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NUMERICAL SIMULATION ON SCREECH TONE GENERATED BY TWO-DIMENSIONAL SUPERSONIC JETS

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ABSTRACT

The screech tone generated by a two-dimensional supersonic jet is studied numerically by solving the Euler equations with the ENO (essentially non-oscillatory) scheme. The details of shock cell structure, large-scale vortices, and sound generation mechanisms are elucidated. Numerical results for streak lines show clearly that shear layers begin to roll up at the third shock cell and grow into large-scale vortices destroying the shock cell structure further downstream. Beyond the third shock cell large-scale vortices cease to grow and convect at a nearly constant speed. In the growing process of large-scale vortices, it is observed that the jet plume and the vortex core compress the ambient air confined between them increasing its total temperature, whereas both of them losing their own energy. This higher energy fluid is pressed out of the vortex structure forming a sound source. Acoustic intensity analysis indicates that several sound sources along the jet plume bring acoustic interactions which make it possible that an acoustic energy feedback occurs only at the first shock cell.

1 INTRODUCTION

Powell [1] first used a feedback loop model to describe the supersonic jet screech generation mechanism. This model is as follows: the instability wave and the shear layer

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develop enough to interact with the shock cell structure; this interaction generates a sound which propagates upstream and excites the instability wave at the nozzle exit. The existence of this feedback loop is proved by the fact that the screech tone weakens when sound propagation is shielded or strengthens when a reflector is set on the nozzle lip. Westly and Wooley [2] measured the field around a circular jet. Rice and Taghavi [3] investigated sound source structure of a rectangular jet. Many investigators studied acoustic fields and the other characteristics of screech tones such as frequency, mode, directivity, and effects of nozzle shape [4].

Although Powell's feedback loop model has been widely accepted, there have been no satisfactory answers to the following questions:

- What does the interaction between the instability wave and the shock cell structure actually mean?
- How does the sound wave excites the instability wave?

To answer these questions there are two different approaches. One is to measure and observe details of supersonic jets flow and acoustic fields. The other approach is to simulate comprehensively by Computational Fluid Dynamics (CFD).

Suda and Kaji [5] investigated high aspect-ratio rectangular over- and under-expanded supersonic jets. They showed the strongest sound source exists around the third shock cell and found traveling waves in the third shock cell. Figure 1 shows an instantaneous schlieren photograph of an over-expanded jet. The condition is as follows: A 1.9 Mach number over-expanded supersonic jet is blowing into an ambient air; the total pressure of the jet is 4.0 times as large as the static pressure of the ambient air.

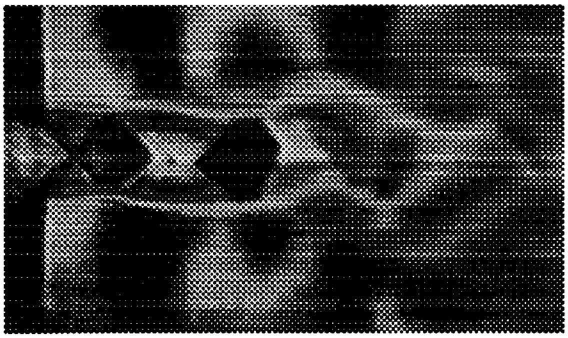

Figure 1: Schlieren photograph of an over-expanded rectangular supersonic jet.

Kaji and Nishijima [6] solved two-dimensional under-expanded jets by the symmetric TVD scheme. They described that several sound sources exist at the end of each shock cell compression portion, and these sound sources create several singular points around which acoustic energy swirls. These singular points were found by a pressure measurement with side walls. One pair of singular points nearest to the nozzle exit are so close to the shear layers at the first shock cell, the swirling acoustic energy flows into the shear layers.

This paper deals with a two-dimensional over-expanded supersonic jet. The main objective is to confirm that an acoustic energy feedback exists at at the first shock cell in an over-expanded jet as an under-expanded jet and to reveal the interaction between large-scale vortices and shock cell structure including traveling waves in the third shock cell. Results show good agreement with features of screech tones and also give some indication on the sound generation mechanism.

