Experimental Research on Noise Load Characteristics of Supersonic Jets in Rectangular Nozzles with Different Mach Numbers

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cAbstract: Aiming at the jet noise problem of the rectangular supersonic nozzle, rectangular nozzle test models with Mach numbers of 1.35 and 1.65 were designed and processed. Using the jet noise test platform in a full anechoic chamber, the nozzle supersonic jet noise characteristic test was carried out. The test results show that the surface noise load of the model gradually increases along the nozzle axis; the unsteady flow field structure at the nozzle exit position has complex evolution, with strong turbulent pulsation and high noise load; the directivity trend of the far-field noise total pressure level of the two nozzles is basically the same, and the directivity is obvious in the upstream and 90° direction of the nozzles; from the far-field sound pressure spectrum, it can be seen that the far-field noise is composed of broadband noise and discrete frequency noise. The amplitude of the second order frequency varies significantly from 70° to 90° of upstream, and the fourth harmonic frequency of the whistling mode is captured in the direction of 90°.

1. Introduction
With the intensification of international competition and the transformation of independent innovation and development of weapons and equipment in China, the requirements for advanced fighters are becoming increasingly stringent. Not only are they required to have excellent aerodynamic characteristics, but also required to have good acoustic and stealth capabilities. Aerospace vehicles will generate aerodynamic noise caused by air flow during flight, which noise sources are mainly divided into two categories: Airframe noise, which is mainly due to the interaction of the flow with the trailing edge of the wing, the landing gear and the cavity on the surface of the aircraft; Jet engine noise, including turbofan noise and jet noise [1-3]. As one of the main noise sources of advanced fighter jets, jet noise will not only cause serious noise interference to the aircraft itself, deteriorate the working environment inside and outside the cabin, and adversely affect the normal operation of airborne electronic equipment and the comfort of flight attendants, but the high-intensity jet noise will also cause the structure of the aircraft to break due to acoustic fatigue, which will seriously threaten the structural safety and flight safety of the engine tail nozzle and the aircraft, and shorten the service life.
of the tail nozzle. Therefore, in order to adapt to the development trend and requirements of supersonic nozzles, it is particularly necessary to analyze and study the noise characteristics of supersonic jets.

Since Lighthill [4] published a paper on aeroacoustics in 1952, acoustic research has made great progress. However, due to the limitation of experimental conditions and turbulence problems, the generation mechanism of jet noise has not been accurately explained. Generally speaking, the turbulent structure of different levels in the jet can produce noise, and their ratio depends on the jet Mach number, temperature and observation angle [5-6]. At present, it is generally believed that supersonic jet noise mainly contains three basic components [7], namely turbulent mixed noise, broadband shock noise and whistling noise. They have rich frequency spectrum and directivity characteristics, which are completely different from subsonic jet noise. Among them, most research progress of broadband shock noise comes from the basic research work carried out by Norum and Seiner et al. in NASA in the 1980s [8-14]. These studies involve the measurement of near-field shock position, turbulent pulsation level, static pressure and far-field sound pressure.

Supersonic jet is a multi-scale complex flow problem including turbulence, shock wave, vortex and acoustic wave. Correctly explaining the generation mechanism of supersonic jet noise, predicting and ultimately controlling jet noise have important theoretical research value and extensive engineering applications background. Domestic researches on jet noise of exhaust nozzles mostly focus on axisymmetric circular nozzles, and there are few studies on supersonic jet noise of rectangular nozzles. The main content of this paper is to study the regular characteristics of jet noise load of rectangular nozzle under supersonic speed.

2. Experimental scheme
This test was conducted on the jet flow test platform in the full anechoic chamber of the Aviation Noise and Dynamic Intensity Key Laboratory of Aviation Science and Technology of AVIC 623. The test site is shown in Figure 1. The measured volume of the anechoic chamber after the installation of the anechoic wedge is 144m³, and its size is 6m×6m×4m. The laboratory air source can provide continuous, dry compressed air for 1 minute. The pressure control valve of the test platform can control the opening of the outlet pressure, and the maximum air supply pressure is 0.75MPa.

A high-intensity microphone (B&K 4938-A-011) was used for the far-field sound field measurement, and a pulsating pressure microphone (Kulite XCQ0062) was used for the near-field sound field measurement. The test equipment was all intact, the measuring instruments were recalibrated before each test, and the ambient temperature and atmospheric pressure before and after the test were recorded.

