Investigations on the influence of one and two-sided jet deflector on acoustic environment of multi-nozzle launch vehicle at lift-off

Ch L Xing, G G Le*, Ch F Zhao and H Zheng

School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China

* Corresponding author: leguigao@njust.edu.cn

Abstract. To study the acoustic environment of multi-jet impinging the jet deflector when the launch vehicle takes off, a compressible flow model of gas-air is established. The turbulence equation of scale-adaptive simulation (SAS) and the acoustic analogy method (FW-H) are solved numerically by using the second-order Roe scheme. The jet noise of a single rocket engine is numerically simulated. The error between numerical results and experimental data is within 3dB, and the reliability of the numerical method is verified. On this basis, the flow field and acoustic environment of the multi-nozzle launch vehicle are studied, and the effects of the jet deflector configurations on the acoustic environment of the vehicle are analyzed. The results show that, compared with the one-sided jet deflector, the two-sided jet deflector can reduce the overall sound pressure level around the vehicle by up to 6.6%. For the one-sided jet deflector, the overall sound pressure level of the receivers at the outlet of the jet deflector is larger than that of the other side. The analysis method and research results in this paper provide reference for predicting the acoustic environment of the launch vehicle and improving the acoustic environment.

1. Introduction

The high-temperature and high-pressure gas in the combustion chamber discharges the hot high-speed gas through the Laval nozzle and interacts with the stationary air to induce strong jet noise during the ignition lift-off stage of a Multi-nozzle Launch Vehicle. The sound wave radiated by the acoustic source has a very high acoustic load on the rocket body of the launch vehicle, which has an impact on the astronauts and the precision instrument equipment in the cabin section, which seriously affects the launch safety of the rocket. Therefore, it is of great significance to correctly predict the rocket lift-off noise to improve the acoustic environment and to improve the design of the jet deflector.

At present, the main methods to study the acoustic environment during the launch of the launch vehicle include engineering experience, numerical calculation and model scaling test. Based on the flight data and scaling model test data, Eldred [1] summarized a formula for predicting jet noise on launch vehicle at lift-off, which provides a useful basis for the design of control noise. In order to
build a more accurate prediction method, many researchers have improved the limitations of Eldred’s method [2-4]. Although these studies are carried out to improve the accuracy of prediction noise, they do not take into account the influence factors such as sound source motion, the launch pad, the service tower and the jet deflector.

Nonomura et al. [5] used numerical calculation to study the influence of the plate angle on the acoustic waves at 30°, 45° and 60° by the supersonic jet on inclined plate. And Nonomura used the modified weighted compact nonlinear scheme to the three-dimensional compressible Navier–Stokes equations. Tsutsumi et al. [6] numerically studied a plate with a Mach number of 1.8 with an impact at an inclination of 45 degrees, analyzed the noise emission phenomenon, and found two other noise sources, i.e. 1) the interaction between shock wave and shear layer vortex; 2) Mach wave emitted by jet flowing from inclined plate. Tsutsumi et al. [7] used an implicit LES method to carry out numerical research, and studied the generation mechanism of pressure wave radiation of H-IIA rocket during take-off. The Mach wave radiated by the wave shear layer of the plume is a strong noise source. Tsutsumi et al. [8] used LES and FW-H sound analogy method to calculate the noise during the lift-off of the 1/42 scale Epsilon launch vehicle model during lift-off, and the overall sound pressure level (OASPL) of the fairing position reaches the maximum when the rocket is up to 14 times the outlet diameter of the nozzle.

Many researchers study jet noise with small thrust nozzle, low Mach number and plate instead of jet deflector. Therefore, it is necessary to study the complex flow field and noise of multi-nozzle rocket impact jet deflector. In addition, with the development of computational fluid dynamics, the prediction accuracy and computer performance of computational aeroacoustics are improved, which provides a good condition for the research of acoustic environment of large thrust multi-nozzle rocket.

In this paper, the full-scale model of noise environment of multi-nozzle launch vehicle is established, and the gas/air two-component model, second-order Roe scheme [9] and SAS turbulence model [10] are used to solve the three-dimensional compressible Navier-Stokes equation. Combined with acoustic analogy integration method (FW-H), the influence of the configuration of jet deflector on the acoustic environment of multi-nozzle rocket impingement deflector is studied by numerical simulation. The research results provide a certain reference for designers to improve the acoustic environment of rocket.

