Jet Noise Reduction of Double-Mixing Exhaust System

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Abstract: A jet noise reduction technique by using the external chevron nozzle with lobed mixer in the double-mixing exhaust system is investigated under cold conditions. The computations of jet field and the experiments of noise field are conducted with scaled model of high-bypass-ratio turbofan engine mixing exhaust system composed of external chevron nozzle with lobed mixer. The computational results indicate that comparing with the baseline nozzle with lobed mixer, the external chevron nozzle with lobed mixer increases mixing of jet and ambient air near the nozzle exit. The experimental results show that the external chevron nozzle with lobed mixer has better jet noise reduction at low frequencies, and this reduction rises with the increase of chevron bend angle. The experimental results also show that the external chevron nozzle with lobed mixer has sound pressure level (SPL) increase which is not obvious at high frequencies. With chevron bend angle increasing, SPL has relatively marked increase at 60°(directivity angle measured from upstream jet axis) and little fluctuations at 90° and 150°. The external chevron nozzle with lobed mixer has overall sound pressure level (OASPL) reduction in varying degrees at 60° and 150°, but it has little OASPL increase at 90°.

Key words: aerospace propulsion system; high-bypass-ratio turbofan engine; mixing exhaust system; lobed mixer; chevron nozzle; jet noise reduction

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0 Introduction

Jet noise is one of the main noise sources of turbofan engine. To meet increasingly stringent noise standards published by International Civil Aviation Organization (ICAO) and related countries, the jet noise reduction technique is one of the important issues in aviation industry[1].

The total acoustic power emitted from a jet is nearly proportional to the eighth power of the jet velocity on the whole. Spectra of jet noise have a direct bearing on the jet field structures and they have clear directivities[2]. For this reason, jet noise reduction could be realized by reducing jet peak velocity, changing jet field structures and controlling radiation way of jet noise. With regards to the high-bypass-ratio turbofan engines, the highly efficient mixing between core flow and fan flow, as well as the enhanced mixing of jet and ambient air are two key ways for jet noise reduction.

Since the mid-1980s, an advanced forced mixer named as lobed mixer has been employed in turbofan engine mixing exhaust systems for enhancing the mixing between core flow and fan flow. The technique can help to reduce the noise. For example, CFM56-5C engine by using lobed mixer produces 12.8 dB reduction compared with CFM56-3 engine. Another technique for enhancing the mixing of jet and ambient air by using chevron nozzle is also employed in turbofan engines with separated exhaust system. The basic mechanism of the chevron nozzle is to create array stream-wise vortexes which enhance the mixing of jet and ambient air [3-6], thus reducing jet noise at

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low frequencies.

In recent years, the studies on the aerodynamic performance of forced mixing exhaust system with lobed mixer [7-12] and the jet noise reduction technique of separated exhaust system and mixing exhaust system[13-16] in turbofan engines had been successively conducted. But the comprehensive study on the combination of forced mixing between core flow and fan flow with lobed mixer and enhanced mixing between jet and ambient air with chevron nozzle had not been nearly conducted at home and abroad. In this paper, an experimental study on jet noise reduction by using the lobed mixer and chevron nozzles is conducted on the jet noise test rig under cold conditions with scaled model. The far field spectra of jet noise and the effect of chevron bend angles on noise reduction are discussed. Besides, numerical simulations of flow fields are performed to reveal the mechanism of double-mixing on jet noise reduction.

1 Nozzle Models

For subsonic jet noise, the nozzle exit structure has a remarkable influence on the jet field. It is expected that different nozzle exit structures have different effects on jet noise reduction. Chevron nozzle is regarded as an effective way to reduce jet noise with minimal performance or weight impacts in high-bypass-ratio turbofan engine. Based on Refs. [10—15], three types of scale model nozzles were designed to study the effects of different chevron nozzles on jet noise reduction. These nozzles include a nozzle with conventional annular mixer (Nozzle-A), a nozzle with 16-lobes scalloped lobed mixer (Nozzle-B), and three nozzles coupled with 16-lobes scalloped lobed mixer and chevron outlets (Nozzle-C). Three types of scale model nozzles and their parameters are shown in Fig. 1 and Table 1. Five different nozzles have the same core flow exit area, fan flow exit area, and nozzle exit area.

