Numerical Simulation of Supersonic Screech Tone Noise using High-order, High-resolution Optimized Compact Scheme

In Cheol Lee*, and Duck-Joo Lee

Department of Aerospace Engineering
Korea Advanced Institute of Science and Technology(KAIST)
373-1 Guseong-dong, Yuseong-gu, Daejeon, 305-701 Republic of Korea
E-mail:essence@acoustic.kaist.ac.kr - Web page: http://acoustic.kaist.ac.kr

Key Words: computational aeroacoustics, screech tone, jet noise, compact scheme

ABSTRACT

As well known, supersonic jet noise consists of three principal components: turbulent mixing noise, broadband shock-associated noise, and screech tones.[1] In this work, among three components of jet noise, the screech tone of an underexpanded jet is numerically calculated. It will be useful to understand the basic characteristic of screech tone noise. Also the correct result will show the validation of present numerical method.

All the governing equations of motion for the two dimensional/axisymmetric inviscid flow are:

$$\frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \frac{\partial \mathbf{F}}{\partial y} + \alpha \mathbf{H} = 0 \tag{1}$$

where

$$\mathbf{Q} = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho e_t \end{bmatrix}, \mathbf{E} = \begin{bmatrix} \rho u \\ \rho u^2 + p \\ \rho uv \\ (\rho e_t + p)u \end{bmatrix}, \mathbf{F} = \begin{bmatrix} \rho v \\ \rho vu \\ \rho v^2 + p \\ (\rho e_t + p)v \end{bmatrix}, \mathbf{H} = \frac{1}{y}\begin{bmatrix} \rho v \\ \rho vu \\ \rho v^2 \\ (\rho e_t + p)v \end{bmatrix} \tag{2}$$

and $\alpha = \begin{cases} 0 \text{ for a two - dimensional planar flow} \\ 1 \text{ for a two - dimensional axisymmetric flow} \end{cases}$

In this research, axisymmetric Euler equations are used so α goes to 1. It is one of the characteristics that Euler equation is used and no effect of viscous flow is considered. For the case of three dimensional calculations, the governing equation that is used in this work can be written as below:

$$\frac{\partial \mathbf{Q}}{\partial t} + \frac{\partial \mathbf{E}}{\partial x} + \frac{\partial \mathbf{F}}{\partial y} + \frac{\partial \mathbf{G}}{\partial z} = 0 \tag{3}$$

Details are similar as the case of axisymmetric equation.

To accurately simulate screech tone, the flow near the nozzle exit should be simulated correctly and the wave, which propagates upstream with relatively small amplitude, should be analyzed precisely. Hence to make a successful analysis of screech tone, we use the method of CAA (computational aeroacousitcs), which has high-resolution and high-order.

In this work, we use fourth-order OHOC (optimized high-order compact) schemes by Kim and Lee[2][3] for the evaluation of spatial derivatives and the fourth-order Runge-Kutta scheme for the integration in time. To prevent unwanted non-physical reflections around the computational boundaries, we use generalized characteristic boundary conditions by Kim and Lee[4] as the time-dependent boundary conditions. Also, artificial dissipation model developed by Kim and Lee[5] and buffer zone technique are used. All numerical schemes are shown in Figure.1.

The computational domain consists of three sub-domains. The total number of grid points is about 160,000 for axisymmetric computation, and about 1,200,000 for three dimensional computation. and grid points are condensed around the nozzle exit both in the x and y directions

All lengths are non-dimensionalized by the diameter of nozzle exit. The thickness of nozzle is 0.4 times of nozzle diameter.

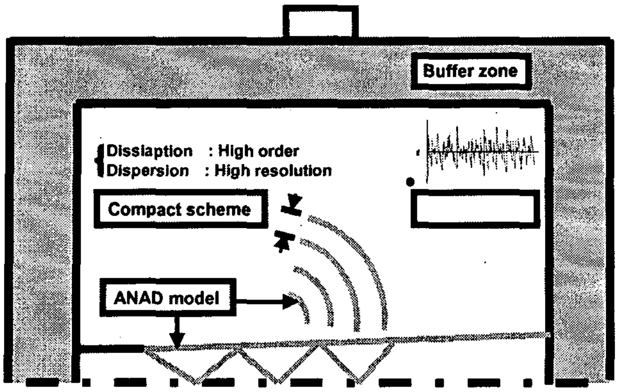


Figure 1. Schematic draw of numerical schemes

The IBM p690 machines are used to simulate supersonic screech tones numerically. Using Open MP, the program was parallelized. When single CPU is used, it takes about 150 hours to get a meaningful result and when four CPUs are used, it takes about 80 hours. The efficiency of parallelization is low because the algorithm of artificial dissipation model which was used in this paper is difficult to be parallelized efficiently.

