Experimental Investigation of Jet Noise Sources in a Hypersonic Nozzle at Takeoff

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I. Introduction

INVESTIGATING the noise sources in the high-speed exhaust jet is one of the most important technical issues in the development of the next generation's supersonic/hypersonic engines. In the Japan Aerospace Exploration Agency (JAXA), a precooled turbojet (PCTJ) engine, which is capable of accelerating the vehicle from takeoff to Mach 5 with a single engine cycle, is under development [1-5]. In the PCTJ engine, a variable hypersonic nozzle with an external ramp is employed to compensate for the drastic change in the nozzle pressure ratio (NPR). The

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NPR changes from 2 at takeoff to 200 at cruise; at takeoff, the nozzle operates under off-design, overexpanded condition [1]. One of the largest concerns in the development of this engine is the intensive jet noise at takeoff. From the viewpoint of the noise suppressor design [3-4] for such a realistic hypersonic nozzle having complicated geometry and operating under off-design conditions, understanding the complicated behavior of the noise sources is quite important.

Panda et al. [6, 7] investigated the behavior of jet noise sources in a single round jet. They applied Rayleigh scattering method to measure the local density fluctuation in the jet, and by directly comparing the data with the pressure fluctuation obtained with far-field microphones, a cross-correlation analysis was carried out. The coherence between these two data is indicated with isocontours, wherein the location of the sources is clearly illustrated. Panda et al. [7] pointed out that the noise source measured by the Rayleigh scattering method exhibits strong directional characteristics, and they offered an explanation for the observed directional variation based on the two-noise source model [8-10]. These works provided essential information in terms of the behavior of the source, and these experimental evidences contribute to the important paper by Tam et al. [11], wherein the behavior of the jet noise sources is clearly illustrated.

In the present study, based on the methods proposed in these pioneering works, the behavior of the source is investigated. Since the Rayleigh scattering method requires significant cost and complexity, the authors applied a simpler method, a variant of schlieren technique. Such optical deflectometry methods have also been employed by several researchers to investigate the behavior of the source [12-14]. In the present study, to gain a high sensitivity capable of detecting the acoustic wave propagation in the ambient, a laser schlieren optical system which realizes a small spot size is utilized. In the present study, the behavior of the source in a supersonic jet issuing from a realistic hypersonic nozzle operating at the takeoff condition is investigated through a cross-correlation analysis between the schlieren data and the far-field noise.

II. Experimental Setup and Procedure

A. Rectangular Hypersonic Nozzle

Figure 1 shows a schematic of the rectangular hypersonic nozzle [3, 5]. The test nozzle consists of a ramp, a cowl, and sidewalls. The width and height of the nozzle throat are W = 20 mm and H = 2.8 mm respectively, which correspond to the takeoff condition (wide open). The origin of the coordinate system is set at the center of the cowl lip, and x, y, and z axes are set along the streamwise, transverse, and spanwise directions, respectively.

Figure 1 also shows a time-averaged schlieren image of the internal nozzle [3, 5]. This nozzle operates under off-design condition (overexpansion mode) at takeoff, and it is designed so that the flow separates from the cowl wall intentionally to compensate for the undesirably large area ratio of the internal nozzle [3, 5]. After separation, the jet flows along the ramp wall and is exhausted into the atmosphere from the ramp lip. The static pressure at the cowl exit matches the atmospheric pressure, and the jet velocity measured at the cowl exit agrees with that estimated assuming isentropic expansion within an error of 2 % [3, 5].

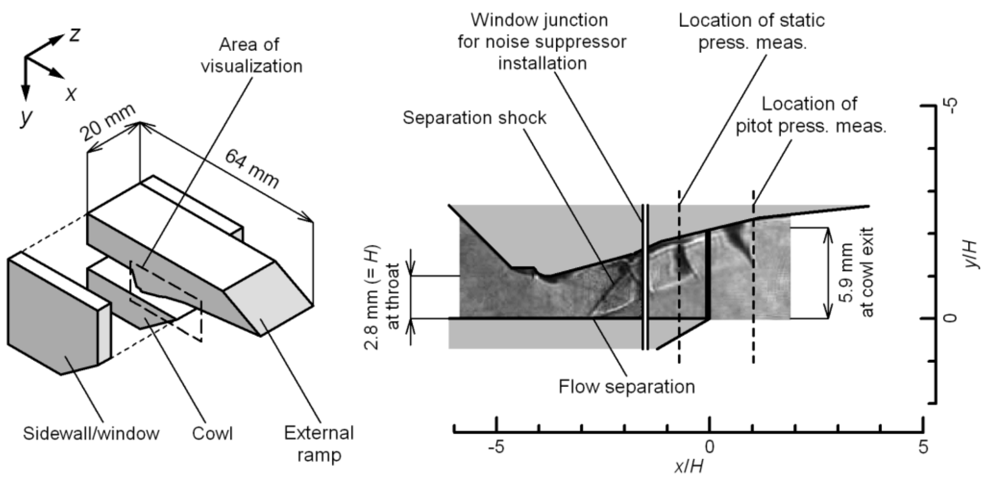


Fig. 1 Schematic of rectangular hypersonic nozzle [3, 5].