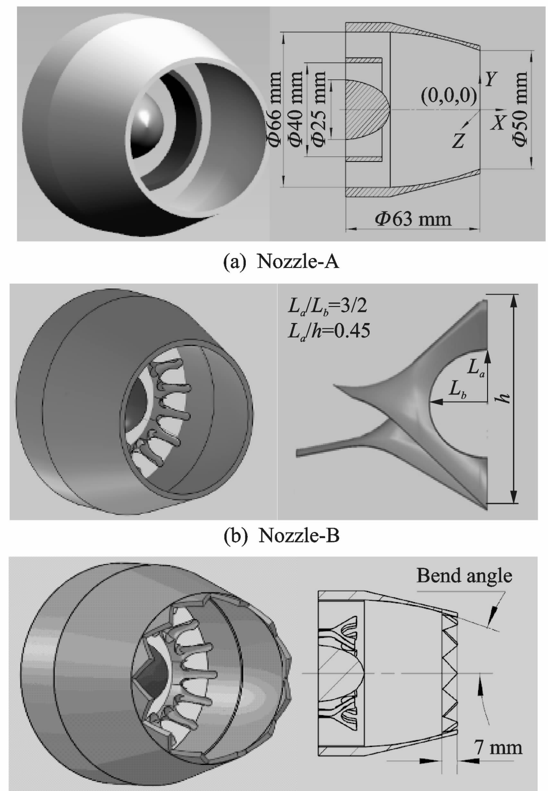


Fig. 1 Schematic diagram of scale model nozzles

Table 1 Parameters of external chevron nozzles

Nozzle-C	0	1	2
Chevron number	12	12	12
Chevron length/mm	7	7	7
Chevron bend angle/(°)	11	18	22

2 Flow Field Simulation

2.1 Computational procedures

Numerical simulation is performed at a core flow exit with *Ma* 0.8 and a fan flow exit with *Ma* 0.5. Combinations of tetrahedral grid and hexahedral grid are used in the solution domain. Computational grid for Nozzle-B is shown in Fig. 2.

The CFD analysis of the steady-state jet plume flow fields is performed using commercial CFD software, which solves the Navier-Stokes (N-S) equations using a standard k-ε turbulence model. The compressible turbulence flow and the no-slid surface condition are used in the flow field computations and wall function is used in the wall treatment options.

