Near-Field Acoustic Characteristics of Supersonic Jets from Chevron Nozzles

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Abstract

The near-field acoustic characteristics of suppersonic jets from chevron nozzles have been investigated by the optical wave microphone. This laser-based microphone not only unobstructs the flow, but it is also able to measure the simultaneous sound propagation both vertical and horizontal directions. As a result, the real time fluctuation of the jet has been observed that the screech tone from 2-notched nozzle is only propagated on the unnotched side with sound speed, and the strongest source of the noise is movable when the notch number is changed.

***Keywords**:* Screech tone, Near-field acoustic, Chevron nozzle, Optical wave microphone.

1. Introduction

Shock associated noise of chocked jets has seriously been investigated since 1950's. The phenomenon directly concerns with many types of engineering applications, such as turbofans, jet engines and high pressure pipelines. In the early 1960's shock noise was first detected that it made some minor cracking at the tailplane of VC 10 aircraft [1]. Furthermore, the sonic fatigue on F-15 and B-1 nozzle flaps from shock associated noise was reported [2]. After the pressure ratio of air jet flow exceeds the critical value, it becomes underexpanded supersonic jet. Higher frequency sound wave is generated by the transition of laminar boundary layer to turbulence, and by the interaction between this mixing layer and shock wave of the large-scale flow [3]. As a result, the jet flow consists of two components: a harmonically related tone called screech tone and a broadband shock noise appearing in repetitive diamond-shape pattern called shock cells. Shock waves are also observed at the end of the cells during contraction and growing to upstream direction in conical shape [4].

There are various methods to overcome shock associated noise. By design, using a proper convergent-divergent nozzle, the shock noise can be reduced or even suppressed, but it is only usable about the design point [5]. Because a circular nozzle produces noisiest jet, the supersonic broadband noise can be decreased with some modification of its geometry, adding tabs or making notches [6, 7]. By the addition of slots or fingers to a convergent axisymmetric nozzle, the mixing close to the nozzle exit is enhanced, and it obviously contributes to a noise reduction [8]. The presence of tabs influences on underexpanded jet by distortion of the velocity flowfield [9]. Using flow visualization shows that a tap being higher than the boundary-layer thickness induces a pair of stationary, counter-rotating streamwise vortices distorting the jet flow effectively [10]. When broadband noise and screech tone are controlled, thrust loss becomes inevitable [11]. Moreover, the chevron geometry is also investigated that it is better than rectangular geometry for the axisymmetric noise reduction [12]. From the far-field acoustic investigation, the benefit of a chevron nozzle is the velocity difference between inner and outer flows, as well as it is suitable at lower frequencies and at aft angles [13]. However, the previous noise study on the jet exhausted from chevron nozzles was only investigated in the far field [14, 15]. The acoustic characteristics in the near field of the jet from the chevron nozzles have still been unsolved.

An optical microphone is a new technology for high-frequency sound measurement. In this paper, the near-field sound measurement technique has been developed to collect both average and instantaneous sound intensity of underexpanded jets from plain, 2-notched and 4-notched nozzles. Next, all average data are analyzed and visualized to determine the main source of sound. Finally, the mechanism of sound propagation of each nozzle is determined by the series of simultaneous data.

2. Optical Wave Microphone

An optical wave microphone, shortly opt-microphone, is a special device for detecting the sound pressure level (SPL) from the 2-dimensional laser-beam diffraction with photodiodes. Without contacting any media, it is ideal for measuring acoustic characteristics to understand the mechanism of the near-field supersonic jet noise. The theorem, frequency properties and directivity of the opt-microphone have been studied by Nakazono and Sonoda [16, 17, 18]. In this work, the sound propagating is measured in 2 modes. The first mode is the horizontal component in *x*-axis called “the horizontal measurement (HM) mode.” The second mode is the vertical component called “the vertical measurement (VM) mode.” Because both modes are independently measured with the opt-microphone at the same time, it not only saves time, but the instantaneous sonic fields and the propagating direction are also collected very close to the main source of the supersonic jet with plain, 2-notched and 4 notched nozzles.