Figure 1 Test site
The nozzle used in the test was a binary rectangular expansion nozzle. The geometric design of the nozzle is shown in Figure 2. The design Mach numbers of Model 1 and Model 2 were 1.35 and 1.65 respectively, and the nozzle pressure ratio NPR (Nozzle Pressure Ratio) was 2.9 and 4.57, respectively. And the geometric shape of the nozzle model is determined according to the references of AIAA86-1867[15], AIAA98-3107[16].

![Figure 2 Binary expansion nozzle](image)

In the test sound field measurement, the near-field adopted a microphone arranged on the nozzle surface along the nozzle axis. The far-field sound field measurement points were arranged as shown in Figure 3. The measuring point radius was 1.5m, and the centroid of the nozzle outlet was the origin. From the upstream 40° to the downstream 100°, there were 7 measuring points arranged at an interval of 10°. During the test, the data acquisition equipment was subjected to silencing treatment, and the surface was covered with silencing sponge.

![Figure 3 Sound field measurement scheme](image)

### 3. Test results and analysis

An this paper, the test results are given and analyzed from the aspects of jet noise sound pressure level, sound pressure spectrum, and modality.
3.1 Analysis of uncertain influencing factors
To ensure the reliability of the test results, the uncertainty of the test was analyzed first:
(1) The machining error of the test piece is ±0.01 mm;
(2) The error of the sound pressure level curve measured between different trains under the same working condition at the main measuring point is less than 1 dB;
(3) The position error of the far-field pressure sensor is as small as 5 cm, and the relative measurement radius error is as small as 2%;
(4) The temperature error of different trains is as small as 2°C.
Figure 4 shows the data comparison curve of the nozzle with a nozzle pressure ratio NPR (Nozzle Pressure Ratio) of 4.57 for 3 repeated tests. It can be seen from the figure that the three curves are very consistent, which proves the repeatability and reliability of the test.

3.2 Near-field sound pressure level characteristics
Figure 5 shows the total SPL (sound pressure level) (dB) of each measurement point obtained from the experiment on the inner wall of the nozzle model axis position. It can be seen from the figure that the noise load of each measuring point on the nozzle contraction section is lower than that of each measuring point in the expansion section. The airflow accelerates into a supersonic flow state after passing through the nozzle throat, and the supersonic airflow in the expansion section is more intensely mixed, resulting in stronger turbulent pulsation. Comparing the noise measurement results of nozzles with different Mach numbers, it is found that, firstly, the sound pressure level will increase sharply at the throat; secondly, the overall noise level of the nozzle will be higher under the condition of high Mach number, indicating that the flow pulsation in the nozzle is stronger and the flow field is more complex.

![Figure 4 Comparison curve of repeatability test](image1)

![Figure 5 Total SPL of each measuring point](image2)
3.3 Frequency spectrum characteristics of far-field sound pressure

From the far-field sound pressure level spectrograms of Models 1 and 2, it can be seen that the far-field sound pressure spectrum is composed of a broadband continuous spectrum and a narrow-band line spectrum. The narrow-band line spectrum indicates that the nozzle whistling phenomenon exists in the jet flow field. The two nozzle models both capture the howling harmonic frequencies in the jet flow field, and the high Mach number jet will excite more harmonic frequencies, the peak frequency of which varies with the observation angle. The second harmonic of the howling mode has the highest sound pressure level in the 90° direction.

It can be seen from Figure 6 that the first-order frequency of howling for Model 1 is 2200 Hz, and the second-order frequency is 4300 Hz. The far-field sound pressure spectrum is composed of a broadband continuous spectrum and a narrowband line spectrum. The second-order frequency amplitude changes significantly from 80° to 90° upstream, and the howling mode has the highest sound pressure level.
Figure 6 Far-field sound pressure level spectrum

It can be seen from Figure 7 that the first-order frequency of Model 2 is also 1800 Hz, the second-order frequency is about 3600 Hz, the third-order frequency is about 5600 Hz, and the fourth-order frequency is 7100 Hz. The second-order frequency amplitude changes significantly from 70° to 90° upstream, and the howling mode has the highest sound pressure level.

Figure 7 Near-field sound pressure level spectrum

a) Measuring point 1

b) Measuring point 2

e) Measuring point 5

f) Measuring point 6

g) Measuring point 7
3.4 Frequency spectrum characteristics of far-field sound pressure
The far-field noise total sound pressure level directivity trend of the two nozzles studied in this paper is basically the same, and the directivity is obvious in the upstream of the nozzle and in the direction of 90°. Comparing the two nozzles, it is found that the nozzle far-field noise directivity under high compression ratio is more obvious and its amplitude is larger, but the change law is basically the same.
In Model 1, the nozzle pressure ratio NPR (Nozzle Pressure Ratio) is 2.9, and the measured total sound pressure level directivity of the 7 measuring points is shown in Figure 8. The total sound pressure level at the 90° measuring point is the largest, which is 133dB, and the total sound pressure level at the upstream 60° is the smallest, which is 128dB. The nozzle noise has obvious directivity both upstream of the nozzle and perpendicular to the nozzle.

