Localization of Noise Sources in Jets Flowing from Lobed Nozzles

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Abstract. The noise of jets formed using conical and lobed nozzles has been measured. The possibility of jet noise reduction by using a lobed nozzle shape has been demonstrated. The localization of noise sources in jets formed using various nozzles has been carried out. A planar 9-beam 54-channel Bruel & Kjaer micro-phone array and Delay-and-Sum Beamforming technique were used. As a result, the position of noise sources in a turbulent jet in one-third octave frequency bands was obtained. The deviation effect of the position of noise sources when using lobed nozzles relative to the standard jet formed by a conical nozzle is demonstrated.

1 Introduction

The high bypass ratio of modern aircraft engines has led to a significant reduction in jet noise. However, the turbulent jet remains one of the significant noise sources of modern aircraft, especially during take-off.

The most common direction of work for further reduction of jet noise is to change the design of engine exhaust devices, leading to a change in the conditions of jet outflows and their mixing with the environment. Such methods include slot-shaped (rectangular), chevron, bevelled and lobed nozzles [1-6]. The most common are chevron nozzles, which have triangular teeth along the nozzle edge. This shape leads to the intensification of vortex formation in the shear layer and improves the mixing of flows. In [3], a parametric study of the influence of the geo-metrical parameters of chevrons (the length of a chevron, the number of chevrons, and their asymmetry) on the velocity profile and noise radiation in the far field was carried out. It should be noted that chevrons effectively reduce noise in the low-frequency region, but lead to noise amplification at high frequencies. Another type of nozzle that can be used to reduce aircraft engine jet noise is the lobed nozzle. Such nozzles have a slight sinusoidal corrugation in the circumferential direction. In [2, 5], lobed nozzles with a small number of lobes are considered. The effect of noise reduction, which the authors of these works manage to achieve, is 1–2 dB in the region of the jet radiation noise maximum, while the noise at high frequencies increases in the same way as for chevron nozzles. In [7], the possibility of expanding the frequency range and amplitude of jet noise reduction using lobed nozzles by changing the number and size of lobes was demonstrated. The assessment of thrust losses in lobed nozzles demonstrates an increase in losses up to

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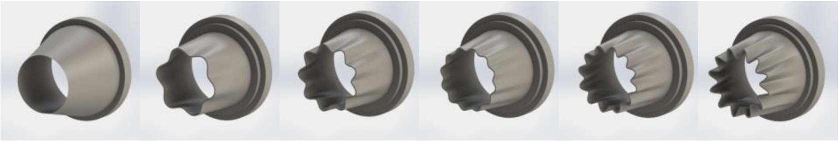
0.6% relative to conical nozzles. It should be noted that in accordance with the "eighth power law", the noise level of the subsonic jet is scaled as the eighth power of the jet velocity or the fourth power of thrust. Accordingly, a change in thrust by 0.5% will result in a change in jet noise of less than 0.1 dB. Consequently, the noise reduction of jets flowing from lobed nozzles is provided to a greater extent by changing the flow structure, rather than by changing the thrust, however, the physical mechanism by which the noise is reduced is not clear and requires further study.

As is known, the noise of a turbulent jet is generated by a multitude of vortices of various scales interacting with each other. This leads to the fact that the sound sources are distributed inside the jet. A change in the nozzle shape leads to a transformation of the jet flow structure itself and can lead to a change in the distribution of sound sources of a given object [4, 8]. This information is especially important for the development of shielding computational models. As is known, noise shielding of jets formed using lobed or chevron nozzles is more effective than jets flowing from traditional conical nozzles [9].

This paper presents the results of studying the noise of turbulent jets formed using a conical nozzle and a family of lobed nozzles. In the first part of the work, noise reduction spectra and noise reduction efficiency due to the lobed nozzle shape are presented. In the second part of the work, the positions of sound sources in jets formed using various nozzles are considered.