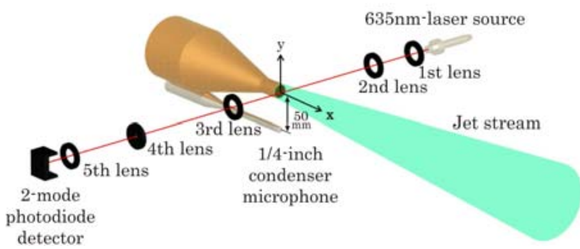

Fig. 1 The experimental apparatus.

Nozzle Types	Diameter, D [mm]	No. of Notches	Angle, θ [deg]	Depth, S [mm]
Plain	10	-	-	-
2-Notched	10	2	90	5
4-Notched	10	4	90	5

Table 1 The characteristics of the nozzles.

3. Experimental Apparatus

All experimental data have been tested in a 6.4m×4.6m ×2.5m semi-anechoic room, and the experimental apparatus is shown in Fig.1. A 37-kW compressor is used to supply the airflow to a muffler for reducing the upstream noise. Then, the air is passed through a plenum chamber, and exhausted from a nozzle attached to a plenum chamber. The shapes and photographs of the chevron nozzle are shown in Fig.2, and the sizes of various nozzles are shown in Table 1. Each nozzle has dimensions of 10mm in diameter (*D*), 1mm thick and 5mm deep (*S*). About the nozzle orientations, the direction with some notches is defined as "the notched side," and the direction without notch is defined as "the unnotched side."

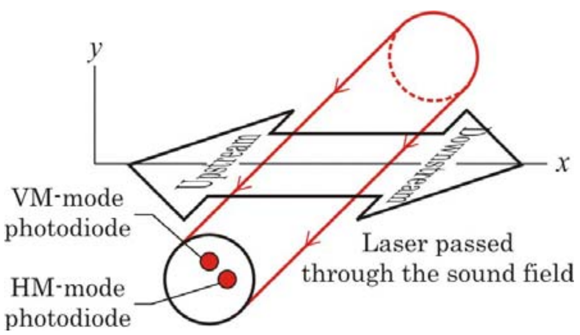

Fig. 3 The photodiode detector

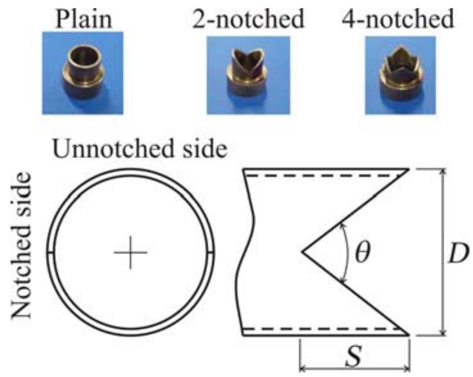

Fig. 2 The nozzle parameters and orientations.

The opt-microphone consists of the set of five convex lenses, a semiconductor laser source and a photodiode detector. The locations of the photodiodes on the detector are shown in Fig. 3. The 10-kHz sound, generated from a horn tweeter both horizontal and vertical directions, is used for the opt-microphone calibration. First, the far-field noise has been measured with a quarter-inch condenser microphone at a distance of 600mm from the nozzle exit with observation angle of 90º from the downstream jet axis or *x*-direction. Then, the near-field acoustic SPL is measured with the opt-microphone. By 2-channel FFT analyzer, the SPL is simultaneously measured in HM and VM modes. Note that the origin is set at the center of the nozzle exit. In the case of the average data, the signal intensity measured by opt-microphone is called "laser signal intensity level, (LIL)," which is defined as [18]

$$LIL = 100 + 20log(V_{signal} / V_{ref}) \quad (1)$$

where V_{signal} is the measured voltage from FFT, and V_{ref} is the reference voltage when the condenser microphone measures the 10kHz source and obtains the SPL at the value of the

100dB. In the case of the simultaneous data, the voltage signal measured from FFT is directly used. When measuring in *x*-direction, the opt-microphone is moved every 2mm-interval from -30mm to 100mm. In *y*-direction, after measuring at the position of 7.5 mm from the jet center axis, the microphone is moved every 2.5mm-interval until 20mm. To capture all of the sound fields, the nozzle is rotated in 5-degree increment from 0 to 180 degrees. At each step the time-series data of the laser signal intensity obtained are recorded in a data recorder. Finally, the data are analyzed by both a computer and a FFT analyzer.