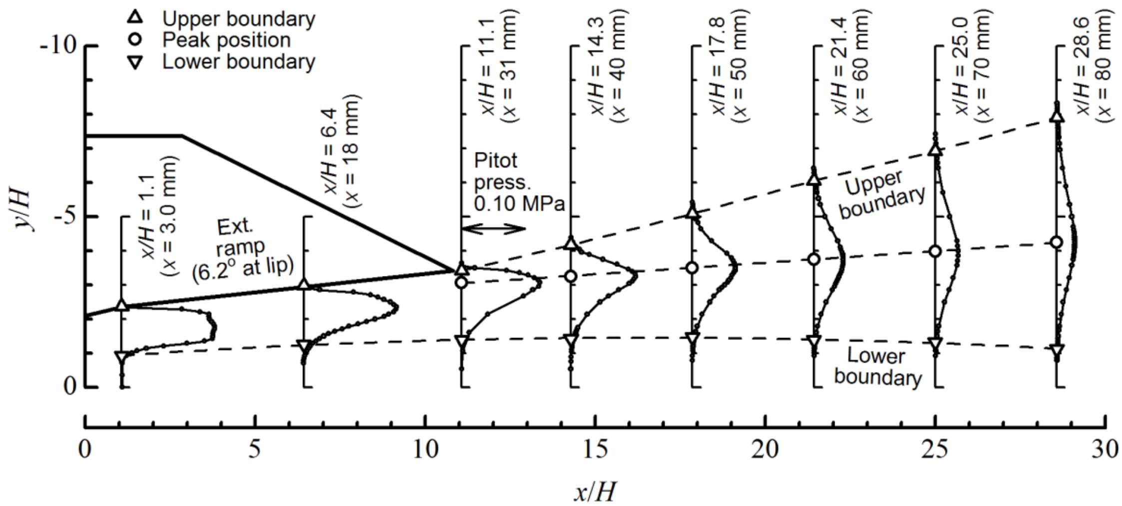


Fig. 2 Pitot pressure profiles at *z*/*H* = 0 [5].

Figure 2 shows Pitot pressure profiles obtained with a 0.3 mm-outer-diameter Pitot tube [5]. The location of peak Pitot pressure is indicated with circles, and the jet boundaries, defined at 5 % of the peak, are indicated with triangles. Just downstream of the cowl exit, the Pitot pressure profile has a flat-top configuration. Because of the asymmetric configuration of the nozzle, the shear layer begins to grow at the slip-line side after the jet leaves the cowl exit, while the jet is still confined by the wall at the external ramp side. Downstream of the ramp end, an asymmetric velocity profile is established, with a steep gradient at the upper shear layer.

Table 1 shows the jet conditions. The NPR is kept at 2.70, which corresponds to the takeoff condition of the vehicle. Since the total temperature is room temperature and the working gas is air, the jet velocity is smaller than that for the actual PCTJ engine where the exhaust consists of heated air and products of combustion.

Table 1 Jet conditions.

Parameter	Value
Nozzle pressure ratio	2.70
Total temperature, K	288
Mach number [a]	1.28
Jet velocity U, m/s [a]	378
Jet density, kg/m^3 [a]	1.63
Working gas	Air

[a] Assuming isentropic expansion and specific heat ratio of 1.402.

B. Far-Field Microphones and Optical Setup

Far-field noise is acquired using 1/8-inch microphones (B&K, 4138). Five microphones are arranged along a straight line at a sideline distance of 0.8 m, which is in the geometric far field [5]. By changing the azimuthal angle of the test nozzle while the microphones are kept aligned along the same straight path, the far-field noise for the ramp and cowl directions is obtained separately. All the microphones point at the origin of the coordinate system for normal incidence of the acoustic wave. The measurement angle θ_{inlet} is defined as that relative to the engine inlet, and the measurements are carried out at aft angles of the nozzle; $90 \leq \theta_{inlet} \leq 150$ deg for the ramp side and $90 \leq \theta_{inlet} \leq 160$ deg for the cowl side.

Figure 3 shows a schematic of the optical setup. By use of laser schlieren optics, the fluctuation of the density gradient in the jet and its acoustic field is detected. A CW He-Ne laser (Melles Griot, 05LHP211) is used as the light source. The refraction of the probe beam due to the density gradient along the beam path is converted into the variation of light intensity by placing a knife edge at the focal point of the probe beam. The spatial resolution is 0.4 mm, which is determined by the size of the pinhole in front of the high-frequency photo sensor (Hamamatsu Photonics, S3071).