2 Jet noise reduction due to the lobed nozzle shape

A conical nozzle and a family of lobed nozzles were used in the work. The conical nozzle is a 12-degree cone with a 50 mm exit diameter. Lobed nozzles had a sinusoidal corrugation in the outlet region, gradually decreasing in the direction of the nozzle inlet. Nozzle inlet geometry and outlet area are equivalent to a basic conical nozzle. The number of lobes varied from 6 to 12, the height varied from 1.5 to 4.5 mm. The appearance of the nozzles is presented in Figure 1.

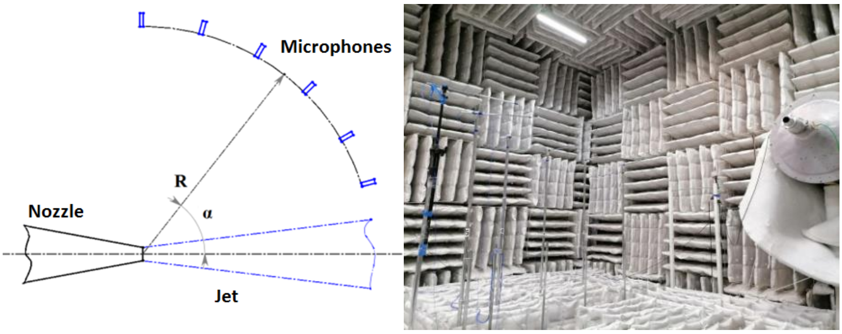


(a) (b) (c) (d) (e) (f)

Fig 1. Appearance of nozzles: (a) – conical nozzle; (b) – 6 lobes 3 mm high; (b) – 9 lobes 3 mm high; (d) – 12 lobes 1.5 mm high; (e) – 12 lobes 3 mm high; (f) – 12 lobes 4.75 mm high.

The measurements were carried out in an anechoic chamber at PNRPU equipped with a jet [10]. Before acoustic measurements, the air supply system was tuned to a jet velocity of 0.6 M using a Pitot-Prandtl tube installed at a distance of 1 caliber from the nozzle exit at the center of the flow.

To record the jet noise, six Bruel & Kjaer 1/4" microphones, type 4958, were used. To study the jet noise, 6 microphones were used, located at a distance R = 2 m from the nozzle exit at observation angles from α = 15º–90º with a step of 15º between the microphones. The scheme and photographs of the experiments are shown in Fig. 2.



(a) (b)

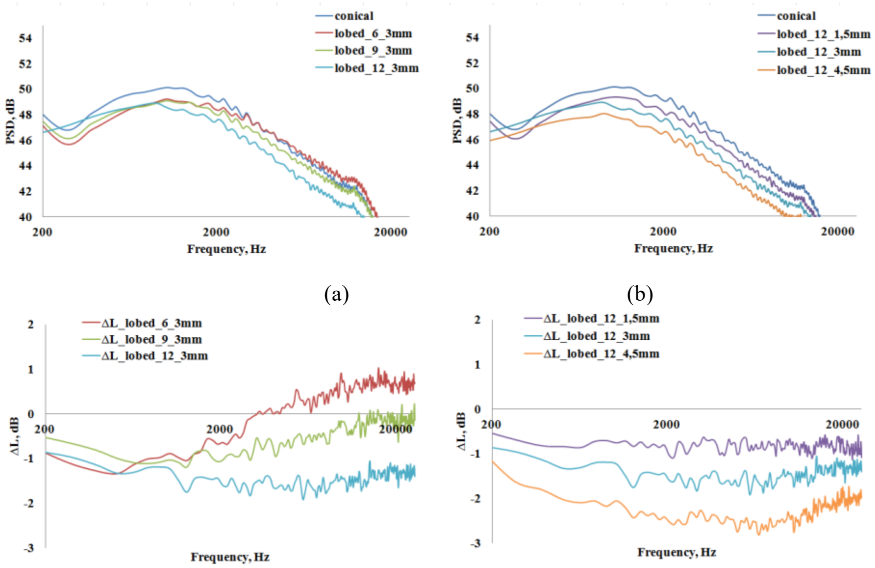
Fig 2. Scheme (a) and photograph (b) of the experiment

The noise reduction efficiency due to the lobed nozzle shape was evaluated using expression (1):

$$\Delta L = L_{lobed} - L_{conical} \tag{1}$$

where L_{lobed} is the sound pressure level of the jet flowing from a lobed nozzle, expressed in dB; $L_{conical}$ is the sound pressure level of the jet flowing from a conical nozzle, expressed in dB.