Using the numerical algorithm described earlier, we have simulated the screech tone of a supersonic jet numerically. Fig. 2 shows the instantaneous pressure contour of a Mach number 1.13 cold jet. From the contour, we observe not only the Mach wave that propagates downstream but also screech tone, which propagates upstream. As is well known, sound waves of screech tones radiate out in a region around the fourth to fifth shock cells downstream of a nozzle exit.

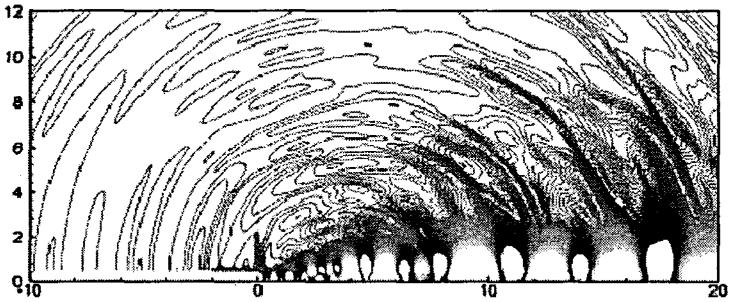


Figure 2. Instantaneous pressure contour (0.91<p/pa<1.09)

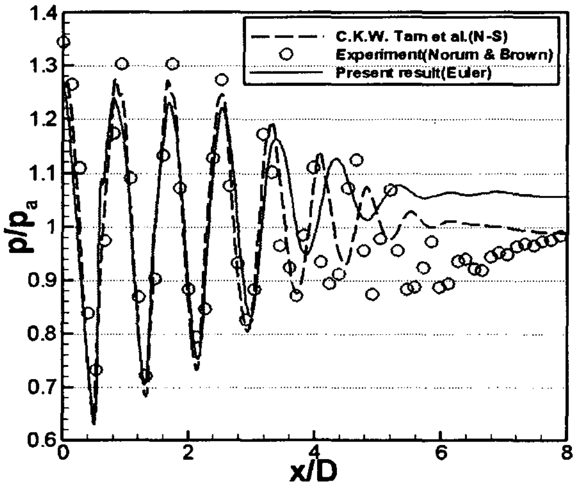


Figure 3. Time-averaged pressure distribution along the centerline of a Mach 1.2 jet

Two important component of screech tone generation is the shock cell structures inside the jet plume and vortices generated at the top of shock cell structures. To ensure that the reproduced shock cells are the same as those in an actual experiment, we compare the time-averaged pressure distribution along the centerline with both the experimental results by Norum[6] and other numerical results by C.K.W. Tam and H. Shen[7]. The time-averaged pressure distribution along the centerline is shown in Fig. 3. It is clear that the first five shock cells are in good agreement with the experiment data in terms of both shock cell spacing and amplitude.

It is well known that at low supersonic jet Mach numbers there are two axisymmetric screech modes: the A1 and the A2 modes. The frequencies of A1 and A2 modes vary and are suddenly shifted with an increase of jet Mach number. Fig. 4 shows the variation of λ/D, where λ is the acoustic wavelength of the tone, with the jet Mach number.

$$\frac{\lambda}{D} = \frac{a_\infty}{fD} \tag{4}$$

The numerical results are compared with both the experimental results of Ponton and Seiner et al.[8] and other numerical results from C.K.W. Tam et al. (1998). The numerical results show good agreement with the other results, particularly the experimental results in Fig. 4.

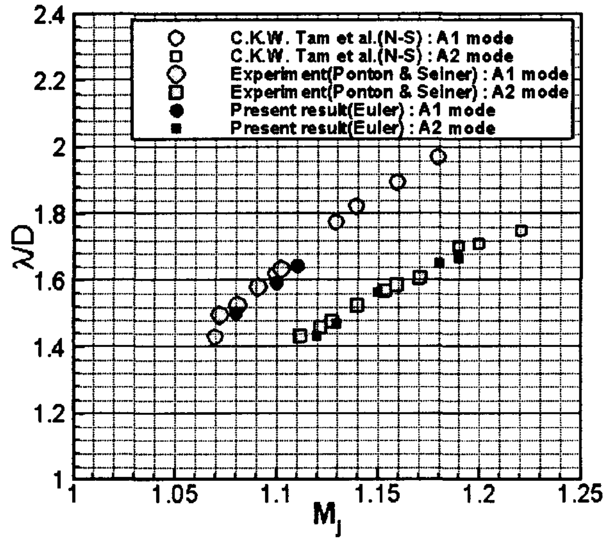
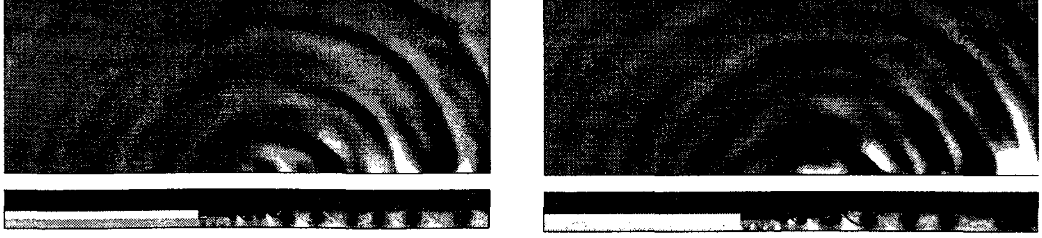