2 NUMERICAL METHOD

To simulate the whole physical phenomena precisely, the Navier-Stokes equations should be applied. But the fundamental elements of screech, i.e. the Kelvin Helmholtz instability and shock cell structure, are presumed to be non-viscous phenomena; accordingly the Euler equations are adopted.

Shu and Osher's ENO (essentially non-oscillatory) -Roe scheme with Runge-Kutta method [7] is applied and the second order accuracy both in space and time is selected. The ENO-Roe scheme is a finite difference method with adaptive stenciling. Usually a high accuracy method is used to calculate an acoustic field, but we can use a low accuracy method because the screech tone is so intense that it is easy to capture. Simultaneously streak lines are solved explicitly which help us to imagine how the jet plume produces large-scale vortices or proceeds in the ambient air.

The calculation region is a 500mm × 200mm rectangular with 250 × 200 stencils. The nozzle exit height is 9.3mm. Grid size near the nozzle is 0.3mm × 0.8mm and the nozzle exit include 31 stencils. The stencils are symmetric with regard to the nozzle exit center. The nozzle exit and the nozzle lip walls (13.5mm thick) correspond to a calculation boundary. A uniform flow condition is imposed on the nozzle exit, slip wall condition on the nozzle lips and characteristic non-reflecting boundary condition [8] on the other boundary. The initial condition for the ambient air is $1.01325 \times 10^5 [Pa]$ static pressure, $288.15[K]$ total temperature, and 0.15 Mach number. For the nozzle exit $4.053 \times 10^5 [Pa]$ total pressure (4.0 times as large as the static pressure of the ambient air), $288.15[K]$ total temperature, and 1.9 Mach number are given. This condition is nearly same as that of the experiment which gives Figure 1 for schlieren visualization except that the ambient air is not still.

Although the calculation stencils are symmetric, truncation errors destroy the numerical flow field's symmetry as calculation time step progresses. Truncation errors in numerical simulations are thought to be similar to disturbances in the real nature. As the oscillation amplitude grows and saturates, the numerical flow field reaches nearly periodic.

3 RESULTS AND DISCUSSION

3.1 Flow field

The over-expanded jet plume oscillates in the vertical direction periodically and both sides of the shear layers emit large-scale vortices alternately. Figure 2 shows instanta-

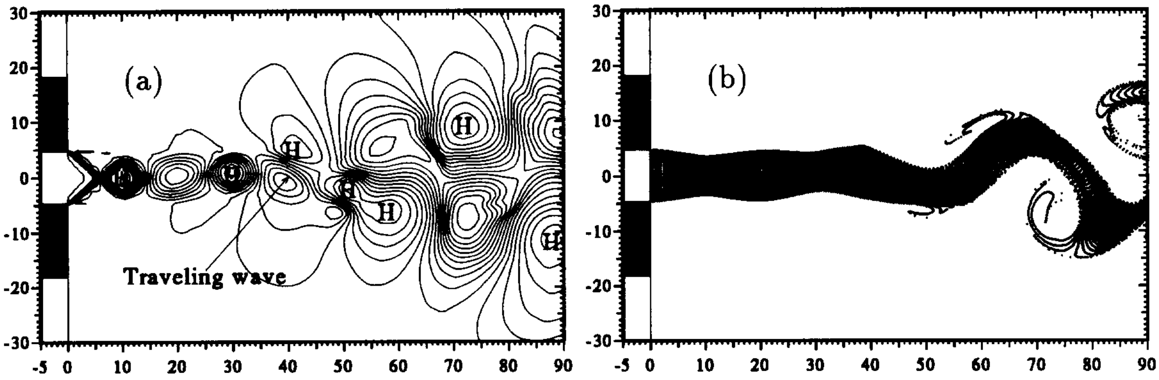

Figure 2: (a) Static pressure contours with 20000[Pa] contour step, 'H' denotes the high pressure peak; (b) Streak lines.

