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Jet Noise Reduction of Turbofan Engine by Notched Nozzle

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ABSTRACT

This paper outlines the recent noise tests using a small turbofan engine conducted in Japan aerospace exploration agency (JAXA). As an ad-on or a retrofit device of reducing jet mixing noise, the authors have studied a notched nozzle. The small and simple structure of the notched nozzle is beneficial in noise suppression with less deterioration of engine performances. JAXA completed a series of noise tests on this mixing device using a DGEN380 turbofan engine. The notched nozzles, designed to have the thrust same as the baseline conical nozzles, were installed on core or bypass nozzles of the engine. The acoustic measurement was carried out by conventional measurement with the far-field microphones and phased-array measurement for beam-forming. Experimental results confirmed that the notched nozzle reduced broadband jet noise relative to the baseline nozzle and the amount of the noise reduction was similar to a serrated nozzle.

Keywords: Jet Noise, Turbofan Engine, Notched Nozzle, DGEN380, Noise Test
I-INCE Classification of Subject Number: 10

1. INTRODUCTION

It is well known that the global air transport has grown in the past decades, and is expected to grow annually at a few percent in near future [1]. Thus, technical efforts are continuously required to mitigate the community noise of present and future aircraft. Aircraft noise mitigation has been implemented by the balanced approaches defined by the committee on aviation environmental protection (CAEP). They are the reduction of noise source, the land-use planning and management, the noise abatement operational procedures, and the operating restrictions [2]. Among these approaches, reducing aircraft noise sources has been studied by many research sectors for decades [3-4]. As for the

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engine noise, typical noise reduction technologies have been focused on fans and nozzles, dominant at high power settings. The impact of the noise reduction on the engine performances should be maintained as well as the amount of noise reduction.

Japan aerospace exploration agency (JAXA) and IHI Corporation (IHI) have promoted collaborative studies on noise reduction for present and future aircraft engines. In the past few years, the collaboration has been for a light-weight acoustic panel and an efficient jet noise suppressor. The aFJR (advanced Fan Jet Research) project of JAXA [5] has dealt with the light-weight acoustic panel. A manufacturing process including moulding resin-based material enabled lighter acoustic panels for fan casings. According to the fan-rig tests, the newly developed acoustic panel proved to have the similar sound absorption performances than conventional metal-based panel. Some reports on the light-weight acoustic panel are found in references [6-7].

A notched nozzle [8] has been experimentally studied in the Green Engine program of JAXA [9]. The notch is here defined as a dent at the nozzle trailing edge (Fig. 1). Although

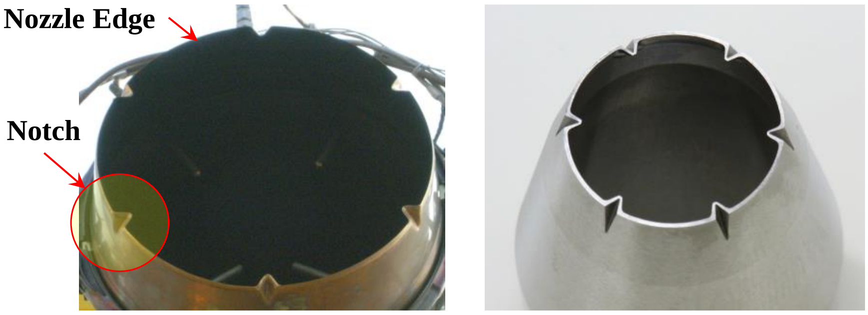


Fig. 1 Examples of notched nozzle

(left: application to a turbojet engine, right: subscale model, D = 25 mm).