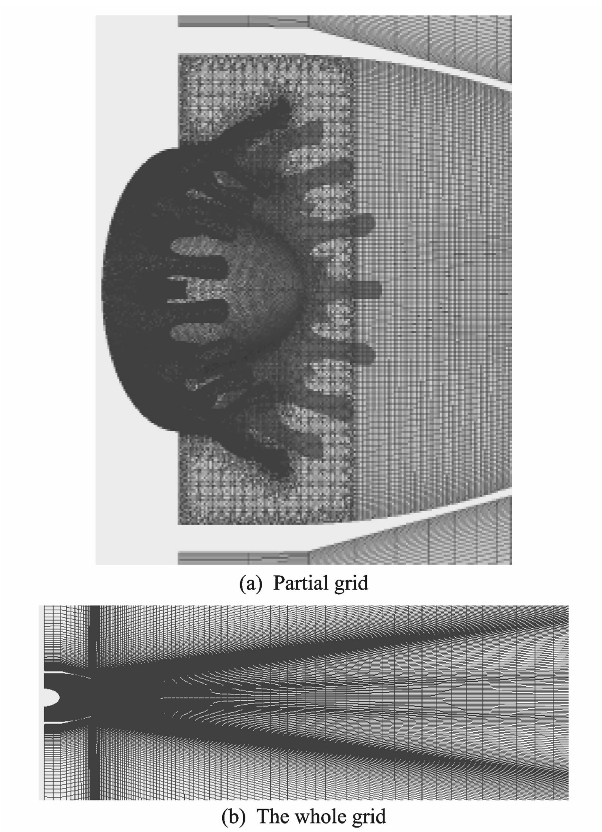


Fig. 2 Computational grid for Nozzle-B

2.2 Computational results

Fig. 3 presents the comparisons of velocity contours on five cross sections of Nozzle-A, Nozzle-B and Nozzle-C1. Compared with Nozzle-A, it is seen that Nozzle-B has a tremendous flow field changes. The lobed mixer strongly distorts the mixing layer to form a lobe-shaped velocity distribution inside the nozzle (As seen at $X/D_j=-1$ and -0.6, where D_j is nozzle exit diameter). The continuing mixing causes the flow to form a round mixing layer downstream the nozzle exit at $X/D_j=2$—10. The enhanced mixing significantly reduces the potential core length and the jet velocity of Nozzle-B, thus contributing to a noise reduction.

Compared with Nozzle-B, it is also seen that Nozzle-C1 has a slight flow field changes inside the nozzle. Chevron nozzle changes the cross-sectional shape of the jet and increases mixing of jet and ambient air near the nozzle exit, thus leading to a rapid increase in the width of the mixing layer. The core jet length and the jet velocity of Nozzle-C1 are further reduced. This can result in more reduction of jet noise.

3 Experiment

3.1 Test rig and measuring implements

The experiments are performed in the full anechoic chamber of Fluid and Acoustic Laboratory in Beihang University which meets the condition of free noise field. With acoustic wedges placed on the walls, the ceiling and the floor, minimizing sound reflections, the full anechoic chamber has a size of 8.9 m×6.8 m×4.65 m (Excepting wedges) and a cut-off frequency of 250 Hz. The dual-flow cold jet noise test rig (See Fig. 4) is composed of test section, flow control section and gas source. The test section is located in the anechoic chamber and is used for the installation of model experiment nozzles and acoustic measuring implements. Flow control section is placed in the control room. The total pressure of the airflow can be adjusted by the pneumatic pressure valve, intelligent pressure transmitter or manual pressure regulator. There is a gas source outside the laboratory, which is used for supplying dry compressed air. Acoustic measuring implements are quarter inch condenser microphones, which have a dynamic range from 56 dB to 170 dB and a sensitivity of 1.33 mV/Pa. Condenser microphone calibration is conducted before every experiment. Atmospheric pressure and temperature are recorded before and after every experiment.

3.2 Measurement scheme

In order to study the amplitude, the frequency characteristics of each component of jet noise and noise directivities, according to the laboratory measurement conditions and the propagation characteristics of each jet noise components, the far field acoustic measurement scheme is obtained by the microphone phased array consisting of