The results obtained are shown in Figure 3. The results obtained for the jets flowing from the six-lobed nozzle are similar to those for the jets flowing from the chevron nozzles: noise reduction is observed in the radiation maximum region, but noise amplification occurs at higher frequencies. With an increase in the number of lobes, the frequency range of the jet noise reduction is expanded. An increase in the lobe size leads to an increase in the amplitude effect of jet noise reduction.



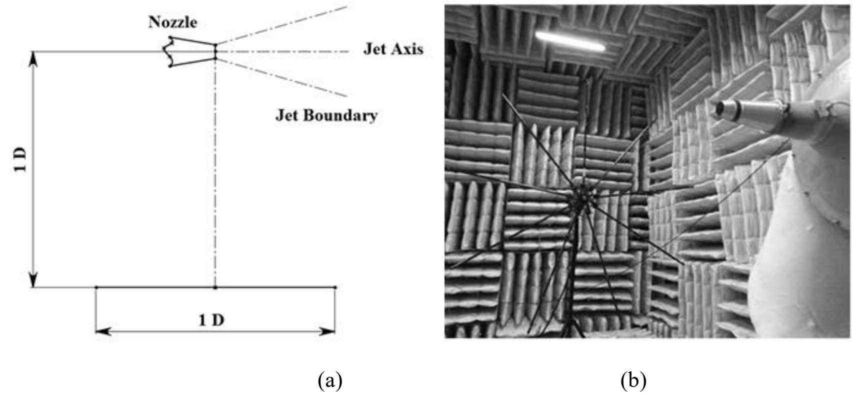
(a) (b)

(c) (d)

Fig 3. Noise reduction spectra (a), (b) and noise reduction efficiency (c), (d) due to lobed nozzle shape for 90° viewing angle.

3 Position of noise sources in jets flowing from various nozzles

In order to localize noise sources in turbulent jets, a 9-beam 54-microphone array Bruel & Kjaer type WA-1676-W-003 was used, in which Bruel & Kjaer type 4944 microphones were installed. The microphone array was installed so that the center of the array was opposite the nozzle exit, and the jet axis crossed the center of the localization map. The array was removed from the jet plane at a distance of 2.5 m. The layout of the microphone array and the photo of the experiment are shown in Figure 4.



(a) (b)

Fig 4. The layout of the microphone array (a) and the photo of the experiment (b).

The measurements were carried out for a jet velocity of 0.6 M. Time signals were recorded using Pulse LabShop NSI Array Fixed Meas software. The received time signals were processed in NSI Array Acoustic Post-Processing software using Beamforming Delay-and-Sum technique [11-14]. As a result, localization maps of noise sources were obtained for each one-third octave frequency band in the range from 315 to 20,000 Hz. As an example, Figure 5 shows the obtained noise source localization maps for a conical and one of the lobed nozzles. As can be seen, the localization maps obtained have a qualitative correspondence, and characteristic manifestations for this type of flow are observed, in particular, as the frequency increases, the source decreases and moves closer to the nozzle exit. The source center in the maximum jet noise region for a given velocity (500–2000 Hz) is located at a distance of 4–9 calibers from the nozzle exit, which corresponds to the end of the initial section and the beginning of the main section in the flow of the submerged jet. At the same time, in a jet formed with a lobed nozzle, the position of the sources is close to the position in a conventional jet, however, with increasing frequency, the source moves faster closer to the nozzle exit.

