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A Numerical Investigation on Supersonic Twin-Jet Noise Using Optimized Compact Monotonicity-Preserving Scheme

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ABSTRACT

A numerical investigation into the noise characteristics of twin-jet is presented. We considered fully-expanded Mach number 1.358 two different distances (s/D=3.0 and s/D=2.5) of inter- nozzles. As proven by experiments in previous studies, these cases have opposite oscillating modes, and the results by present simulations coincident with them. In particular, the symmetric flapping mode generated very large amplitude of acoustic wave so that the dominant frequency reaches up to near 160dB. In addition, by virtue of high-resolution feature of the present scheme, the numerical simulations resolved broadband noise which represented similar level in both cases.

Keywords: High-order, High-resolution, Numerical scheme, Twin jet, Jet noise
I-INCE Classification of Subject Number: 21

1. INTRODUCTION

Supersonic jet in an off-design condition can generate high-level of noise. There are several noise sources in supersonic jet: among them, shock-associated noise and screech noise are dominant components in a broadband spectrum and discrete tone, respectively. In particular, the screech tone which propagates upstream direction has potential to failure the surrounding structures.

Screech tone is generated by the closed feedback loop mechanism. The vortex induced by shear-layer travels downstream, and interacts with a shock-cell at certain position. At this position, a strong acoustic wave is generated so that it excites the nozzle lip with resulting another vortex. The nonlinear behaviour of screech tone and its mechanism have been investigated by several studies [1][2][3].

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In particular, in a twin-jet case, two jet plumes experience the coupling process. Therefore, the characteristics of screech tone becomes different with the single jet case. In practice, Seiner et al.[4] proved that the amplitude of screech tone could highly increase up to 160 dB when the distance between twin nozzles is 1.9D (D is nozzle exit diameter). Actually, this phenomena can be observed in the symmetric oscillation of two jet plumes. The coupling mode of jet plumes can be changed according to the fully expanded Mach number and the distance between twin nozzles. Walker [5] and Wlezien [6] have studied the effect of both of them, and provided various experimental data in coupling or non-coupling twin jet cases. T. Knast et al. [7] has classified several modes of twin jet, and investigated them using the schlieren images for different Mach number and nozzle distance conditions. Furthermore, Walker [5] and Shaw[8] evaluated the screech tone suppression in the experimental way. For a numerical study, J. Gao et al. [9] simulated one of the Walker's experimental case, and showed the different spectrums between single and twin jets. However, there was no numerical study to evaluate the distance between twin nozzles.

In this study, we investigated two different twin jet modes, symmetric and antisymmetric flapping mode, in the numerical way. For the numerical simulation, a 5th order optimized compact monotonicity-preserving scheme (OCMP5) is applied. This scheme is the high-order and high-resolution shock-capturing scheme; therefore, it has capabilities to capture discontinuous solutions in shock-cells, and simultaneously to resolve the acoustic waves in a broad range of wavenumber properties [10]. The behavior of twin jet plumes and acoustic pressure fields in two different nozzle distances are compared. The resonance phenomenon of acoustic pressure is investigated in a pressure-time signal and Fourier-spectrum.

2. NUMERICAL METHODS

2-1. GOVERNING EQUATIONS

In this study, the compressible 3D Euler equation in general coordinates is solved as

$$\frac{\partial \hat{\boldsymbol{Q}}}{\partial \tau}+\frac{\partial \hat{\boldsymbol{E}}}{\partial \xi}+\frac{\partial \hat{\boldsymbol{F}}}{\partial \eta}+\frac{\partial \hat{\boldsymbol{G}}}{\partial \zeta}=0 \qquad \text{(Eq. 1)}$$

and

$$\begin{aligned}
\hat{\boldsymbol{Q}} &= \frac{\boldsymbol{Q}}{J}, \\
\hat{\boldsymbol{E}} &= \frac{1}{J}\left(\xi_t \boldsymbol{Q}+\xi_x \boldsymbol{E}+\xi_y \boldsymbol{F}+\xi_z \boldsymbol{G}\right), \\
\hat{\boldsymbol{F}} &= \frac{1}{J}\left(\eta_t \boldsymbol{Q}+\eta_x \boldsymbol{E}+\eta_y \boldsymbol{F}+\eta_z \boldsymbol{G}\right), \\
\hat{\boldsymbol{G}} &= \frac{1}{J}\left(\zeta_t \boldsymbol{Q}+\zeta_x \boldsymbol{E}+\zeta_y \boldsymbol{F}+\zeta_z \boldsymbol{G}\right)
\end{aligned} \qquad \text{(Eq. 2)}$$