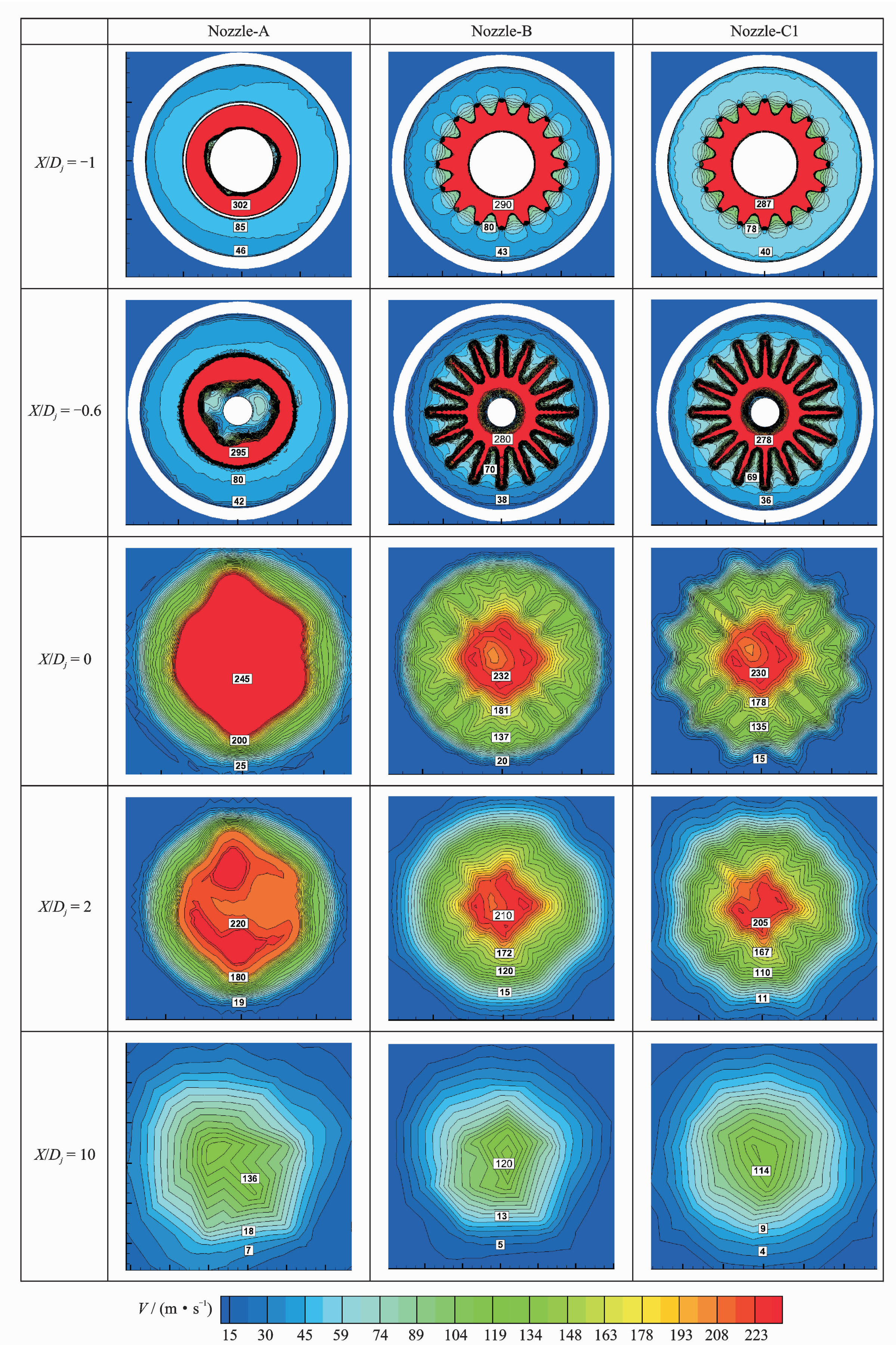
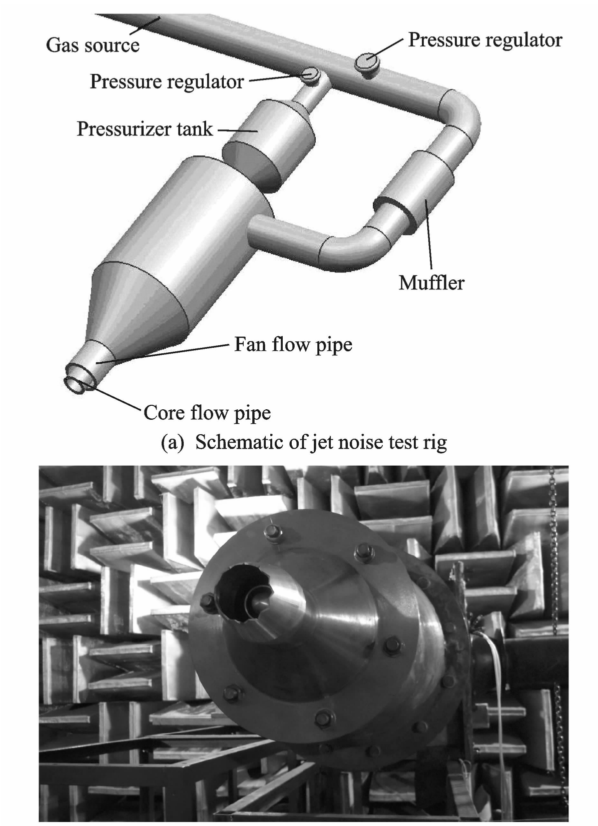


Fig. 3 Velocity contours on five cross sections

eight condenser microphones arranged on a circular arc at the center of the nozzle exit plane, whose radius is 60 times the diameter of nozzle exit. Eight microphones are arranged in the far field every 15° from 45°(Directivity angle measured from upstream jet axis) to 150°, as shown in Fig. 5.