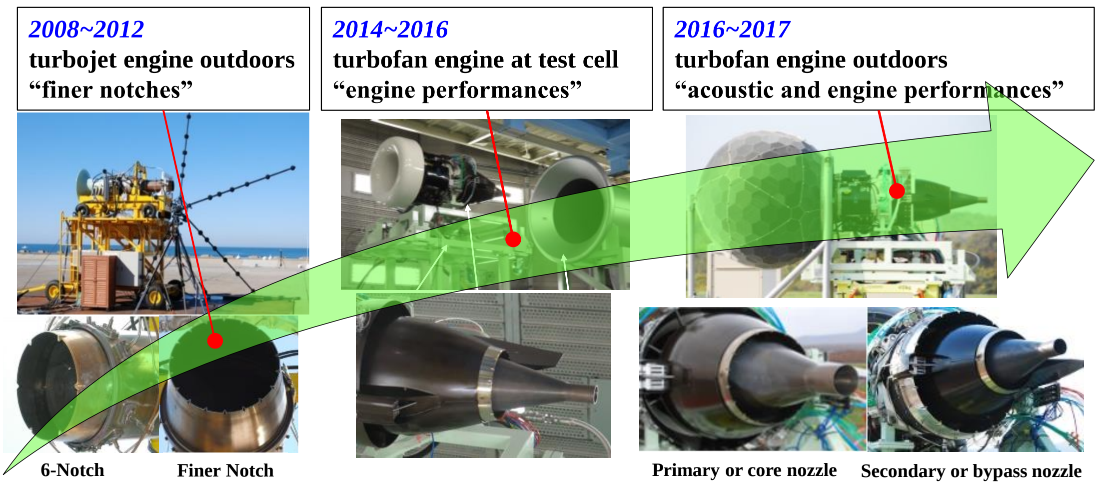


Fig. 2 Research activities on notched nozzle.

the size of a notch is much smaller than the representative scale of nozzle, e.g., nozzle diameter, disturbances due to the notch are sufficient to make the shear stress weaker and suppress the jet noise emission. The small and simple structure of the notch is beneficial to less thrust loss and less weight increase. Recent research activities on the notched nozzle is presented in Fig. 2. The authors have improved the acoustic properties of this mixing device and found that the finer and more notches with some modification of shape would attain better noise reduction [10]. An eighteen notched nozzle installed on a turbojet engine provided noise reduction up to 1.5 - 2 dB. To make the technical readiness higher, it was needed to evaluate the acoustic properties of the notched nozzle under practical co-axial nozzle configurations, typical of commercial aircraft engines. One approach to fulfil the experimental requirements was to investigate the notched nozzles with a high-bypass-ratio turbofan engine. Instead of full-scale engines, a subscale turbofan engine, DGEN380 [11], was chosen for a series of noise tests. This paper outlines the noise tests of the notched nozzles using the turbofan engine. The data in the present report were obtained in the test campaign in 2017, and the corresponding serial numbers are F162-F171. The serial numbers of F162-F164 were for core nozzle and those of F166-F171 for bypass nozzle.

2. EXPERIMENT

2.1 Notched Nozzles

The original design involved larger notches equally located in the circumferential direction of the nozzle. The revised version decreased the exit height by approximately 40% and accordingly increased the number of notches. This revision generate finer and more disturbances over the entire area of the nozzle end. The resultant disturbances contributed to suppressing the higher frequency noise as well as the broad band jet mixing noise. The concept of this finer notch was reflected in the present design for the present turbofan engine tests. The present design employed the less penetration angle of the notch for better aerodynamic performances.

The notched nozzles for the present engine tests are presented in Fig. 3, together with the baseline conical nozzles and referential serrated nozzles. On the core nozzle, the baseline, notched and serrated nozzles were designed via CFD so that the mass flow was adjusted under the identical nozzle pressure ratio. On the bypass nozzle, there are a pylon for the sidemount of the engine and an oil cooler unit. That is why the nozzle was split into top and bottom parts. In case of mixer installation, the bypass nozzles were attached to the original nozzle end via flanges.

2.2 Turbofan Engine for Noise Tests

The DGEN380 is a small turbofan engine. It comprises a 350 mm - diameter fan, a centrifugal compressor, a reversed-type annular combustor, a single-stage high-pressure turbine, a single-stage low-pressure turbine, and short-cowl coaxial nozzles. The fan is driven by the low-pressure spool via a planetary gear so that the fan speed is optimized. The auxiliary units are installed on the engine, for example a starter-generator, an oil circulation unit, a fuel pump, an engine control unit (ECU), and an engine power unit (EPU). The ECU enables a scheduled operation regulating the corrected low-pressure spool speed. Representative specifications are referred to former report [11].