J is the transformation Jacobian. The conservative variables and inviscid flux vectors in the equations are expressed as follows:

$$\begin{aligned}\boldsymbol{Q} &= \left[\rho, \rho u, \rho v, \rho w, \rho e_t\right]^T, \\ \boldsymbol{E} &= \left[\rho u, \rho u^2 + p, \rho v u, \rho w u, (\rho e_t + p)u\right]^T, \\ \boldsymbol{F} &= \left[\rho v, \rho u v, \rho v^2 + p, \rho w v, (\rho e_t + p)v\right]^T, \\ \boldsymbol{G} &= \left[\rho w, \rho u w, \rho v w, \rho w^2 + p, (\rho e_t + p)w\right]^T\end{aligned} \qquad \text{(Eq. 3)}$$

where, ρ, u, v, w, p and e_t are the density, velocities in x-, y-, z-direction, pressure and internal energy, respectively.

2-2. NUMERICAL METHODS

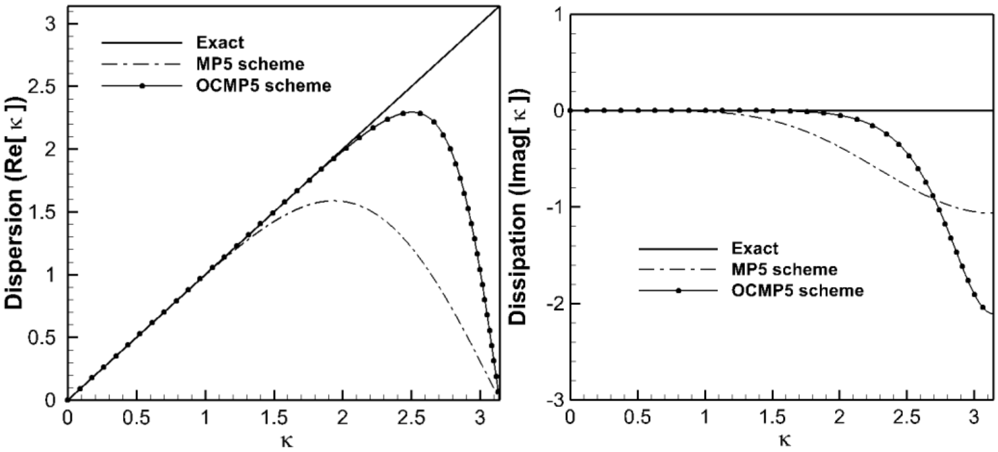
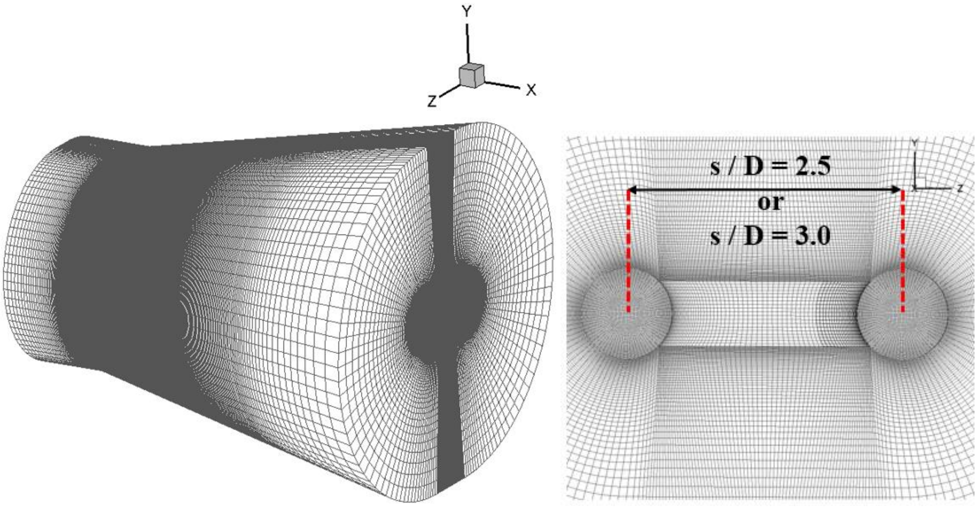