(a) Schematic of jet noise test rig

(b) Photo of jet noise test rig

Fig. 4 Dual-flow cold jet noise test rig

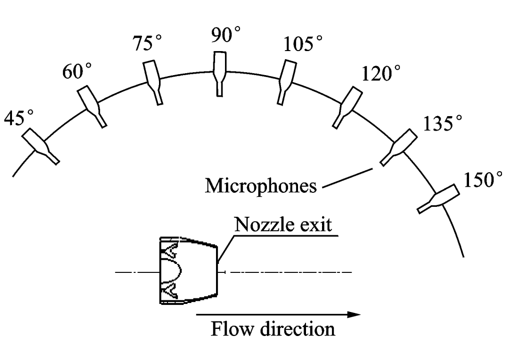


Fig. 5 Vertical view of measurement scheme

4 Results and Discussion

4.1 Far field spectra of jet noise

The experiments are performed at a core flow exit with *Ma* 0.8 and a fan flow exit with *Ma* 0.5. For limited space, we only give the comparisons of noise frequency spectra from Nozzle-C0, Nozzle-C1 and Nozzle-C2 with Nozzle-A and Nozzle-B (See Fig. 6) at upward direction (Directivity angle=60°), sideline direction (Directivity angle=90°) and downward direction (Directivity angle =150°). In consideration of jet noise directivities, the ordinate datum points at 60° and 90 ° have the same value of sound pressure level (SPL) and the ordinate datum point at 150° increases 10 dB than the ordinate datum points at 60° and 90°.

Note that all the frequency spectra in Fig. 6 is normalized as a Strouhal number (St) calculated by

$$St = \frac{fD_j}{U_j} \tag{1}$$

where f is the observation frequency, D_j the nozzle exit diameter, and U_j the nozzle exit jet velocity. SPL is calculated by

$$\mathrm{SPL} = 10\lg \frac{p^2}{p_0^2} = 20\lg \frac{p}{p_0} \tag{2}$$

where p is the sound pressure, $p_0 = 2\times 10^{-5}$ Pa, which is the standard sound pressure.

As it is seen from Fig. 6, similar to Nozzle-A and Nozzle-B, Nozzle-C0, Nozzle-C1 and Nozzle-C2 have far field frequency spectra which have parabolic distribution with low on both sides and high in the middle at 60°, 90° and 150°, which meets similitude law of the far field frequency spectra. In addition, alike to Nozzle-A and Nozzle-B, the comparisons of Figs. 6(a)—(c) show that Nozzle-C0, Nozzle-C1 and Nozzle-C2 successively increase SPL values at low frequencies as directivity angle increases from 60° to 150°. Because the jet at 150° is mainly composed of large scale vortexes which mainly radiate low frequency noise[17-19]. Fig. 7 presents the computational instantaneous density contours for Nozzle-A, and shows jet noise sources of high-bypass-ratio turbofan engine.