To investigate the simultaneous measurement for the HM and VM modes with the opt-microphone precisely, the 4mm-diamerter laser beam, passed through the sound field, has been enlarged 3 times when detected by the photodiodes. Because the laser intensity profile is non-uniform, each photodiode is fixed at the maximum intensity point of its direction to measure sound field effectively.

By placing the condenser microphone as a triggering microphone at 50mm below the center of the nozzle exit, the instantaneous time changes near acoustic field coinciding with the signals from the HM and VM modes have been measured. This method greatly shortens the experimental time, compared to the past one.

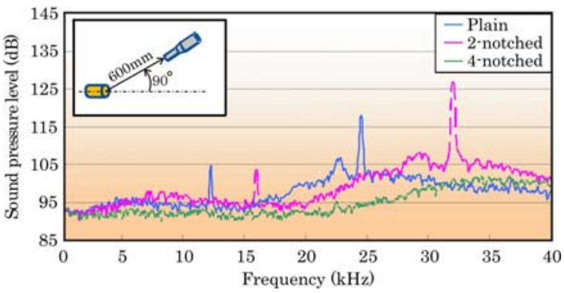

Fig. 4 Sound pressure spectra in the far field.

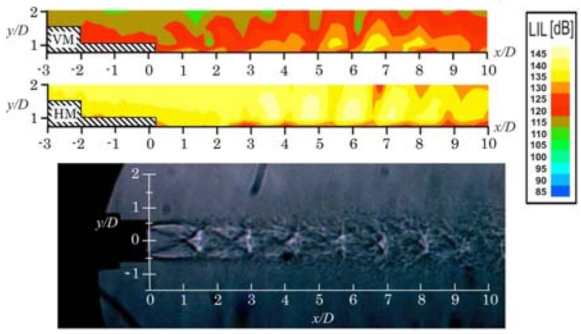

Fig. 5 The 2-mode near-field acoustic characteristics and shadowgraph of the supersonic jet from the plain nozzle.

4. Experimental Results

4.1 Far-field acoustic results

Figure 4 shows the sound pressure spectra of all nozzles in the far field when the nozzle pressure ratio (NPR), the ratio of the settling chamber pressure to the ambient pressure, is set at 3.91. Obviously, the plain and 2-notched nozzles generate the octave screech tone at the frequencies of 12/24 kHz and 16/32 kHz, respectively, whereas the 4-notched nozzle does not generate the tone. It's worth noting that the chevron nozzles are not effective in low-frequency broadband noise, and the 4-notched nozzle is the most effective for screech tone and broadband noise reduction.

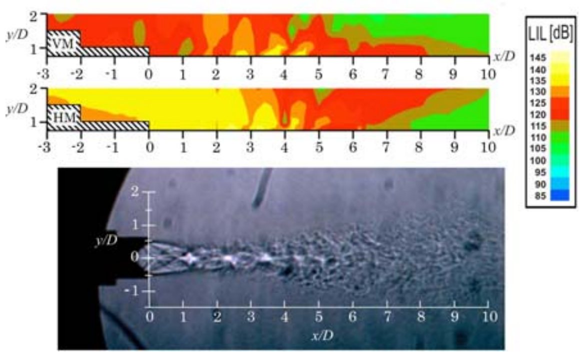

Fig. 6 The 2-mode near-field acoustic characteristics and shadowgraph of the supersonic jet from the 2-notched nozzle (unnotched side).