2. Numerical method

2.1. Turbulence model

The scale-adaptive simulation (SAS) is based on the introduction of the von Kármán length-scale into the turbulence scale equation. The SAS results in an LES-like behavior in unsteady regions of the flow field. At the same time, the model provides standard Reynolds-averaged Navier-Stokes (RANS) capabilities in stable flow regions. SAS adds a term $Q_{SAS}$ to the source term of the $\omega$ equation in the Shear-Stress Transport (SST) $k-\omega$ model. See Egorov and Menter [10] for detailed derivation.

$$Q_{SAS} = \max \left[ \frac{\rho u_k^2}{L_{w}} \right]^2 - C \frac{2 \sigma_p}{\sigma_p} \max \left( \frac{1}{\omega} \frac{\partial \omega}{\partial x_j} \frac{\partial \omega}{\partial x_j} + \frac{1}{\sigma_k} \frac{\partial k}{\partial x_j} \frac{\partial k}{\partial x_j} \right)$$

(1)
Here, $L_{vK}$ is the von Kármán length scale

$$L_{vK} = \frac{\kappa}{\sqrt{\left(\nabla^2 u\right)^2 + \left(\nabla^2 v\right)^2 + \left(\nabla^2 w\right)^2}}$$

and $L_t$ is the length scale of the modeled turbulence

$$L_t = \frac{\sqrt{k}}{c_\mu \omega}$$

### 2.2. FW-H Acoustic Analogy Method

In 1969, on the basis of the Curle equation [11], Williams and Hawkers [12] used the generalized function theory to obtain the FW-H equation, taking into account the influence of the solid wall on the sound.

$$\frac{1}{a_0^2} \frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' = \frac{\partial^2}{\partial x_j \partial x_j} \left[ T_j H(f) \right] - \frac{\partial}{\partial x_j} \left[ \left( P_j n_j + \rho \nu_j (u_j - v_j) \right) \delta(f) \right]$$

$$+ \frac{\partial}{\partial t} \left[ \left( \rho \nu_j + \rho (u_j - v_j) \right) \delta(f) \right]$$

Compared with the Kirchhoff surface integral method, FW-H surface integral method has several advantages, such as it is no longer limited to linear and inviscid wave equations, and the FW-H integral surface can be placed anywhere in the jet calculation region, even in the nonlinear flow region. Therefore, the FW-H integral surface method is used here.

### 2.3. Validating numerical algorithms

The jet noise problem of single nozzle rocket gas impinging on one-sided jet deflector is an example [13]. The Mach number of the nozzle exit is 3.93. There are a total of 4 noise receiving points, which are located directly above the nozzle exit. It is 46m, 34m, 22m and 10.5m, namely Point-1, Point-2, Point -3 and Point-4. In table 1, the calculated value of the overall sound pressure levels of the noise receivers are compared with the test values. The error between numerical results and experimental data is within 3dB, and the reliability of the numerical method is verified.

| Point          | 1    | 2    | 3    | 4    |
|----------------|------|------|------|------|
| CFD/dB         | 127.2| 129.3| 138.4| 143.7|
| Experimental data/dB | 127  | 130  | 140  | 146  |
| Error/dB       | 0.2  | 0.7  | 1.6  | 2.3  |

### 2.4. Physical models and boundary conditions

The schematic diagram of the gas impacting jet deflector and noise receiving point of multi-nozzle rocket is shown in figure 1, which mainly includes nozzle, jet deflector and the service tower. In addition, the tower is located in $L/D = 2.2$, where $L$ and $D$ represent the distance at which the position of the tower changes and the diameter of the nozzle exit, respectively. The noise characteristics of multi-nozzle launch vehicle at
lift-off are studied and the influence of the one and two-sided jet deflector on acoustic environment is analyzed. Figure 2 shows schematic diagrams of one-sided jet and two-sided jet deflectors. It is assumed that there is an adiabatic and isentropic flow in the nozzle, the gas satisfies the ideal gas state equation, the Mach number at the nozzle outlet is 3.93, and the external boundary of the calculation domain is the atmospheric environment, that is, the pressure is 101325Pa, the temperature is 300K, and the nozzle and other walls are adiabatic and non-slip walls.

![Figure 1](image1.png)

(a) The vehicle launch system and the receivers.

![Figure 1](image2.png)

(b) The position of tower.