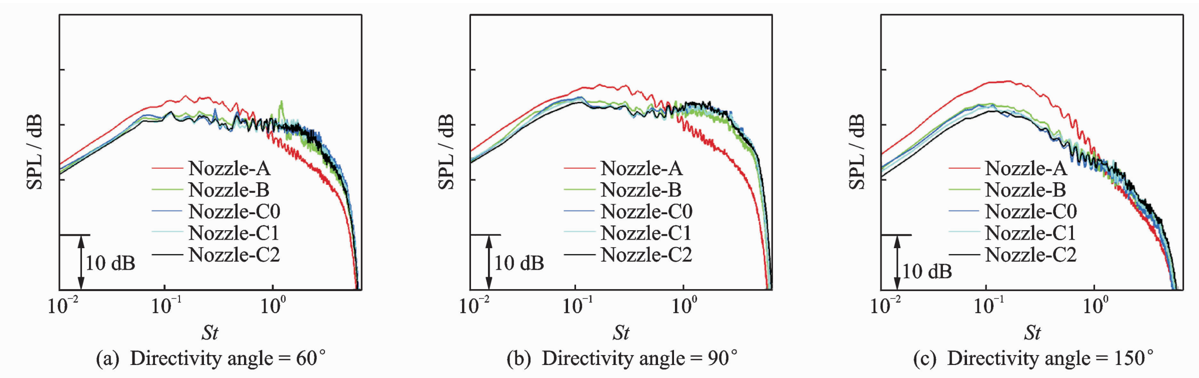


Fig. 6 Comparisons of noise frequency spectra from Nozzle-C0, Nozzle-C1 and Nozzle-C2 with Nozzle-A and -B

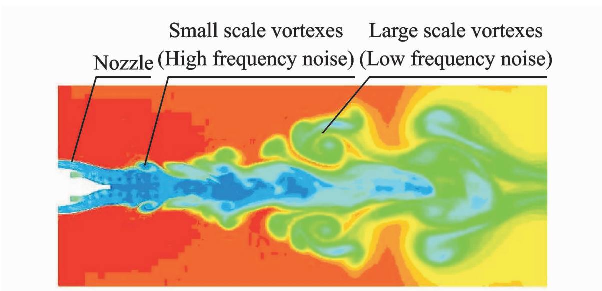


Fig. 7 Jet noise sources of high-bypass-ratio turbofan engine

4.2 Effect of chevron bend angle

At a core flow exit with *Ma* 0.8 and a fan flow exit with *Ma* 0.5, the comparisons of Figs. 6 (a)—(c) show that Nozzle-C2 has a best noise reduction at low frequencies among three different external chevron nozzles with 16-lobes scalloped lobed mixer, produces a 3—4 dB reduction compared with Nozzle-A and a 0.7—1.7 dB reduction compared with Nozzle-B at 60°, 90° and 150° compared with Nozzle-B, the results of noise reduction of Nozzle-C0, Nozzle-C1 and Nozzle-C2 are specifically discussed as follows:

(1) At 60° (See Fig. 6(a)), Nozzle-C0, Nozzle-C1 and Nozzle-C2 have a slight noise reduction at low frequencies, and produce about 0.1—1.3 dB reduction as a whole, but have a clear noise increase at high frequencies compared with noise reduction at low frequencies. Because the double mixing of the external chevron nozzle with lobed mixer further enhances the mixing of jet and ambient air, and makes more large scale vortexes transfer to small ones. Low frequency noise is radiated mainly by large scale vortexes, while high frequency noise is radiated mainly by small scale vortexes. For Nozzle-C0, Nozzle-C1 and Nozzle-C2, when the bend angle increases from 11° to 22°, noise reduction at low frequencies increases slightly, correspondingly, noise increase at high frequencies increases obviously. For Nozzle-C0, Nozzle-C1 and Nozzle-C2, noise reduction at low frequencies is about 0.1—0.4 dB, 0.7—0.9 dB and 0.7—1.3 dB, respectively. This main reason is that the chevrons enhance the mixing of jet and ambient air and make large scale vortexes transfer to small ones with the increase of chevron bend angle from 11° to 22°.