Two test configurations were considered in the outdoor environment. One configuration is for fan noise test including acoustic panels. A lined duct and a measurement duct are inserted between the engine inlet and the bell-mouth [12]. Another configuration is for the present tests, i.e., jet noise tests. The engine is placed on the socalled floating stand that is mechanically suspended from the rigid stand via spring plates [11, 13]. A load-cell unit underneath the floating stand receives the thrust by the engine. In front of the bell-mouth is placed an inflow control device (ICD) or turbulence control system (TCS), made of honeycomb panels. It breaks down the large-scale turbulences in atmosphere and helps to stabilize the state of operation and prevent unexpected noise from generating.

2.3 Data Acquisition

The jet noise measurement is viewed in Fig. 4. The engine stand was put on a rigid plate in an apron zone of Shikabe airfield in Japan. The ECU referred to the atmospheric temperature and regulated the low-pressure spool speed within the scheduled corrected speed, N_L. Here, the N_L, e.g. 95 %, denotes the rate of power setting under standard state. Typical sensors and locations inside and outside the engine are referred to former reports [11, 13-14]. All these data of engine performances were stored at the sampling rate of 10 Hz and averaged over 45 - 60 seconds after all parameters saturated at each power setting. Environmental conditions were also monitored and recorded. Depending on the wind speeds, the confidence interval of the engine parameters suggested that mean values existed within 1 %. The example of the engine performances, the corrected thrust, is plotted in Fig. 5. The notched nozzles of the core and bypass sides as well as the serrated nozzles kept the thrust similar to the baseline nozzles. Other parameters of the notched nozzle, e.g., the mean exhaust velocities, the mass flow rate, the exhaust gas temperature, and the fuel consumption, indicated no remarkable difference from the baseline nozzle at 95 % N_L.

For the acoustic measurement, conventional measurement was carried out using 29 pressure-type microphones in the far-field arcs. The 20 m - arcs were centred by the

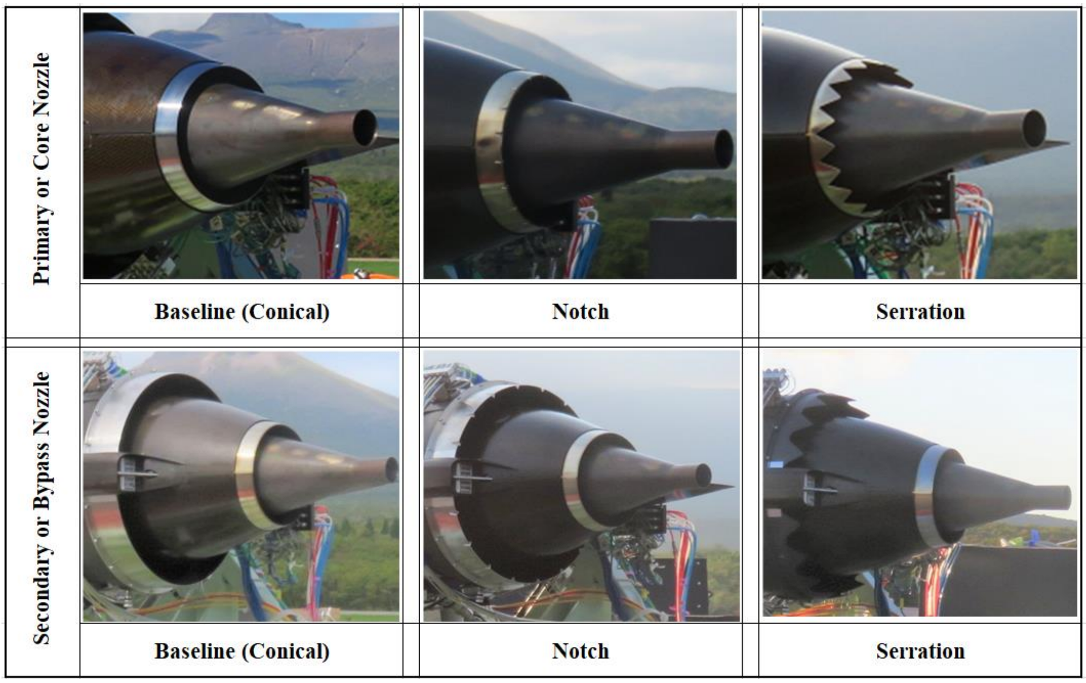


Fig. 3 Mixer nozzles used for the present noise tests.