**Figure 1.** Schematic diagram of vehicle geometry and the receivers.

![Figure 2](image3.png)

(a) Two-sided jet deflector  
(b) One-sided jet deflector

**Figure 2.** Jet deflector with two different shapes.
3. Numerical results and discussion

3.1. Flow field of the launch vehicle

![Velocity contours with the different jet deflector.](image)

Figure 3. Velocity contours with the different jet deflector.

Figure 3 shows velocity contours with the one and two-sided jet deflectors. Figure 3(a) is the velocity contour of a one-sided jet deflector. It can be seen that high-speed gas is ejected through the nozzle during the ignition stage of rocket liftoff. Due to the multi-nozzle injection, multiple gas jets interfere with each other. Under the nozzle, three wave knots can be clearly observed. Above the bottom of the jet deflector, the multiple gas jets intersect and then impact the bottom of the jet deflector. Figure 3(b) is the velocity contour of a two-sided jet deflector. The two-sided jet deflector has a flow field similar to that of the one-sided jet deflector. Compared with the one-sided jet deflector, the two-sided jet deflector has two drainage directions, and under the same condition, it has a larger flow area.

![Temperature contours with the different jet deflector.](image)

Figure 4. Temperature contours with the different jet deflector.

Figure 4 shows temperature contours with the one and two-sided jet deflectors. It can be seen that compared with the two-sided jet deflector, the one-sided jet deflector is obviously different in two places: first, at the inlet of the jet deflector, the one-sided jet deflector has greater temperature gradients. Because the one-sided jet deflector has a smaller flow area, it is not conducive to the gas being discharged from the inlet of the jet deflector and from the outlet of the jet deflector through the jet deflector. Second, at the outlet of the jet deflector, the one-sided jet deflector will cause more expansion waves, as well as more fluctuations. In both cases, the acoustic load around the rocket will be increased and the overall sound pressure level around the rocket will be increased.
3.2. OASPL variation at receivers

Figure 5. OASPL variation of receivers.

Figure 5 shows the comparison of the overall sound pressure level of the receivers between the one-sided jet deflector and the two-sided jet deflector, where Z is the vertical distance from the receiver to the nozzle outlet. It can be seen that with the decrease of the distance between the receiver and the nozzle outlet, the overall sound pressure level of the receiver increases at first, then decreases, and then increases. The reason for the decrease is that the receiver-4 at the booster is located on the periphery of the intersection of multiple gas jets.

In addition, it shows that the pressure pulsation tends to weaken during the propagation of the pressure pulsation; the overall sound pressure level of the one-sided jet deflector is larger than that of the two-sided jet deflector at the receivers at the same location, the smallest difference is 7.17dB, and the maximum difference is 11.26dB. Compared with the two-sided jet deflector, the flow area of the one-sided jet deflector is smaller, and the gas jet flows into the deflector to splash back, which strengthens the pressure pulsation, resulting in the acoustic environment around the rocket increases.

Table 2. Comparison of OASPL at the circumferential receivers.

| receiver                  | 4   | 5   | 6   | 7   |
|---------------------------|-----|-----|-----|-----|
| two-sided jet deflector   | 151.06 | 149.66 | 150.38 | 151.73 |
| one-sided jet deflector   | 159.12 | 158.87 | 158.0  | 158.90 |

Table 2 is a comparison of the overall sound pressure levels at the circumferential receivers in the configuration of the deflector. It can be seen that the overall sound pressure level of the receivers near one side of the tower is smaller. Under the two-sided jet deflector, the maximum difference is 2.08dB, and under the one-sided jet deflector, the maximum difference is 1.12dB. For the one-sided jet deflector, the overall sound pressure level of the receivers at the outlet of the jet deflector is larger than that of the other side. In addition, it is verified that the overall sound pressure level of the one-sided jet deflector is larger than that of the two-sided jet deflector.
3.3. Spectral variation at receivers

![Spectral variation at receivers](image)

Figure 6. Spectral variation of receivers.

To compare the effect of the configuration of the different jet deflector on the acoustic environment of the rocket, figure 6 shows the spectral at the receivers of different height. Five receivers are shown, in order of receiver-1–receiver-4 and receiver-8. It can be seen that the closer the receiver is to the nozzle
outlet, the greater the sound pressure level gradually increases, showing a positive correlation with the variation of the overall sound pressure level. In addition, the sound pressure level of each receiver is similar, and the sound pressure level decreases gradually with the increase of the frequency.