(2) At 90° (See Fig. 6(b)) and 150° (See Fig. 6(c)), SPL variation of Nozzle-C0, Nozzle-C1 and Nozzle-C2 at low frequencies is similar to that at 60°, and produce about 0.1—1.0 dB reduction at 90° and about 0.1—1.7 dB reduction at 150° as a whole. About 0.1—0.3 dB reduction of Nozzle-C0, about 0.1—0.5 dB reduction of Nozzle-C1, and about 0.7—1.0 dB reduction of Nozzle-C2 are produced at 90°. About 0.1—0.7 dB reduction of Nozzle-C0, about 0.7 dB reduction of Nozzle-C1, and about 1.5—1.7 dB reduction of Nozzle-C2 are produced at 150°. As the chevron bend angle increases from 11° to 22°, SPL variation of Nozzle-C0, Nozzle-C1 and Nozzle-C2 at high frequencies is different to that at 60°, which is fluctuant and is not obvious compared with that at 60°. High frequency SPL of Nozzle-C0, Nozzle-C1 and Nozzle-C2 slightly increases compared with that of Nozzle-B at 90°, and is equal to that of Nozzle-B at 150°.

4.3 Noise directivities

Fig. 8 is the comparisons of noise directivity from Nozzle-C1 with Nozzle-A and Nozzle-B at a core flow exit with *Ma* 0.8 and a fan flow exit with *Ma* 0.5. In Fig. 8, over all sound pressure level (OASPL) is the sum of the different SPLs, which have a range from 200 Hz to 50 000 Hz. OASPL is calculated by

$$\text{OASPL} = 10\lg(10^{0.1\text{SPL}_1} + 10^{0.1\text{SPL}_2} + \cdots + 10^{0.1\text{SPL}_n}) \quad (3)$$

As it is seen from Fig. 8, the double-mixing of Nozzle-C1 further enhances the mixing of jet and ambient air. Nozzle-C1 has a OASPL reduction in varying degrees at 60° and 150°, and the reduction is about 0.2 dB at 60° and about 1.1 dB at 150°. But Nozzle-C1 has a slightly OASPL increase of about 0.5 dB at 90°. In addition, compared with Nozzle-A, Nozzle-C1 has a clear OASPL reduction of about 4.6 dB at 150°, but has some OASPL increase of about 1.7 dB at 90° and about 0.9 dB at 60°.

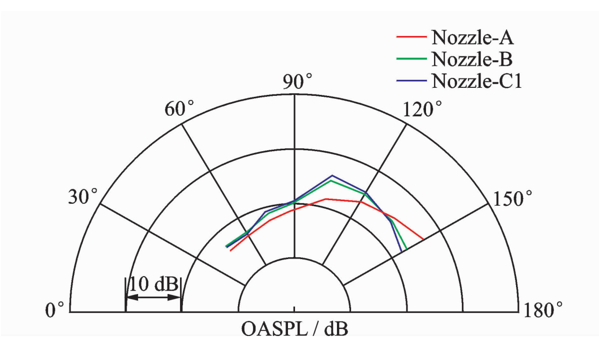


Fig. 8 Comparisons of noise directivity from Nozzle-C1 with Nozzle-A and Nozzle-B

5 Conclusions

In this paper, the investigation shows that compared with the nozzle with lobed mixer, the optimum external chevron nozzle with lobed mixer increases mixing of jet and ambient air near the nozzle exit and has better noise reduction at low frequencies. The main results of this present are described as follows:

(1) Compared with the nozzle with lobed mixer, the external chevron nozzle with lobed mixer largely reduces jet noise at low frequencies. The jet noise reduction at low frequencies increases a little with the increase of chevron bend angle. Nozzle-C2 (Chevron bend angle of 22°) produces a 0.7—1.7 dB reduction compared with the nozzle with lobed mixer and a 3—4 dB reduction compared with the nozzle with annular mixer at low frequencies.

(2) Compared with the nozzle with lobed mixer, the external chevron nozzle with lobed mixer has a SPL increase which is not obvious at high frequencies. SPL has relatively clear increase at 60° and little fluctuation at 90° and 150° with chevron bend angle increasing.

(3) Compared with the nozzle with lobed mixer, Nozzle-C1 with a chevron bend angle of 18° has OASPL reduction in varying degrees at 60° and 150°. It produces about 0.2 dB reduction at 60° and about 1.1 dB reduction at 150°, but has a slightly OASPL increase of about 0.5 dB at 90°.

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