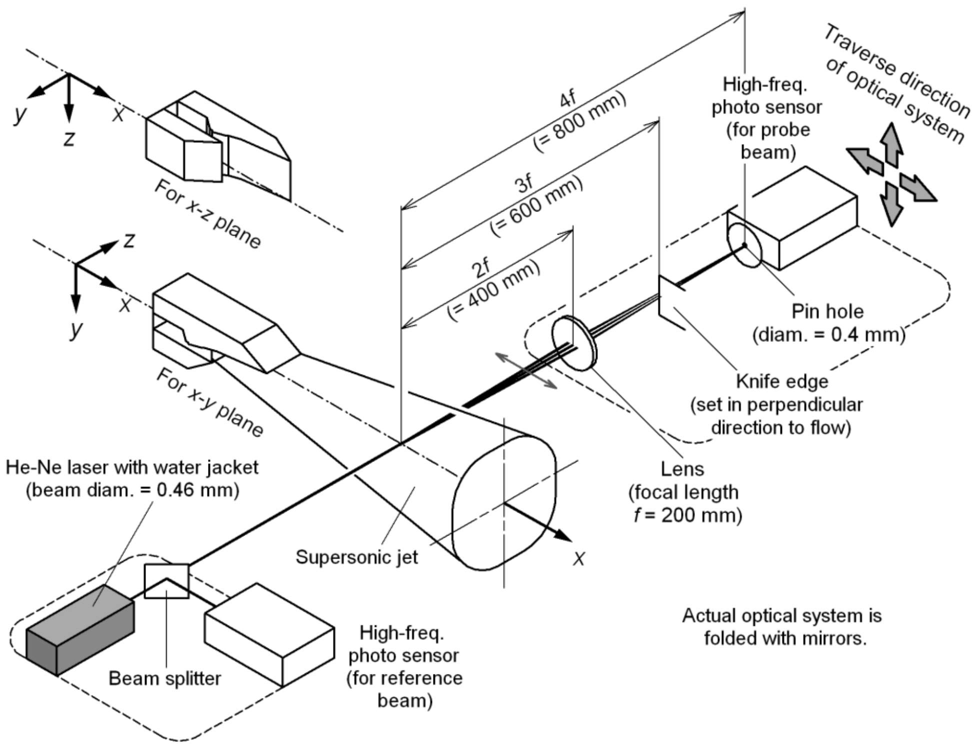


Fig. 3 Schematic of optical setup (not to scale).

By traversing the entire optical setup, the spatial distribution of the light intensity fluctuation on the *x*-*y* and *x*-*z* planes is acquired. The optical setup is traversed in the streamwise direction every 3.0 mm at minimum and in the transverse direction every 0.5 mm, respectively. In the present study, by rotating the test nozzle, the probe beam path is set in two different directions, while the knife edge is always inserted in the perpendicular directions to the flow. The density gradient in the same direction (in *x* direction) is always detected regardless of the direction of fluctuation of the probe beam.

The signals from the five microphones and the two photo sensors (for the probe and reference beams) are acquired at the same timing and sampling rate with two digital oscilloscopes, which have totally eight input channels and are synchronized by an external trigger signal. The cross-correlation curve obtained in the present study has a peaky nature, and to ensure the accuracy of the maximum cross-correlation, the sampling rate is set at 1.0 MHz while the maximum actuator response of the microphone is 140 kHz. The acquired data, whose length is 1,250,000 at each measurement point, are processed by fast Fourier transform every 8,192 samples, and from the average of them, the spectra are obtained.

III. Results and Discussions

A. Far-Field Noise

Figure 4 shows the far-field noise spectra. The spectral levels are corrected assuming that the nozzle throat area $HW = 1\ \text{m}^2$ and that the measurement distance $r = 20$ m [5]. The horizontal axis indicates the Strouhal number based on the jet velocity U and the nozzle throat height H. As was shown in the previous work [5], the F-spectrum and the G-spectrum [8-11] can fit the experimentally observed spectra. While shock structures are observed at the downstream part of the nozzle throat, their effect on the far-field noise spectra seems to be relatively small.

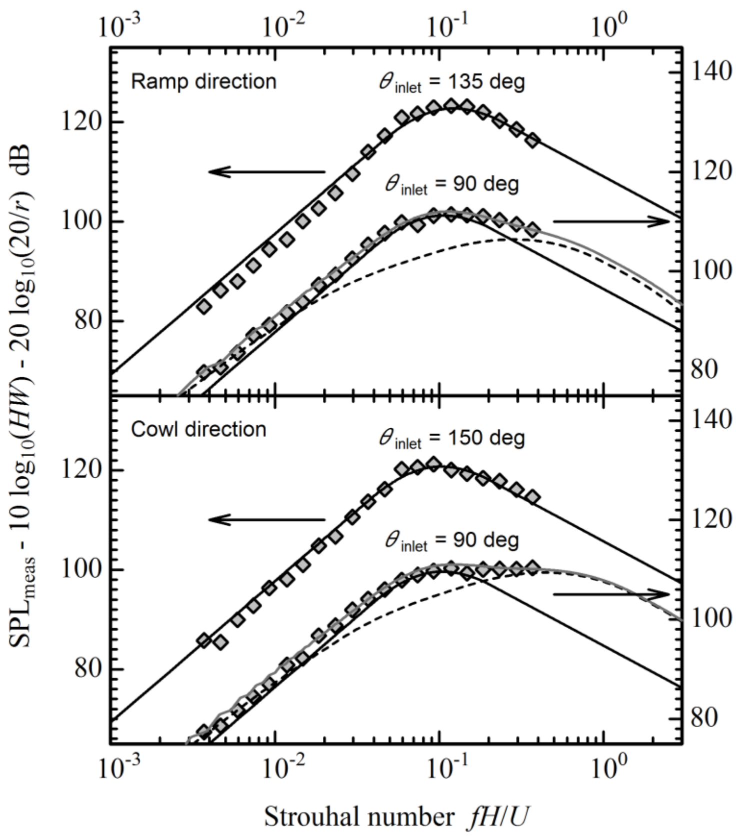


Fig. 4 Far-field noise spectra with F-spectrum (solid line) and G-spectrum (dashed line).