Figure 9 shows the total sound pressure level directivity of the 7 measuring points measured in the Model 2 when the compression ratio NPR (Nozzle Pressure Ratio) is 4.57. The total sound pressure level at the 90° measuring point is the largest at 138dB, and the total sound pressure level at the upstream 70° is the smallest at 131dB. Similarly, the nozzle noise has obvious directivity both upstream of the nozzle and perpendicular to the nozzle.

4. Conclusion
This paper analyzes the experimental data of the noise test of two nozzles at different Mach numbers, and reveals the spectral characteristics of the noise load of the binary expansion and expansion supersonic nozzle. In the far-field sound pressure spectrum, the high-frequency narrow-band line spectrum is prominent, and the jet noise has obvious directivity in the upstream of the jet and perpendicular to the nozzle axis; by comparing different Mach number nozzles, it is found that the noise load intensity of the high Mach number nozzle is higher in the near-field, and the high Mach number jet will excite the multi-order howler harmonic frequency in the far-field spectrum, moreover,
the sound pressure level corresponding to the second order harmonic frequency near 90° upstream of
the jet is the highest, hence the noise load characteristics of the dual diverging nozzle are further
mastered. The test results show that the Mach number has a certain effect on the noise load
characteristics, magnitude and modal frequency of the nozzle; the test data and analysis results can be
used to verify the numerical calculation results of the noise characteristics of the binary diffusive
supersonic nozzle. Our next research step will focus on the noise control method of the dual diverging
nozzle supersonic jet.

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References
[1] ZHOU L. Study on Linear Stability and Noise Mechanism of Compressible Free Shear Flow[D].
[PhD Thesis]. Hefei: University of Science and Technology of China.2012.
[2] Paliath U. Numerical Simulation of Jet Noise[D]. [PhD Thesis]. The Pennsylvania State University,
2006.
[3] Shih-Chieh Lo. Numerical Simulations of Supersonic Jet Flows[D]. [PhD Thesis]. West Lafayette,
Indiana: Purdue University, 2010.
[4] Lighthill M J. On sound generated aerodynamically I [J]. General theory Proceedings of the Royal
Society of London Series A, 1952, 211(1107): 564-587
[5] Tam. C. K. W. Supersonic Jet Noise [J]. Annu. Rev. Fluid Mech. 1995, 27, 17-43.
[6] GAO Z-H. Numerical Simulation of Supersonic Jet Scream Generation Mechanism [D]. [PhD
Thesis]. Beijing: Beijing University of Aeronautics and Astronautics. 2005.
[7] Tam C K W. Computational aeroacoustics-issues and methods [J]. AIAA Journal, 1995, 33(10):
1788-1796
[8] Seiner, J. M. and Norum, T. D. Experiments of shock associated noise on supersonic jets[C].AIAA
Paper 79-1526, 1979.
[9] Seiner, J. M. and Norum, T. D. Aerodynamic aspects of shock containing jet plumes[C].AIAA
Paper 80-0965, 1980.
[10] Norum, T. D. and Seiner, J. M. Location and propagation of shock associated noise from
supersonic jets[C]. AIAA Paper 80-0983, 1980.
[11] Seiner, J. M. and Yu, J. C. Acoustic near field and local flow properties associated with
broadband shock noise[C]. AIAA Paper 81-1975, 1981
[12] Norum, T. D. and Seiner, J.M. Measurements of Mean Static Pressure and Far Field Acoustics of
Shock-Containing Supersonic Jets[R]. NASA-TM-84251, 1982.
[13] Norum, T. D. and Seiner, J. M. Broadband Shock Noise from Supersonic Jets [J].AIAA Journal.
1982, 20(1): 68–73.
[14] Seiner, J. M. and Yu, J. C. Acoustic Near-Field Properties Associated with Broadband Shock
Noise [J].AIAA Journal. 1984, 22(9):1207–1215.
[15] J C Seiner. Acoustic properties associated with retangular geometry supersonic nozzle [J].AIAA
Journal, 1998,3107
[16] Craig A Hunter. Experimental the ogoretical and computational investigation of separated nozzle
flows [J]. AIAA Journal, 1986, 1867