neous static pressure contours and jet streak lines. They show good agreement with the schlieren photograph (Fig. 1). The over-expanded jet creates two shock waves and shear layers at both ends of the nozzle exit. The shear layers reflect these shock waves as expansion waves, and again reflect them as compression waves. The jet plume and the shear layers repeat this for a couple of times creating shock cell structure. The first and the second shock cells [2] appear clearly while the third shock cell dynamically changes its shape with the traveling waves. A traveling wave sweaps downstream with some rotary motion in the third shock cell. The ENO scheme can't capture traveling waves as clearly as schlieren photographs, but the resolution is enough to observe this phenomena.

The jet streak lines (Fig. 2(b)) show obviously how the large-scale vortices grow and the jet plume flows. One side shear layer begins to roll up at the third shock cell after the other side shear layer periodically. The shear layer rolls up, grows into a large-scale vortex and complete its growth behind the third shock cell. After ceasing to grow, the vortex convects at a nearly constant speed. The jet plume which is not caught in the vortices winds its way through the vortex structure. The high pressure portions in the vortex structure correspond to the positions where the jet plume bends its flow direction, i.e. the maximum deflection points in the flapping motion. It seems the jet plume does not have the shock cell structure beyond the third shock cell.

The shock cell structure and the shear layers interact with each other remarkably at the third shock cell. The details of this interaction will be described below.

3.2 Acoustic field

To understand how acoustic energy propagates, acoustic intensity analysis is very helpful. Acoustic intensity is the time-averaged acoustic energy flux passing through a unit area and the time-averaged total-enthalpy flow equals the acoustic intensity in a moving media. The acoustic intensity $\hat{\mathbf{I}}$ is defined as follows in a non-rotational and isentropic

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[2] One shock cell means one structure between two neighboring compression portions. An over-expansion jet has an expansion portion at the nozzle exit. The first shock cell is between the nozzle exit and the first compression portion.

flow,

$$\hat{\mathbf{I}} = \overline{\left(\frac{p'}{\rho_0} + \mathbf{u}' \cdot \mathbf{u}_0\right)(\rho_0 \mathbf{u}' + \rho' \mathbf{u}_0)} \tag{1}$$

where p is static pressure, ρ density, $\mathbf{u}$ velocity vector, and superscript ’$'$’ denotes perturbation value, subscript ’0’ time-average. We can use this definition to observe outside of the jet because the flow field is nearly non-rotational and isentropic apart from the jet plume, the shear layers and the vortex structure.