Fig. 1 Resolution of OCMP5 scheme: (left) dispersion; (right) dissipation

In this study, 5th order optimized compact monotonicity preserving scheme (OCMP5) was applied to simulate the supersonic flows and near-field noise of twin-jet. The OCMP5 scheme is the improved version of the monotonicity-preserving (MP) shock-capturing scheme. The OCMP5 scheme involves the compact reconstruction (implicit interpolation) with optimized coefficients so that the resolution characteristics could be maximized [10, 11]. Fig. 1 briefly introduce the resolution characteristics of OCMP5 scheme compared with MP5 scheme using the modified wavenumber analysis. The figure prove that OCMP5 scheme is beneficial to resolve high-wavenumber properties. In addition, by virtue of MP constraints (limiter part), the excellent capability for shock-capturing and acoustic wave-resolving performance can be achieved. Consequently, the OCMP5 scheme can be useful numerical method to be applied in supersonic jet noise. Indeed, the OCMP5 scheme have been used to simulate Mach=2.0 supersonic jet noise [10]. For a time-integration, a 3rd order total-variation-diminishing (TVD) Runge-Kutta method was used.

The studies of Walker [5] and T. Knast et al.[7] were referred for validation. The selected test cases were nozzle pressure ratio (NPR)=3, and we considered two different distance of twin nozzle as s/D=3.0 and s/D=2.5 (s is the nozzle distance). Fig. 2(a) summarize the entire computational grid we used. The total number of grid was about 12 million. The enlarged figure at the nozzle exit was presented in Fig. 2(b). We use dense grids near the shear layer region, and the minimum size of grids in axial and radial direction are $\Delta x = 0.03$ and $\Delta r = 0.0075$, respectively.



(a) (b)

Fig. 2 The entire computational grid and enlarged figure near the nozzle exit.

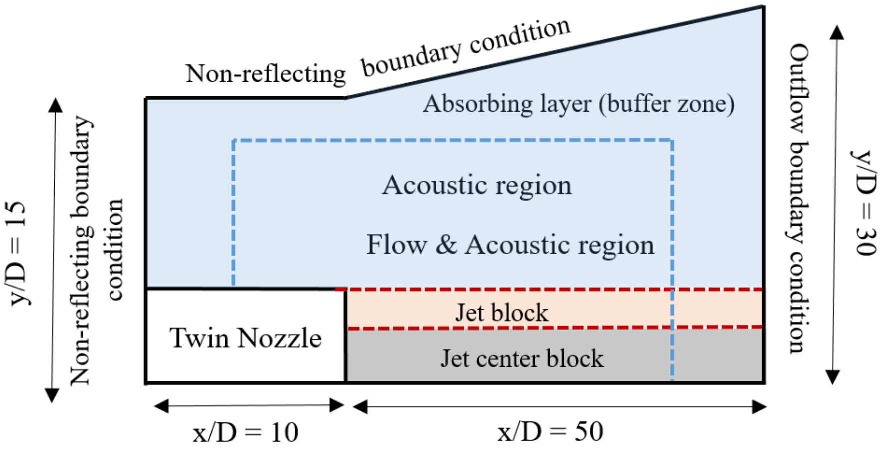


Fig. 3 Boundary conditions

Fig.3 summarizes the boundary conditions we used. The boundaries at left and radial directions are non-reflecting boundary condition to prevent reflection of non-physical waves. On the right boundary, we use the outflow condition. Furthermore, an artificial absorbing layer is applied along the far-field domain. We did not solve the flows inside the nozzle. Instead, a supersonic inlet condition is imposed at the jet exit boundary derived using isentropic relations. The equation can be given as follow:

$$
\begin{aligned}
\rho_e &= \frac{\gamma(\gamma+1)p_e}{2T_\mathrm{r}} \\
p_e &= \frac{1}{\gamma}\left[\frac{2+(\gamma+1)M_j{}^2}{\gamma+1}\right]^{\frac{\gamma}{\gamma-1}} \\
u_e &= \sqrt{\frac{2T_\mathrm{r}}{\gamma+1}}
\end{aligned}
\qquad \text{(Eq. 4)}
$$

where T_r is the temperature ratio, and $T_r = 1$ is used for the cold jet. Note that a convergent nozzle is considered so that Mach number at the nozzle exit is unit. The fully expanded Mach number is set by 1.358. The non-dimensional time step was 0.005. It corresponds to the maximum courant-Friedrichs-Lewy (CFL) number about 0.4.