B. Light Intensity Fluctuation

Figure 5 shows typical spectra of the light intensity fluctuation obtained at the upper shear layer of the initial free jet region (top figure) and at the lower boundary of the jet (bottom figure). In the region wherein the intensive fluctuation is observed (top figure), a hump appears at around the peak (the energy containing region), and at high frequencies (the inertia region) the amplitude of the light intensity fluctuation decreases monotonously.

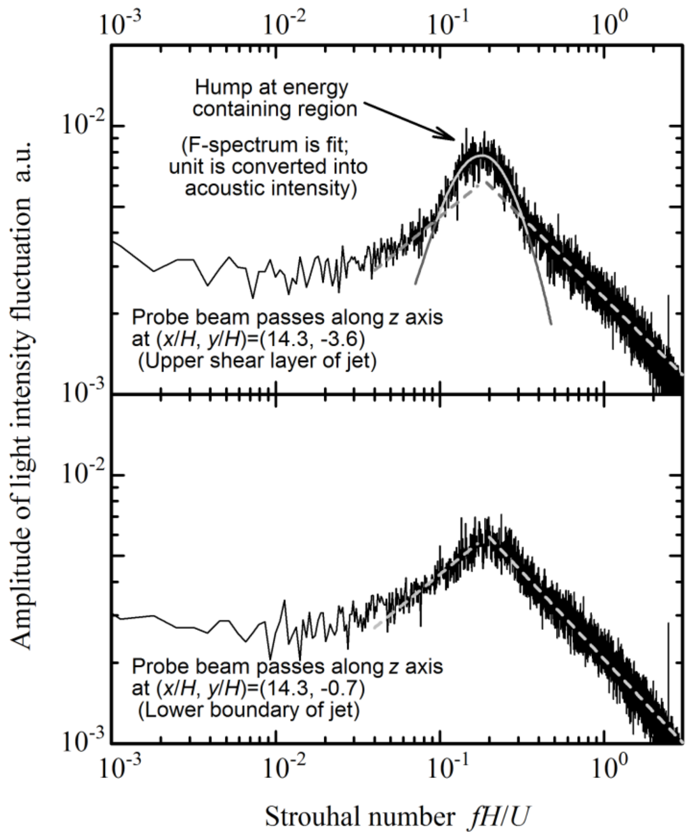
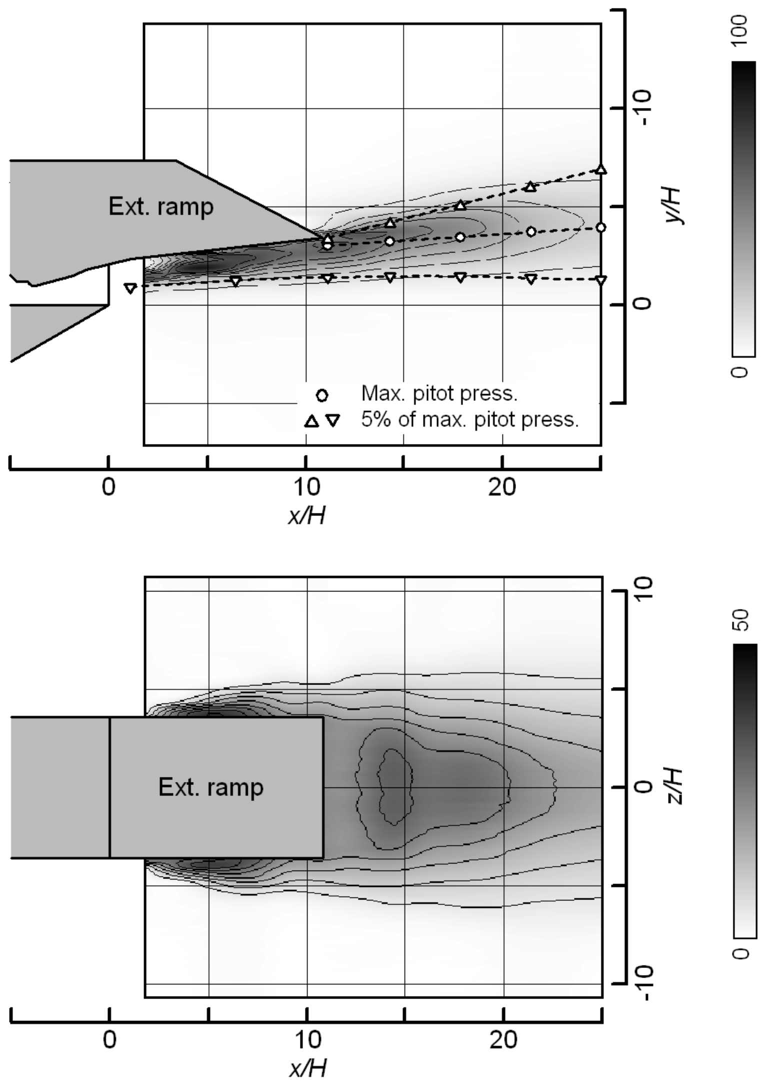


Fig. 5 Typical spectra of light intensity fluctuation.