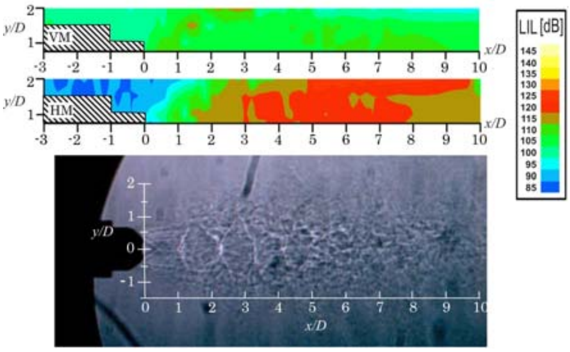

Fig. 7 The 2-mode near-field acoustic characteristics and shadowgraph of the supersonic jet from the 2-notched nozzle (unnotched side).

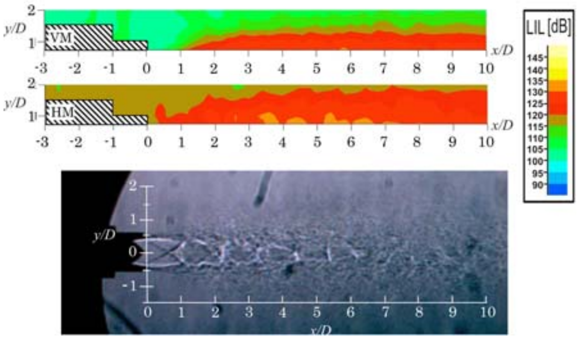

Fig. 8 The 2-mode near-field acoustic characteristics and shadowgraph of the supersonic jet from the 4-notched nozzle.

4.2 Average near-field acoustic results

Next, the near-field jet noise of the plain, 2-notched and 4-notched nozzles with the opt-microphone has been investigated in two modes. Figure 5 illustrates the acoustic characteristics and shadowgraph of the plain nozzle at NPR equal to 3.71, corresponding to the perfect expanded jet at Mach number (M_j) equal to 1.51. The horizontal and vertical axes are the nondimentional lengths of the *x*- and *y*-axes with respect to the nozzle diameter. On the *x*-axis, the plus and minus signs mean the downstream and upstream directions, respectively. Note that two regions are not measureable. The first one is the area, which the laser beam hits the nozzle shown as the hatching lines. Another region is the area inside the shock cells, which the laser beam has high degree of diffraction when passing through these cells.

The measurement shows that the HM mode noticeably generates the stronger noise than the VM mode. The strongest noise of the HM mode is located at the third, forth and fifth shock cells, and it indicates that the screech tone propagates upstream. It is noticed that the noise source of the screech tone is at the position from *x*/D=3 to7.

The near-field acoustic and the shadowgraph of the unnotched side of 2-notched nozzle are shown in Fig.6. From the shadowgraph, the distance between shock disks of the jet from this nozzle becomes shorter than that from the plain nozzle, but the cross-sectional area of the shock cells at the same distance is narrower. The stream vortices apparently generated on the chevron side forms the subdominant jet outside the main jet for spreading out to the unnotched side. At the distance of *x*/D=2, the jet has the minimum diameter, and starts diffusing. In this case, the noise source of the screech tone locates from *x*/D=2 to 4. When compared with the previous case, the screech tone source moves to the upstream.

The near-field acoustic characteristics and shadowgraphs of the notched-side of 2-notched nozzle corresponding to its screech tone are displayed in Fig.7. In the HM mode, there is no screech tone propagating to the upstream. The position of the strongest broadband noise generated by the interaction between the turbulence and the shock wave is between x/D=3 and 7. The shadowgraph shows that the jet starts diffusing itself at the nozzle exit because of the mixing enhancement from the notched nozzle. As a result, the shock wave is weakened, and the screech tone are not generated.

Figure 8 represents the near-field characteristics and the shadowgraph of the 4-notched nozzle. From the shadowgraph, the shock wave shows a complex structure with the same length of the cells as one of the 2-notched nozzle. The strength of the jet is weakened by the notches. Like the plain nozzle, the main noise source is now located between x/D=3 and 7, corresponding to the third, forth, and fifth shock waves. Although the sound propagates downstream, the screech tone is not observed.

Clearly, the measurement shows that the 4-notched nozzle has the best characteristics of the acoustic fields among others because the screech tone is avoidable or it generates the least level of the jet noise as described. The sound field of 2-notched nozzle, however, is complicated because of its asymmetry.