3. Results

The instantaneous pressure contours (x-z plane) are presented in Fig.3. The left and right figure show the case of s/D=3.0 and s/D=2.5, respectively. These contours were obtained at certain time after the jet plumes were fully developed (non-dimensional time > 1.25). We can clearly recognize that each case shows different twin-jet modes. In the case of s/D=3.0, two jet plumes are oscillating in the same direction. This is so called the symmetric flapping mode, and such phenomenon also can be found in the experimental schlieren images for similar geometry and flow conditions [7]. On the other hand, the distance between nozzles is closer as s/D=2.5, two jet plumes are strongly coupled so that the oscillating mode is changed. The oscillating direction of each plume is opposite (phase difference is 180 deg). This is so called antisymmetric flapping mode, and it can be found in ref. [5][7].

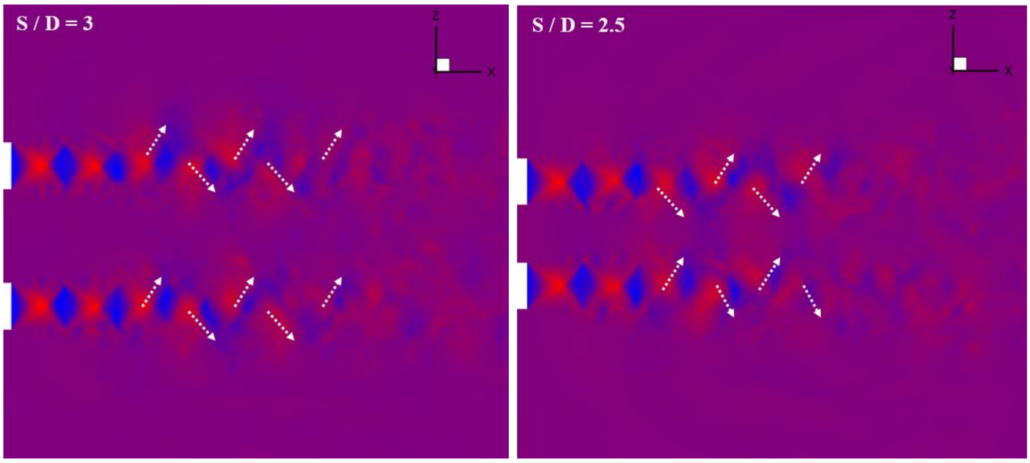


Fig. 3 Instantaneous pressure contours : (left) s/D=3; (right) s/D=2.5

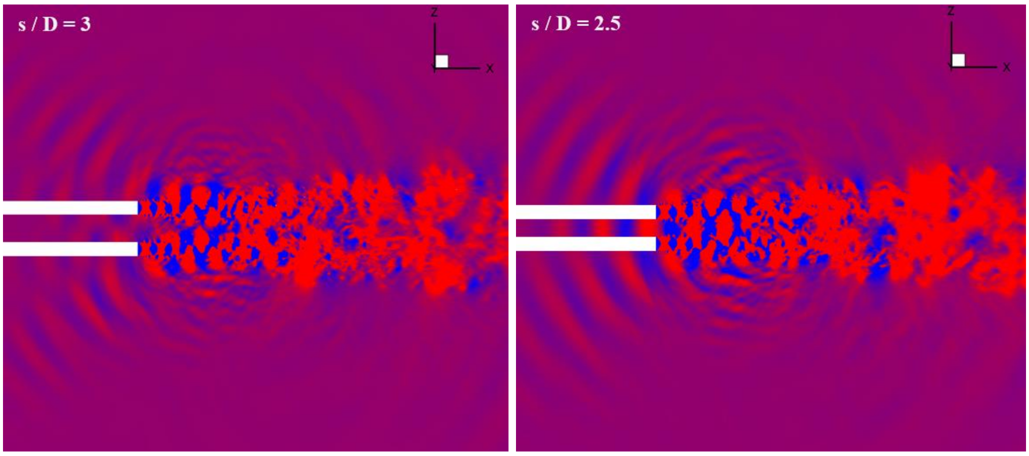


Fig. 4 Instantaneous acoustic pressure contours : (left) s/D=3; (right) s/D=2.5

Fig. 4 presents instantaneous acoustic pressure ($0.99<p_{(non\text{-}dim)}<1.01$) of two different nozzle conditions. Each jet plume of the symmetric flapping mode, s/D=3.0, generates screech tone in the same phase. Therefore, the wave propagation to upward presents different phase at the same *x*-location. In particular, at the center position of twin nozzle (*x*, *z*=0) where screech tone generated by each plume meets, the amplitude of acoustic wave is may low due to superposition of different phase waves. In other words, the case of s/D=3.0, the most dominant discrete tone in entire acoustic-fields will be similar with the single jet case.

On the other hand, in the antisymmetric flapping mode of s/D=2.5 case, generates screech tones in 180 deg different phase. Consequently, the amplitude of acoustic wave at the center position of twin nozzle is highly increased due to superposition of same phase waves. As a results, the most dominant discrete tone can be observed at *x*, *z*=0.