Figure 6 plots isocontours of the overall amplitude of the light intensity fluctuation, obtained by integrating all the frequency components in Fig. 5. In Fig. 6a, the boundary of the light intensity fluctuation coincides with the jet boundary, and intensive oscillation is observed in the entire region of the jet. In Fig. 6b, intensive oscillation is again observed in the jet region, especially downstream of the external ramp, which implies that rapid mixing occurs in the upper shear layer of the initial free jet region due to the steep velocity gradient.



a) b)

Fig. 6 Overall amplitude of light intensity fluctuation: a) *x-y* plane and b) *x-z* plane.

C. Cross-Correlation between Light Intensity Fluctuation and Far-Field Noise

Figure 7 shows a typical cross-correlation between the light intensity fluctuation and the far-field noise. The distance of the two measurement points is 1.096 m, and the delay for the acoustic wave propagation is estimated to be 3.22 ms. While different physical quantity is compared, the cross-correlation sharply increases up to 0.25 at the arrival of the acoustic wave, which implies that the fluctuation of the density gradient in the jet is strongly related to the acoustic radiation. The delay calculated by the cross-correlation analysis is τ = 3.18 ms, which agrees well with that estimated from the distance of the two measurement points and the sonic speed.

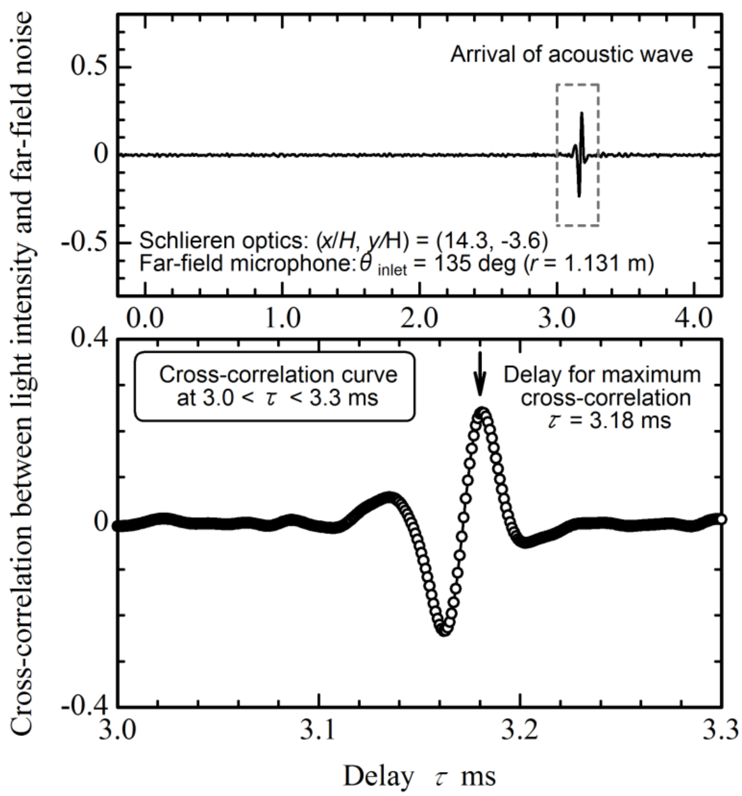


Fig. 7 Typical cross-correlation between light intensity fluctuation and far-field noise.

Figure 8 plots isocontours of the maximum cross-correlation between the light intensity fluctuation and the far-field noise; the reference microphone is set at θ_{inlet} = 135 deg at ramp side, where the maximum overall sound pressure level is observed around the nozzle [5]. In Fig. 8a, strong cross-correlation is observed in the upper shear layer of the initial free jet region (at around x/H = 14), and this strongly implies that the turbulent motion in this region acts as the dominant source of the far-field noise at θ_{inlet} = 135 deg. In the lower shear layer, on the contrary, the cross-correlation is rather small, which implies that no dominant source exists.

Relatively large cross-correlation is observed outside of the jet, which corresponds to the acoustic wave propagation. While the reference microphone is set at the ramp side of the nozzle, strong cross-correlation is also observed in the ambient at cowl side, which shows that the acoustic radiation at cowl side is coming from the same source as that at ramp side. Regarding other far-field microphones at ramp side, while the absolute values are smaller, qualitatively similar results are obtained.