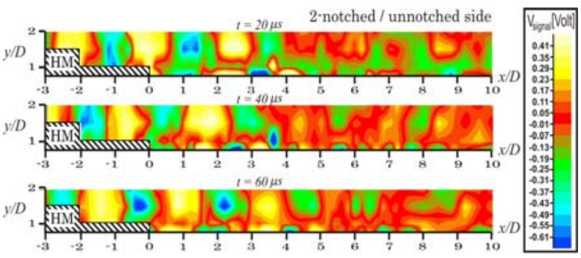

Fig. 9 The instantaneous HM-mode near-field acoustic characteristics of the supersonic jet measured from the unnotched side of the 2-notched nozzle.

To understand the complexity of the sound field of this nozzle, it has been selected to study the instantaneous near-field acoustic characteristics both in the HM and VM modes. The results are discussed in the next section.

4.3 Instantaneous near-field acoustic results

The experiment has been done by a conditional sampling method, in which a condenser microphone has been selected as a triggering microphone. The sampling frequency is 150 kHz, and the signal intensity distribution with time series is obtained by 10-data averaging values. The highest amplitude of the sound is assumed to be the starting time set at t equal to 0 μs. Then, the data from the opt-microphone are recorded and analyzed to obtain the real-time sound pressure level. Finally, the results are displayed in the series of time, t equal to 20, 40 and 60 μs, respectively.

Figure 9 shows the instantaneous acoustic field radiated on the unnotched side in HM mode. At t=20 μs, the maximum and minimum values of the noise are switching in position close to the shock cells from the nozzle exit to x/D equal to 4. This phenomenon also

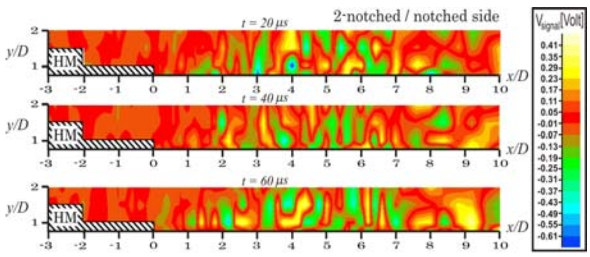

Fig. 10 The instantaneous HM-mode near-field acoustic characteristics of the supersonic jet measured from the notched side of the 2-notched nozzle.

happens at the downstream. When considering the alternating voltage in time series, the screech tone are propagating upstream with sound speed. If the *x*/D is more than 4, the tone propagation will not be observed. That means the sound source of the screech tone is located at *x*/D=4. This information coincides with both the average data of the sound field and the shadowgraph as shown in Fig. 6. It also explains how the strength of shock wave at *x*/D=3.3, corresponding to the third shock position counted from the nozzle exit, generates of the screech tone to upstream.

Figure 10 illustrates the instantaneous acoustic near field generated on the notched side in HM mode. At t=20μs, the sound field fluctuates at low level from downstream to *x*/D=1, When *x*/D is more than 1, the sound field has the complex distributions because the mixing is enhanced by the notch as being noticeable from the shadowgraph in Fig.7. The jet flow diverges from the plume at high angle. Unlike the unnotched side, the screech tone is not detected when considering in time series. The 2-notched VM modes of the notched- and unnotched sides are also evaluated instantaneously. The results are similar to the previous case; there is no screech tone.

5. Conclusions

The near acoustic field characteristics of supersonic jet noise from the three types of the chevron nozzle have been studied using an opt-microphone and shadowgraphs. The following results have been obtained.

1) An opt-microphone is possible to measure simultaneously the sound propagating to the vertical direction against the jet axis and to the jet direction.
2) For the 2-notched nozzle, the screech tone propagates with a sound speed on the unnotched side, but it is not generated on the notched side. Therefore, the 2-notched nozzle forms the complex sound field depending on the notched direction.
3) The notch number influences the main noise source of the screech tone. With 2-notched nozzle, the main noise is moved to the upstream side of the jet.
4) The 4-notched nozzle alleviates the shock wave of the jet and does not generate the screech tone.

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