Fig. 5 presents acoustic pressure-time signals at the center of two nozzle. Even though enough time passes, the signal trend of s/D=3.0 case does not change. On the other hand, the amplitude of pressure gradually increases in the case of s/D=3.0 so that it reaches up to ±3000 Pa.

We perform the fast Fourier transform (FFT) using the time signals after T=250 which the solution is almost converged. Fig. 6 demonstrates that the case of s/D=2.5 clearly shows the dominant discrete tone and first harmonic component while that of s/D=3.0 case does not. The Walker et al.'s experimental data [5] and present results are in good agreement in terms of not only the discrete tone but also broadband spectrum. The difference between the amplitude of dominant tones of each case s/D=2.5 and s/D=3.0 is almost 20dB. However, the broadband spectrum is almost same which could be induced by interaction of shock-cells and turbulence: shock-associated noise (see, Fig. 4).

4. CONCLUSIONS

In this study, the twin-jet oscillating modes were investigated in the numerical way. We consider Mach number 1.358 (cold) twin jets in the two different nozzle distances as s/D=3.0 and s/D=2.5. The previous studies related to the similar conditions have proven that s/D=3.0 condition shows the antisymmetric flapping mode of twin jets while the s/D=2.5 condition shows a symmetric one. In practice, the present numerical simulations presented the corresponding mode of each case, and such facts can be clearly observed in the static and acoustic pressure fields. We investigated the pressure-time signals on the observer located at the center of two nozzles (*x*, *z*=0). The resonance phenomena was observed in case of s/D=2.5 with a good agreement with experimental results. The difference between the amplitude of dominant tones is almost 20dB; however, the broadband spectrum is almost same which may be inferred as the shock-associated noise.