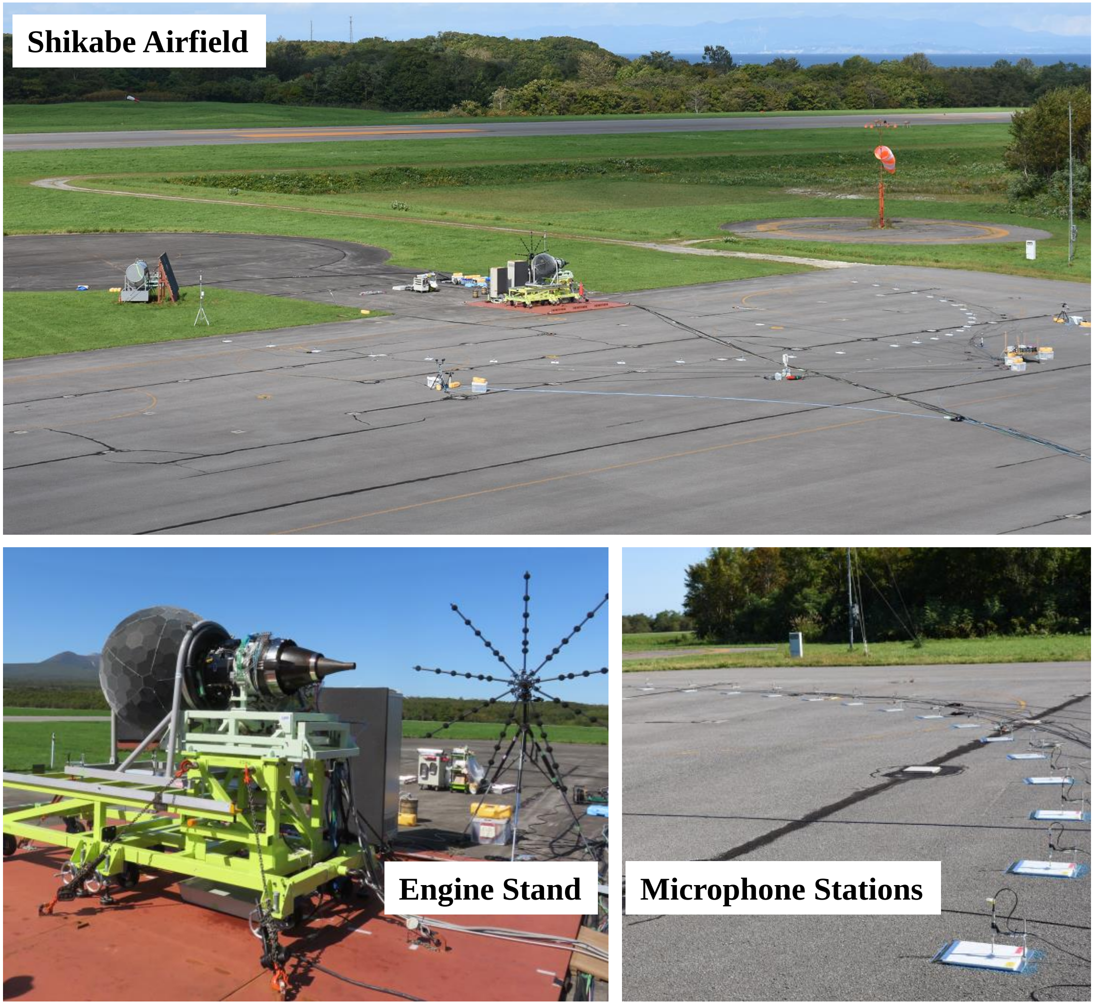


Fig. 4 Whole view of noise test, engine stand, and microphone stations.

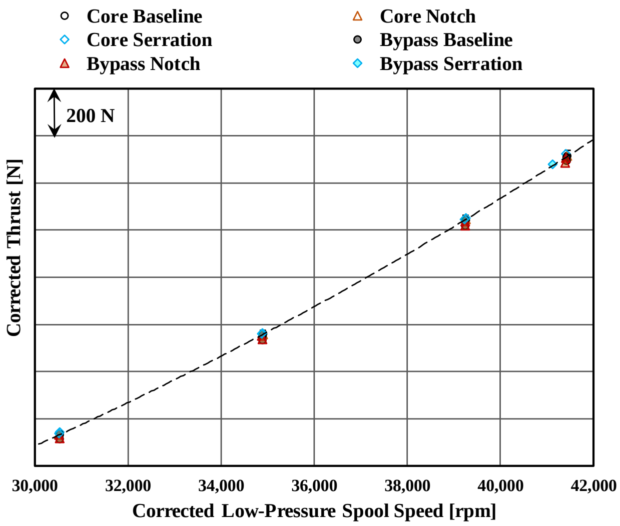


Fig. 5 Corrected thrust versus corrected low-pressure spool speed.