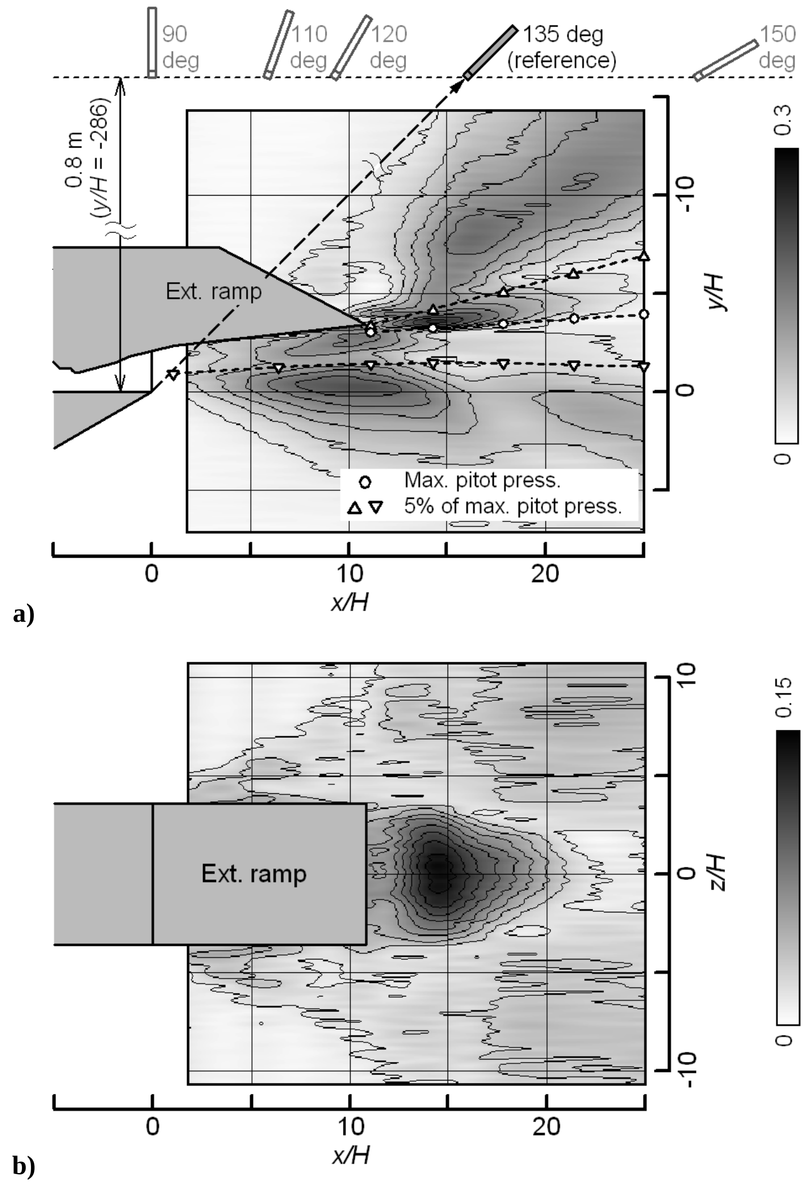
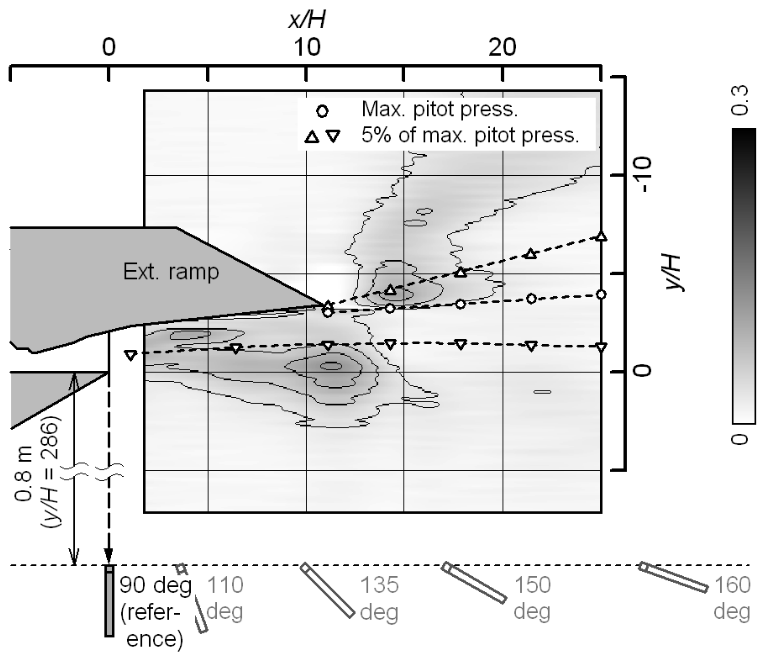


Fig. 8 Maximum cross-correlation between light intensity fluctuation and far-field noise at ramp side: a) *x*-*y* plane and b) *x*-*z* plane (microphone distance is not to scale).