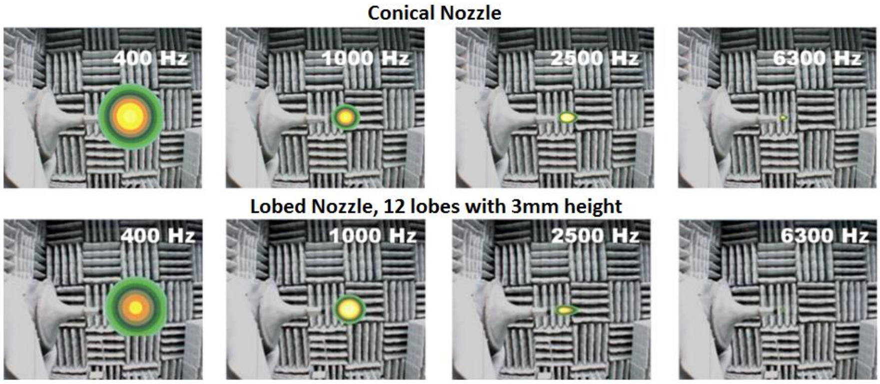


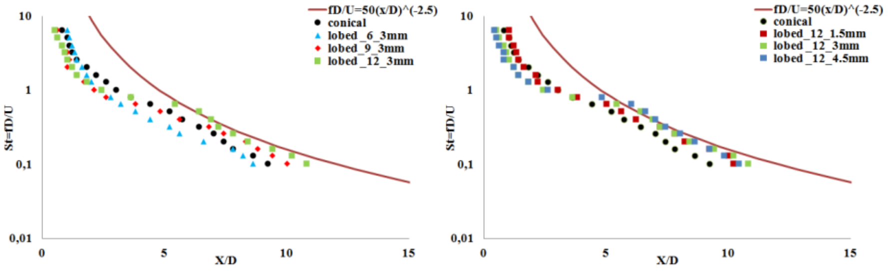
Fig 5. Localization maps of noise sources for a conical and lobed nozzle.

Subsequently, a more detailed analysis of the positions of jet noise sources was carried out in accordance with [8]. In this work, the position of the center of the noise source on the localization map for turbulent jets was considered. In this case, the position of noise sources at different frequencies is concentrated near (2):

$$St = 50\left(\frac{x}{d}\right)^{-2.5} \tag{2}$$

where St is the Strouhal number; x is the position of the noise source center on the localization map; d is the nozzle diameter.

Figure 6 shows the dependences of the position of sound sources in jets formed using various nozzles. The set of experimental points for a conical nozzle is approximated by an inverse power function similar to formula (2). The approximate values of the constants included in formula (2) are 1.9 and 8 for the power factor and the real factor, respectively. The reasons for the difference in the position of noise sources from the calculated curve were discussed in detail in [15] and are related to the difference in the initial conditions of the jet outflow and the localization methods used. The use of lobed nozzles leads to a deviation of the positions of sound sources in jet; the greatest manifestation of this effect occurs at high and low frequencies. At high frequencies, the source is shifted closer to the nozzle exit compared to a conical nozzle, and at low frequencies it is shifted farther from the nozzle. An increase in the number or amplitude of lobes leads to a stronger deviation of the position of noise sources from the positions of noise sources in a conventional jet flowing from a conical nozzle.



(a) (b)

Fig 6. Dependence of the source position on localization maps for various nozzles: (a) – influence of the number of lobes; (b) – influence of lobe height.

4 Conclusion

The paper considers the acoustic characteristics of jets flowing from conical and lobed nozzles. Lobed nozzles have from 6 to 12 lobes with a height of 1.5 to 3 mm. The experiments carried out to measure the turbulent jet noise showed that the efficiency of the created lobed nozzles can reach 2-3 dB without amplifying the noise at high frequencies.

The localization of noise sources in a turbulent jet formed using conical and lobed nozzles was carried out. A planar 9-beam 54-channel Bruel & Kjaer microphone array and Delay-and-Sum Beamforming technique were used. As a result, the position of noise sources in a turbulent jet in one-third octave frequency bands was obtained. The use of lobed nozzles leads to a deviation of the position of the noise sources relative to the jet formed by the conical nozzle. The positions of noise sources at higher frequencies relative to the emission maximum are shifted to the area closer to the nozzle exit, and at lower frequencies, on the contrary, they move away from the nozzle exit. An increase in the number of lobes and their size leads to stronger deviations in the positions of noise sources.

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