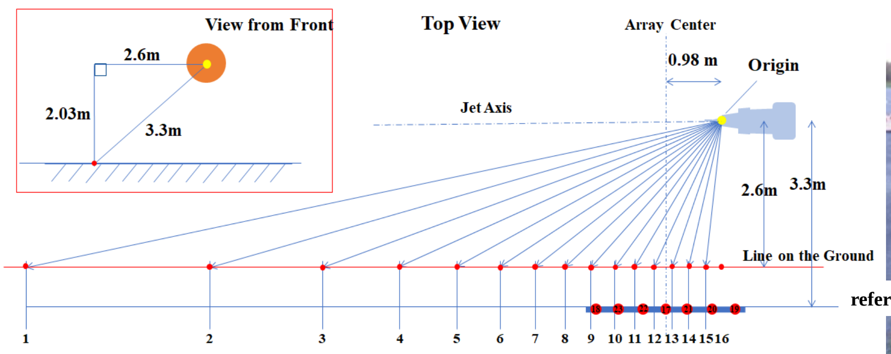
engine inlet and the nozzle exit. A microphone station has a 30 cm × 30 cm rigid plate, an inversely installed quarter-inch microphone. The time signals of microphones are simultaneously recorded for 30 seconds at the sampling rate of 50 kHz or 100 kHz. To attenuate the influence of grazing wind around the microphones, a high-pass filter was applied before the data recording system. Post-processing provides narrow band spectra, one third octave band spectra, overall sound pressure levels within limited frequency bands, and other acoustic indices. Correction regarding ground reflection at the microphone station and air absorption was taken into account. The confidence interval of the sound pressure levels was small enough at the concerning frequencies for jet noise, here less than 2000 Hz.

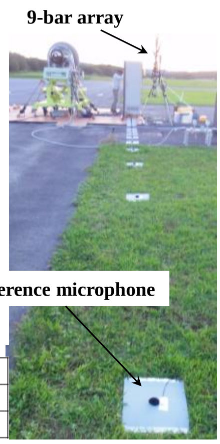
Beam-forming with a phased array microphone system was applied in the noise tests. As jet noise sources are not coherent, the conventional delay and sum (DAS) algorithm provides relatively vague or low-resolution sources. One of the authors proposed alternative algorithm as NNLS or CLEAN-SC instead of DAS [15-16] and showed better special resolution for the incoherent sound sources. In the present tests, a nine-bar fordable array system, Brüel & Kjær Type WA-1676-W003, was placed at the side of the nozzle. The array is 2.5 m in diameter and contains 54 microphones. The array centre was 3.3 m away from the jet axis and 0.7 m behind the end of tail pipe [17]. For the purpose of evaluating directional contributions of sound sources, reference microphones were placed in a line that is parallel with jet axis as seen in Fig. 6.

3. RESULTS AND DISCUSSION

3.1 Jet Noise

An example of the post-processing is shown in Fig. 7a. The narrow band spectrum (dotted line) was obtained under the power setting of 95%, the spool speed of which was approximately 41400 rpm. The radiation angle was 125° from engine inlet. This condition radiates the broadband jet mixing noise at relatively low frequency less than 2000 Hz. Fan tones at fan blade passing frequencies (BPFs), tones of the centrifugal compressor, and turbine tones are observed at the higher frequencies. The tones appearing over 650 - 900 Hz in the spectrum are attributed to the rotational speed of both low-pressure and high-pressure spools. The primary purpose of the present post-processing was to extract





Ref. no	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Angle (°)	165	160	155	150	145	140	135	130	125	120	115	110	105	100	95	90
Distance (m)	-11.34	-8.09	-6.10	-4.74	-3.73	-2.95	-2.32	-1.79	-1.33	-0.93	-0.56	-0.22	0.10	0.40	0.69	0.98

Fig. 6 Layout of the 9-bar array and reference microphones.

the jet mixing noise. Reflection on the surface of the microphone stand, air absorption, undesirable tones as well as distance attenuation were corrected as shown in the figure (solid line). The corrected spectra are transformed into one third octave band spectra. The sound pressure levels accumulated over 100 Hz - 1600 Hz bands, i.e., the limited overall sound pressure levels, are assumed the representative jet mixing noise in this post-processing.