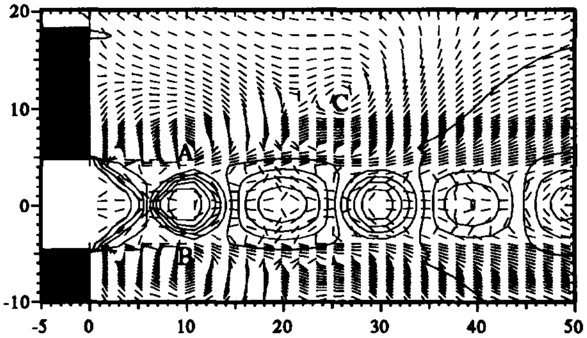
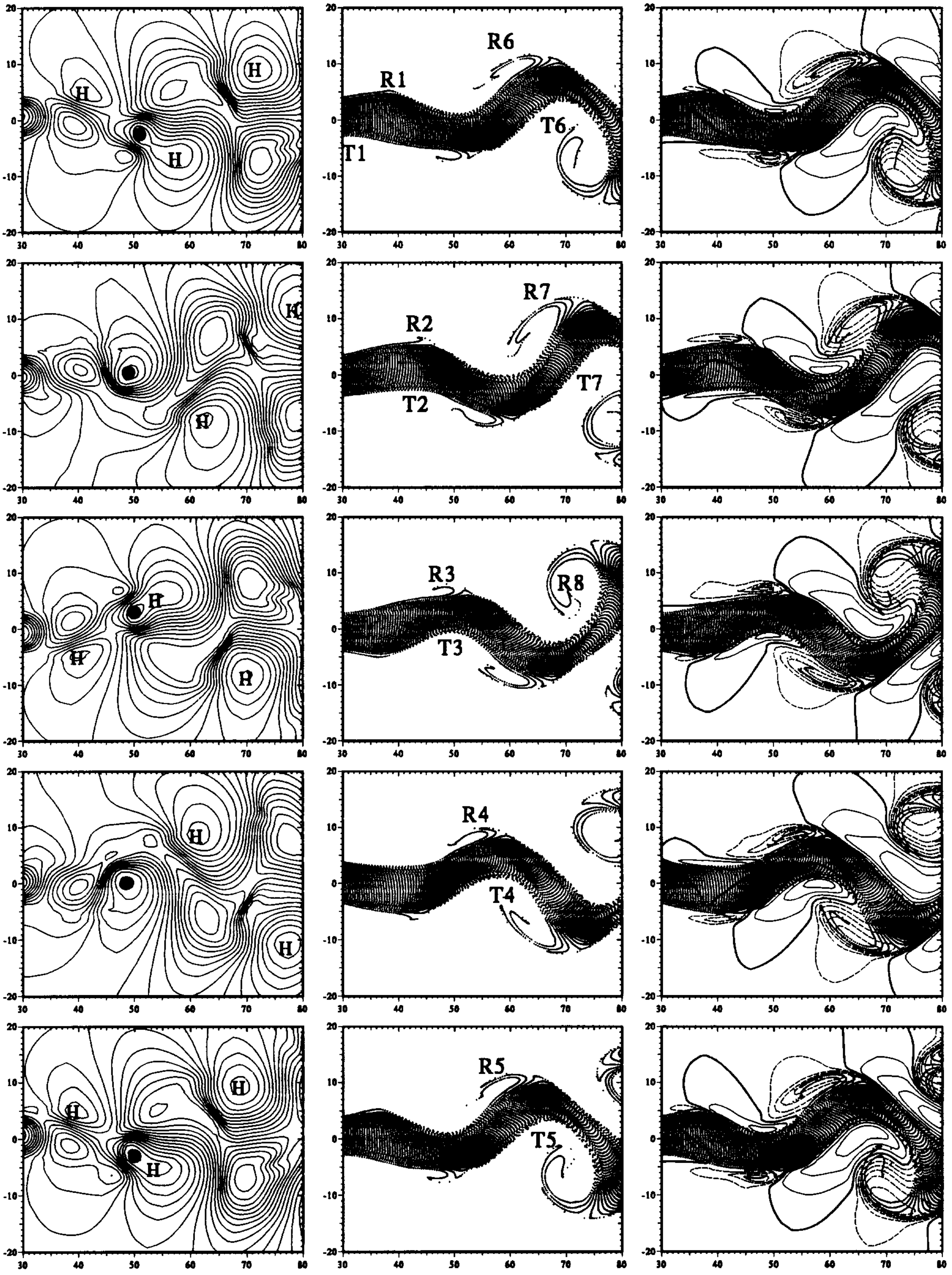


Figure 3: Acoustic intensity unit vectors.

Figure 3 shows unit vectors of acoustic intensity with the time-averaged static pressure contours. We can find several singular points (e.g. points A, B, and C) around which acoustic energy flow swirls. The acoustic energy flow swirls counterclockwise around the points A and C, and clockwise around the point B. The acoustic energy near the points A and B flow into the shear layers at the first shock cell. As Kaji and Nishijima [6] pointed out in a calculated under-expanded supersonic jet, it seems an acoustic energy feedback exists near the first shock cell in an over-expanded jet. These singular points are derived from several sound sources. In an acoustic field where several sound sources exist there appear singular points where phase is not continuous and SPL (Sound Pressure Level) is quite low. These singular points correspond to the points around which the acoustic energy flow swirls. In this acoustic field it seems sound sources exist at the end of each shock cell compression portion. The acoustic feedback is not realized only by the most intense sound source around the third shock cell but by the other sound sources.

