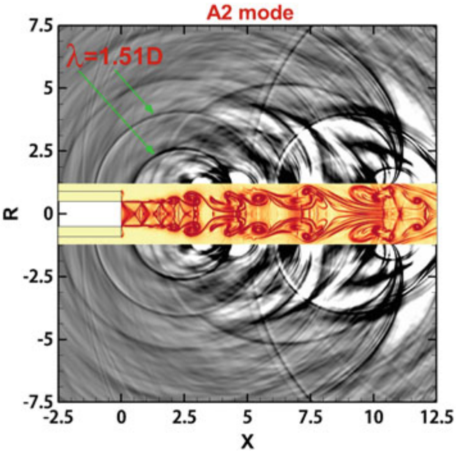


Fig. 5 Flowfield and acoustic field corresponding to the screech of the A_2 mode

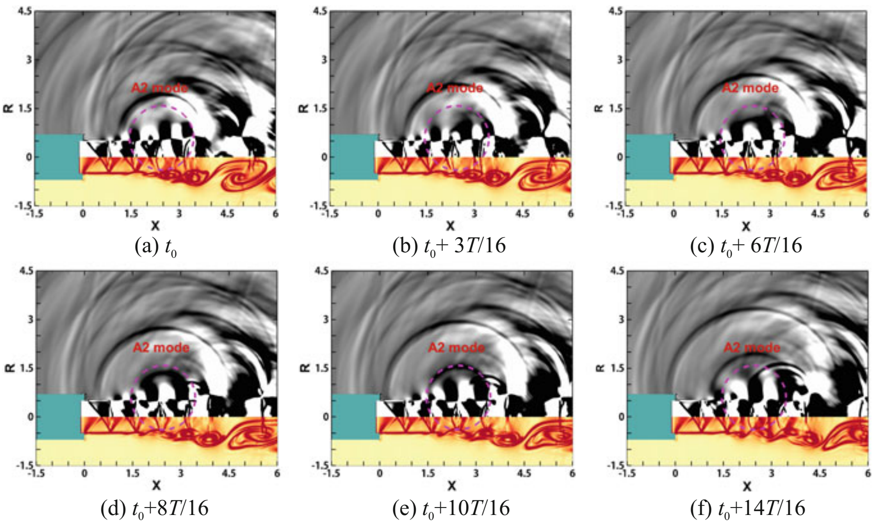


Fig. 6 Spatial and temporal evolution of flow structures and acoustic field associated with screech tone of A_2 mode in its period (the part with orange red color is flow structure characterized by numerical schlieren and the gray part is acoustic field characterized by dilatation (positive value means expansion, white color; negative value means compression, black color))

This interaction can lead shock wave to be bent and straightened, accompanying with shock-tip's backward and forward oscillation. At the ending of the period, an new vortex saddle point forms at original position, where the compressive region outside shear layer and shock tip inside shear layer make links again. As thus, the next A_2 mode screech generation cycle is ready to start.

Although it gives the spatial and temporal evolution of flow structures and acoustic field which describes the A_2 mode screech tone's generation, informations provided by Fig. 6 are not limited to that. At the fourth shock-cell's trailling edge (streamwise location of $x = 3.25D$), another vortex saddle point appears in the jet shear layer (see Fig. 6b), where the nearby flow structures and acoustic field undergo same spatial and temporal evolution as that occurs at streamwise location of $x = 2.43D$. Such dynamic process of evolution also generates acoustic wave (see Fig. 6f), and it should be screech tone of A_1 mode.

4 Conclusions

In this paper, direct numerical simulations of axisymmetric underexpanded supersonic jet issuing from sonic nozzle at jet Mach number of $M_j = 1.19$ are carried out using fifth order finite difference WENO scheme. The frequencies and amplitudes of near-field screech tones, including A_1 and A_2 mode, are obtained. The axisymmetric mode screech tone's generation mechanism is revealed through analyzing the corresponding spatial and temporal evolution of flowfield and acoustic filed in complete cycle. It is concluded that the axisymmetric A_1 mode and A_2 mode screech tones are generated at the trailing edges of fourth and third shock-cell respectively. The investigation also indicates the relationship between screech tones's generation and compressive regions outside jet shear layer.

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