Figure 9 plots isocontours of the maximum cross-correlations for far-field microphones at the cowl side, where some significant differences from the ramp side are noted. Now the sideline microphones hear the noise from the semi-confined jet region. In Fig. 9a, for the reference microphone at 90 deg, relatively large cross-correlations are found both in the semi-confined jet region on the ramp (at around $x/H = 3$) and in the upper shear layer of the initial free jet region (at around $x/H = 14$). In a previous study [5], to investigate the directional characteristics of the large turbulence structure noise in the rectangular hypersonic nozzle, a microphone-to-microphone cross-correlation analysis was carried out based on the method in Ref. [11]. By comparing the signals of eight far-field microphones set at aft angles of the rectangular hypersonic nozzle, the maximum cross-correlations for all the combinations of microphone pairs were investigated [5]. The acoustic field generated by the large turbulence structure is highly coherent, and cross-correlation becomes large when the two microphones selected as a pair hear the noise from the same source. It was shown that, at the cowl side of the rectangular hypersonic nozzle, relatively large cross-correlations were obtained for microphone pairs located within two sectors; the sideline sector of $90 \le \theta_{\text{inlet}} < 135$ deg and the downstream sector of $135 < \theta_{\text{inlet}} \le 160$ deg. When the 135 deg microphone, located at the turnover angle of the two sectors, was chosen as the reference, no correlation was obtained with any other microphones. It was implied that, at the cowl side, two kinds of far-field noise having high spatial coherency and strong directional characteristics are coming from two individual sources.

It is believed that the two regions identified in Fig. 9a correspond to the two noise sources. As was shown in Fig. 1, shock structures are observed at the downstream part of the nozzle throat, and it is believed that the relatively strong cross-correlation found in the semi-confined jet region might be attributed to the shock-associated noise rather than the large turbulence structure noise because it exhibits strong directional characteristics to the sideline angles. While the contribution to the far-field noise spectra seems to be small, apparent spikes or humps associated with the shock structure are not fund in Fig. 4, the footprint of the shock-turbulence interaction is imprinted in the far-field noise, resulting in the relatively large cross-correlation due to the high spatial coherency intrinsic to the shock-associated noise.

In Fig. 9b, for the reference microphone at 135 deg which corresponds to the turnover angle of the two sources implied in Ref. [5], quite weak cross-correlation is observed throughout the domain, which is consistent with the result of the microphone-to-microphone cross-correlation analysis [5]. In Fig. 9c, for the reference microphone at 150 deg, relatively strong cross-correlation is observed in the upper shear layer of the initial free jet region (at around $x/H = 14$). At such downstream angles, similarly to the ramp side, the turbulence motion in this region acts as the dominant source.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Max. pitot press.
5% of max. pitot press.
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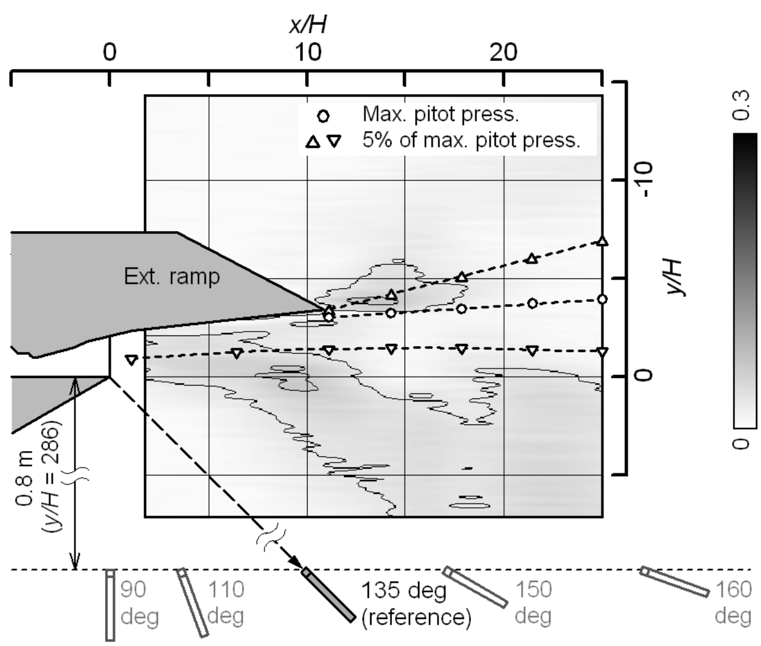
a)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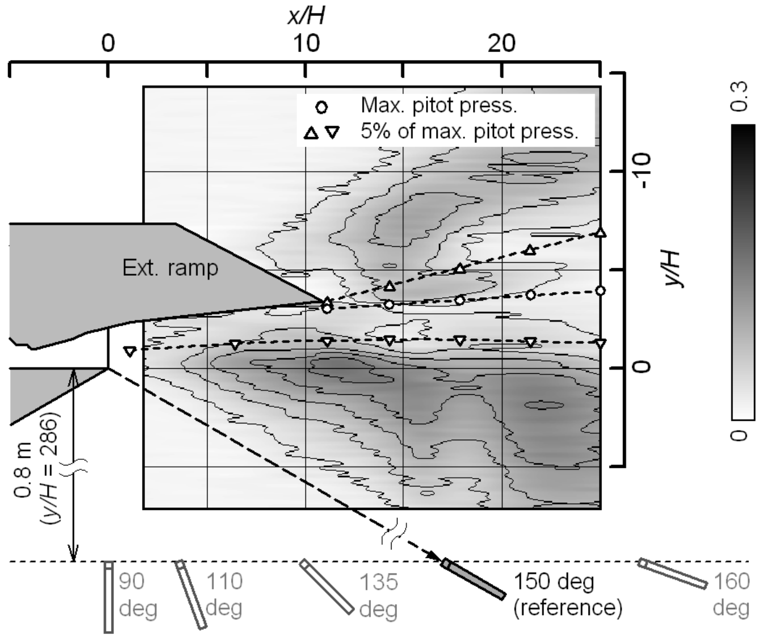

c)

Fig. 9 Maximum cross-correlation between light intensity fluctuation and far-field noise at cowl side (microphone distance is not to scale).