3.3 Interaction between large-scale vortices and shock cell structure

Figure 4 shows series of one period static pressure contours (a), jet streak lines (b), and total temperature contours with jet streak lines (c) around the third shock cell. In Fig. 4(a) a black circle indicates the third compression portion of the shock cell structure and an ’H’ the high static pressure peak. In Fig. 4(b) each of R1-R8 indicates the position of the shear layer roll up or the large-scale vortex and each of T1-T8 indicates the high total temperature peak. In Fig. 4(c) the 288.15[K] (the initial condition for



(a) (b) (c)

Figure 4: Series of one period. (a) Static pressure contours with 20000[Pa] contour step; (b) Streak lines; (c) Total temperature contours with 15[K] contour step, bold lines 288.15[K], dashed lines under 288.15[K], and solid lines over 288.15[K].

both the jet and the ambient air) contours are drawn with bold lines, under 288.15[K] contours with dashed lines, and over 288.15[K] contours with solid lines.

Figure 4(a) shows the motion of the third compression portion and the traveling waves. It appears the third compression portion doesn't move remarkably in the horizontal direction but move dynamically in the vertical direction. It means the jet plume oscillates in the vertical direction sustaining the shock cell structure. Beyond the third shock cell there is no remarkable interaction. Of course compression or expansion occurs in the jet plume, but this compression or expansion is not by waves reflected by the shear layers. This confirms that the jet plume dose not have the shock cell structure beyond the third shock cell.

Figure 4(b) shows clearly how the shear layers grow into the large-scale vortices. The shear layer roll up can be seen by following the points R1-R8. It is observed that one end of the traveling wave corresponds to the location of the shear layer roll up (e.g. R1 and R2) and the other end is located on the other side of shear layers near the third compression portion.. After the vortex core goes beyond the third compression portion, vorticity increases and a large-scale vortex rapidly grows.

The total temperatures of the jet plume and the ambient air at the beginning are the same (288.15[K]), so energy exchanges in the flow field can be investigated easily by observing total temperature. The ambient air confined between the jet plume and the vortex core increases its total temperature in the growing process of large-scale vortices. The total temperature is near 288.15[K] at T1 and reaches over 350[K] at T4. With the jet plume oscillation and the vortex growth, the jet plume and the vortex core compress the ambient air between them and press that higher energy fluid out of the vortex structure. On the other hand the jet plume and the vortex core lose their own energy. It can be assumed this process produce an intense sound source. A further deep investigation into the relation between this energy exchange and the sound generation is needed.

4 SUMMARY

The ENO-Roe scheme for the Euler equations was applied to solve an over-expanded supersonic jet's flow field and acoustic field. As in a calculated under-expanded jet, an acoustic energy feedback occurs at the first shock cell with several sound sources (Figure. 3). The jet streak lines clearly showed the shear layer roll up, the large-scale vortex structure, and their interaction with the shock cell structure (Fig. 2). The ENO scheme succeeded in capturing the traveling waves observed in schlieren photographs and found that one end of the traveling wave corresponds to the location of the shear layer roll up (Fig. 4). The shear layer begins to roll up at the third shock cell and grows into a large-scale vortex. The growth rapidly proceeds behind the third compression portion, and beyond the third shock cell there is no more shock cell structure and the jet plume winds its way through the vortex structure with no reflected expansion waves nor compression waves. In growing process of large-scale vortices, the oscillating jet plume and the vortex core compress the ambient air confined between them and press it out of the vortex structure. This process may emit an intense sound.

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