When the frequency is greater than 2000Hz, the sound pressure level of one/two-sided jet deflector at receiver-4 coincides. In addition, the sound pressure level of the one-sided jet deflector at other receivers is larger than that of the two-sided jet deflector.

Compared with the two-sided jet deflector, the one-sided jet deflector increases large-scale turbulent noise sources and the fine-scale turbulent noise sources, which is mainly caused by the interference and superposition of the radiation of the two noise sources. The rocket is located at the initial take-off altitude. The first kind of noise source is the Mach wave radiation in the free jet region, the second kind of noise source is the additional noise source generated by the interaction between the jet and the launcher, as well as the interaction between acoustic wave and launcher, tower and jet deflector, resulting in refraction or diffraction.

4. Conclusions
In this paper, the acoustic model of supersonic gas jet impinging jet deflector during launch vehicle takeoff is established, and the influence of the configuration of jet deflector on acoustic environment of rocket is studied. The overall sound pressure level and spectrum characteristics of receivers are analyzed, and the following conclusions are drawn:

1) At the outlet of the jet deflector, the one-sided jet deflector will cause more expansion waves, as well as more fluctuations.

2) The overall sound pressure level of the receiver increases at first, then decreases, and then increases. The overall sound pressure level of the one-sided jet deflector is larger than the overall sound pressure level of the two-sided jet deflector, the minimum difference is 7.17dB, and the maximum difference is 11.26dB.

3) Compared with the two-sided jet deflector, the one-sided jet deflector increases large-scale turbulent noise sources and the fine-scale turbulent noise sources.

Acknowledgments
We gratefully acknowledge the financial support of the China Manned Space Project (010101) for this work.

References
[1] Eldred K M 1971 Acoustic Loads Generated by the Propulsion System NASA SP-8072
[2] Koudriavtsev V, Varnier J and Safronov A 2004 A Simplified Model of Jet Aerodynamics and Acoustics 10th AIAA/CEAS Aeroacoustics Conf
[3] Varnier J and Raguinet W 2002 Experimental Characterization of the Sound Power Radiated by Impinging Supersonic Jets AIAA J. 40 pp 825-31
[4] Varnier J 2001 Experimental Study and Simulation of Rocket Engine Freejet Noise AIAA J. 39 pp 1851-9
[5] Nonomura T, Honda H, Nagata Y, Yamamoto M, Morizawa S, Obayashi S and Fujii K 2015 Plate-Angle Effects on Acoustic Waves from Supersonic Jets Impinging on Inclined Plates *AIAA J.* pp 1-12

[6] Tsutsumi S, Takaki R, Nakanishi Y, Okamoto K and Teramoto K 2011 Numerical Study on Acoustic Radiation from a Supersonic Jet Impinging to an Inclined Plate *17th AIAA/CEAS Aeroacoustics Conf.* pp 2011-922

[7] Tsutsumi S, Takaki R, Shima E, Fujii K and Arita M 2008 Generation and Propagation of Pressure Waves from H-IIA Launch Vehicle at Lift-Off *46th AIAA Aerospace Sciences Meeting and Exhibit*

[8] Tsutsumi S, Ishii T, Ui K, Tokudome S and Wada K 2015 Study on acoustic prediction and reduction of epsilon launch vehicle at liffoff *J. SPACECRAFT ROCKETS.* 52 pp 350-61

[9] Roe P L 1986 Characteristic-based schemes for the Euler equations *ANNU REV FLUID MECH.* 18 pp 337-65

[10] Menter F R and Egorov Y 2010 The scale-adaptive simulation method for unsteady turbulent flow predictions part 1: theory and model description *FLOW TURBUL COMBUST.* 85 pp 113-38

[11] Curle N 1955 The Influence of Solid Boundaries upon Aerodynamic Sound *Proceedings of the Royal Society of London* 231 pp 505-14

[12] Williams J E F and Hawkings D L 1969 Sound generation by turbulence and surfaces in arbitrary motion *Philosophical Transactions of the Royal Society A: Mathematical Physical and Engineering Sciences.* 264 pp 321-42

[13] Li F, Liu X and Bao F 2009 Research on Noise Measuring and Prediction of Rocket Engine *J. AUDIO ENG.* 33 pp 53-7