IV. Conclusions

The behavior of the noises sources in the exhaust jet issuing from a rectangular hypersonic nozzle operating at takeoff condition were investigated experimentally. The working gas was cold air, and the NPR was set at 2.70. By use of schlieren optics, the density gradient fluctuation in the jet and its acoustic field was detected as the variation of the light intensity. Using five 1/8-inch microphones set at aft angles of the nozzle, the far-field noise was acquired at the same timing and sampling rate with the schlieren optics. In the data obtained with the schlieren optics, intensive fluctuation of the light intensity is observed in the entire region of the jet. By use of cross-correlation analysis between the light intensity fluctuation and the far-field noise, relatively large cross-correlation, approximately 0.25 at maximum, is obtained while different physical quantity was compared. From the local maximum cross-correlation, it is considered that, both at the ramp and cowl sides, the major source for the far-field noise at downstream angles exists in the upper shear layer of the initial free jet region because of the rapid mixing due to the steep velocity gradient. Regarding the cowl side, relatively large cross-correlation for the sideline microphones is also observed in the semi-confined jet region on the ramp, which might be attributed the shock-associated noise due to the strong directional characteristics to the sideline angles.

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References

[1] Kojima, T., Kobayashi, H., Taguchi, H., Fukiba, K., Fujita, K., Hatta, H., Goto, K., and Aoki, T., "Design Study of Hypersonic Components for Precooled Turbojet Engine," *15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference*, Dayton, OH, AIAA Paper 2008-2504, 2008.

[2] Kojima, T., Kobayashi, H., Taguchi, H., and Goto, K., "Design and Fabrication of Variable Nozzle for Precooled Turbojet Engine," *16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference*, Bremen, Germany, AIAA Paper 2009-7312, 2009.

[3] Araki, M., Fukuda, M., Kojima, T., Taguchi, H., and Shiga, S., "Feasibility of Aerodynamic-Tab Jet Noise Suppressors in a Hypersonic Nozzle at Takeoff," *AIAA Journal*, Vol. 50, No. 3, 2012, pp. 751-755.

[4] Araki, M., Tsukamoto, M., Kojima, T., Taguchi, H., and Shiga, S., "Thrust Measurement of a Rectangular Hypersonic Nozzle Using an Inclined Baffle Plate," *Journal of Propulsion and Power*, Vol. 28, No. 6, 2012, pp. 1258-1267.

[5] Araki, M., Ijuin, Y., Nishida, S., Imamura, O., Kojima, T., and Taguchi, H., "Mean-Flow and Acoustic Characteristics of Cold-Jets from a Rectangular Hypersonic Nozzle", *Journal of Propulsion and Power*, Vol. 30, No. 1, 2014, pp. 221-232.

[6] Panda, J., and Seasholtz, R. G., "Experimental Investigation of Density Fluctuations in High-Speed Jets and Correlation with Generated Noise", *Journal of Fluid Mechanics*, Vol. 450, 2002, pp. 97-130.

[7] Panda, J., Seasholtz, R. G., and Elam, K. A., "Investigation of Noise Sources in High-Speed Jets via Correlation Measurements", *Journal of Fluid Mechanics*, Vol. 537, 2005, pp. 349-385.

[8] Tam, C. K. W., Golebiowski, M., and Seiner, J. M., "On the Two Components of Turbulent Mixing Noise from Supersonic Jets," *2nd AIAA/CEAS Aeroacoustics Conference*, State College, PA, AIAA Paper 96-1716, 1996.

[9] Tam, C. K. W., and Zaman, K. B. M. Q., "Subsonic Jet Noise from Nonaxisymmetric and Tabbed Nozzles," *AIAA Journal*, Vol. 38, No. 4, 2000, pp. 592-599.

[10] Dahl, M. D., and Papamoschou, D., "Analytical Predictions and Measurements of the Noise Radiated from Supersonic Coaxial Jets," *AIAA Journal*, Vol. 38, No. 4, 2000, pp. 584-591.

[11] Tam, C. K. W., Viswanathan, K., Ahuja, K. K., and Panda, J., "The Sources of Jet Noise: Experimental Evidence," *Journal of Fluid Mechanics*, Vol. 615, 2008, pp.253-292.

[12] Panda, J., "An Experimental Investigation of Screech Noise Generation", *Journal of Fluid Mechanics*, Vol. 378, 1999, pp. 71-96.

[13] Doty, M. J., and McLaughlin, D. K., "Space-Time Correlation Measurements of High-Speed Axisymmetric Jets Using Optical Deflectometry," *Experiments in Fluids*, Vol. 38, Issue 4, 2005, pp. 415-425.

[14] Papamoschou, D., Morris, P. J., and McLaughlin, D. K., "Beamformed Flow-Acoustic Correlations in a Supersonic Jet," *AIAA Journal*, Vol. 48, No. 10, 2010, pp. 2445-2453.