Figure 4. Wavelengths of screech tone

From experimental data, we observe two axisymmetric screech tone modes, and the mode change occurs in the region of jet Mach number between 1.10 and 1.11. The present numerical simulations show that the axisymmetric mode changes between jet Mach number 1.11 and 1.12. So the region of Mach number for mode change is similar between experiments and present results.

Fig. 10 and 11 shows density contours of whole flow filed with different range of density. The flow region of vortices and shock cells and noise region are separated to be observed each of them clearly. When the jet Mach number is 1.08, second and third vortices make a vortex pairing, which can be also seen clearly in Fig. 8. However third and fourth vortices make a vortex pairing when the jet Mach number is 1.12 in Fig. 11.



Mj=1.08 Mj=1.12

Figure 10. Density contours of whole flow field

To see the three dimensional effect, the supersonic jet which has the Mach number of 1.15 is simulated numerically.

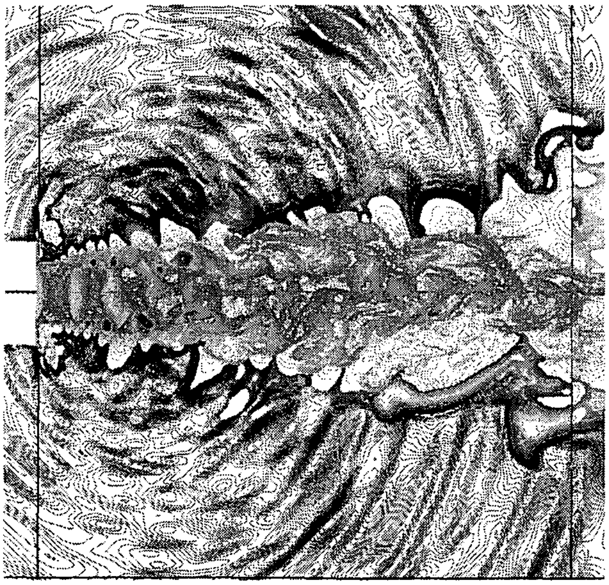


Figure 12. Density contour of Mach number 1.15 (flow+noise)

From Fig. 12, we can know that even for the case of axisymmetric jet, the symmetry breaks down as flow goes further from nozzle exit.

ACKNOWLEDGEMENT

This work was supported by the Strategic Supercomputing Support Program of Korea Super Computing Center.

REFERENCES

[1] C.K.W. Tam (1997). "Supersonic jet noise", *Annual Review of Fluid Mechanics*, Vol. **27**, pp. 17-43.

[2] J.W. Kim, D.J. Lee, (1995). "Optimized compact finite difference schemes with maximum resolution", *AIAA Journal*, vol. **23**, No. 5, pp. 887-893.

[3] J.W. Kim, D.J. Lee, (1997). "Implementation of boundary conditions for optimized high-order compact scheme", *Journal of Computational Acoustics*, Vol. **5**, No. 2, pp. 177-191.

[4] J.W. Kim, D.J. Lee, (2000). "Generalized characteristic boundary conditions for computational Aeroacoustics", *AIAA Journal*, Vol. **38**, No. 11, pp. 2040-2049.

[5] J.W. Kim, and D.J. Lee, (2001). "Adaptive nonlinear artificial dissipation model for computational Aeroacoustics", *AIAA Journal*, Vol. **39**, No. 5, pp. 810-818

[6] T.D. Norum, (1983) "Screech Suppression in Supersonic Jets", *AIAA Journal*, Vol. **21**, No. 2, pp. 235-240.

[7] C.K.W. Tam, H. Shen (1998). "Numerical simulation of the generation of axisymmetric mode jet screech tones", *AIAA Journal*, Vol. **36**, No. 10, pp. 1801-1807.

[8] M.K. Ponton, J.M. Seiner (1992). "The Effects of Nozzle Exit Lip Thickness on Plume Resonance", *Journal of Sound and Vibration*, Vol. **154**, No. 3, pp. 531-549.