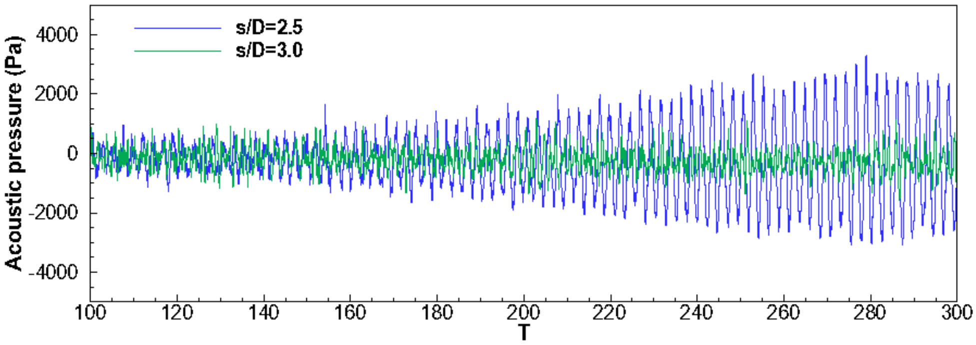


Fig. 5 Acoustic pressure signal at the center of twin-nozzle

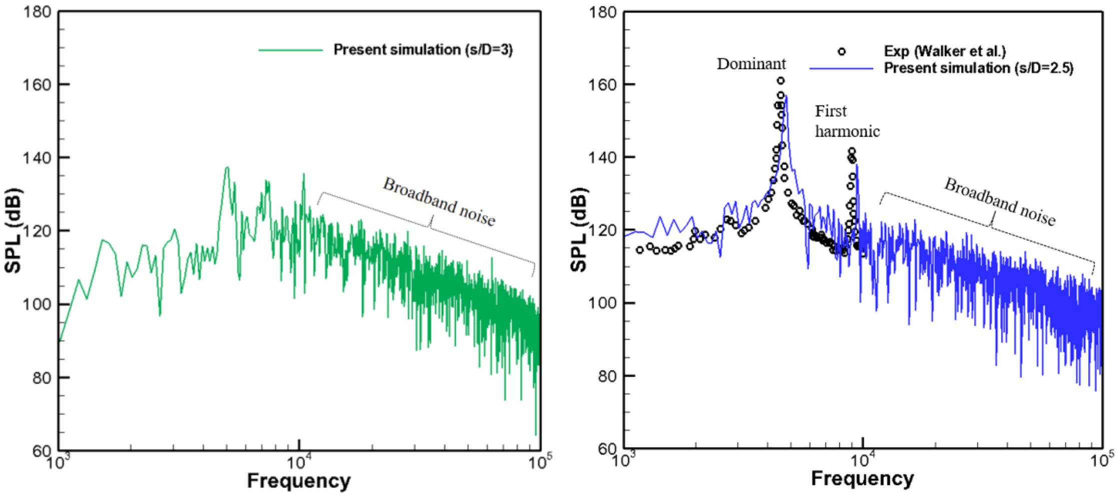


Fig. 6 Noise spectrum using time signals after T=250

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5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. A. Powell, “*On the Mechanism of Choked Jet Noise*,” Proceedings of the Physical Society, Section B, Vol. 66, No. 12, p.1039 (1953)
2. T. D. Norum, “*Screech Suppression in Supersonic Jets*,” American Institute of Aeronautics and Astronautics Journal, Vol. 21, pp. 235-240 (1983)
3. A. Powell, Y, Umeda, and R. Ishii, “*Observations of the Oscillation Modes of Choked Circular Jets*,” Journal of the Acoustical Society of America, Vol. 92, No. 5, pp. 2823-2836 (1992)
4. J. M. Seiner, J. C. Manning, and M. K. Ponton, “*Dynamic Pressure Loads Associated with Twin Supersonic Plume Resonance*,” American Institute of Aeronautics and Astronautics Journal, Vol. 26, No. 9, pp. 954-960 (1988)

5. S. Walker, "*Twin Jet Screech Suppression Concepts Tested for 4.7% Axisymmetric and Two-Dimensional Nozzle Configurations*," American Institute of Aeronautics and Astronautics Paper, 1990-2150 (1990)
6. R. W. Wlezien, "*Nozzle Geometry Effects on Supersonic Jet Interaction*," American Institute of Aeronautics and Astronautics Paper, 1987-2694 (1987)
7. T. Knast, G. Bell, M. Wong, C. M. Leb, J. Soria, D. R. Honnery, and D. Edgington-Mitchell, "*Coupling Modes of an Underexpanded Twin Axisymmetric Jet*," American Institute of Aeronautics and Astronautics Journal, Vol. 56, No. 9, pp. 3524-3535 (2018)
8. L. Shaw, "Twin-Jet Screech Suppression," Journal of Aircraft, Vol. 27, No. 8, pp. 708-715 (1990)
9. J. Gao, X. Xu, and X. Li, "*Numerical Simulation of Supersonic Twin-Jet Noise with High-Order Finite Difference Scheme*," American Institute of Aeronautics and Astronautics Journal, Vol. 56, No. 1, pp. 290-300 (2018)
10. M. H. Ahn, M. J. Park, and D. J. Lee, "*Supersonic Jet Noise Prediction Using Optimized Compact Scheme with Modified Monotonicity Preserving Limiter*," American Institute of Aeronautics and Astronautics Paper, 2018-1249 (2018)
11. M. H. Ahn and D. J. Lee, "*Development of High-Order and High-Resolution Schemes for Efficient Shock Capturing in High-Speed Flows*," 30th Congress of the International Council of the Aeronautical Sciences (2016)