Fig. 7b compares typical noise sources found in one third octave bands. Tones at first and second fan blade passing frequencies, e.g., Fan-1BPF and Fan-2BPF, are sound pressure levels at 3150 Hz band and 6300 Hz band respectively. As well, the 10000 Hz band represents the compressor tone. These tones have peaks from 90° to approximately 120° relative to engine inlet. The sound pressure level of the 315 Hz band has its peak over 120° - 150°, which agrees with the limited overall sound pressure level.

3.2 Noise Reduction by Core Notched Nozzle

The notched nozzle when applied to the primary or core nozzle of the DGEN380 provided noise reduction compared with the baseline nozzle. Sound sources of the two nozzles were estimated via beam-forming measurement as shown in the top of Fig. 8. The power setting of the engine was 95%. The source maps by the CLEAN-SC are transformed into the contributions to the reference microphone on the ground [15]. The contributions correspond to the source maps as if observed at the reference position. The maps are obtained bellow 500 Hz to exclude the tones in the broadband jet noise mentioned above. According to the source maps, it is found that the dominant noise source is distributed just behind the core nozzle. The distance between the peak position and the nozzle end is four times the equivalent diameter of the core nozzle. As typical jet noise source of subsonic single jet origins from where the potential core disappears, i.e., approximately of the order of five to six times nozzle diameter. Considering the annular shape of the core nozzle, it is anticipated that the noise source begins to emerge closer to the nozzle end. The designated source remains as far as 10 times the nozzle diameter where weak source is observed. In the case of the notched nozzle, shown in the top right figure, the notches seem to weaken the strength of the jet noise sources. Both sound sources just behind the nozzle and at downstream of the nozzle seem to be reduced.

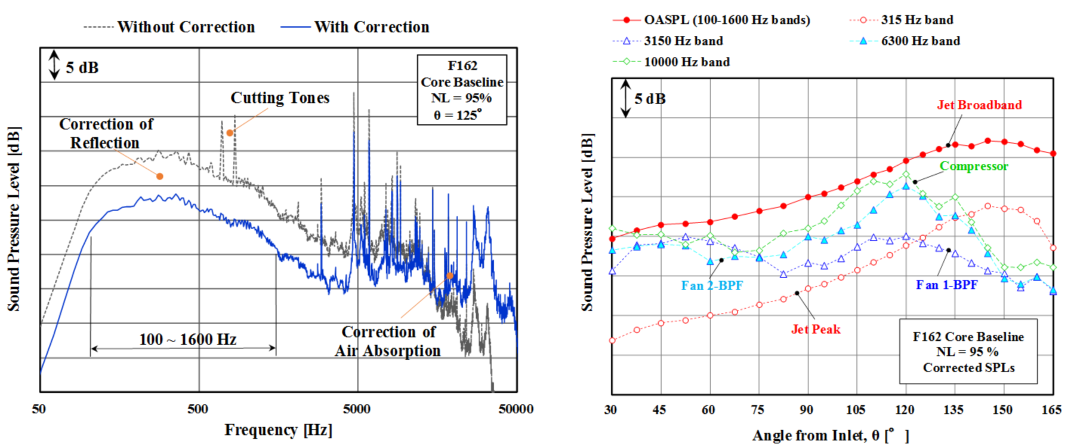


Fig. 7 Example of post-processing the acoustic data.

(a) left: correction of spectra, (b) right: typical noise in 1/3 octave bands.

Similar reduction of the sound source was observed in the former tests using a turbojet engine [10].

Figures on the bottom of Fig. 8 are one third band spectra at 145° from engine inlet, and the limited overall sound pressure levels. These spectra and overall sound pressure levels are averaged over more than 5 samples in different operations. The spectra indicate that the notched nozzle reduced the jet noise of the baseline nozzle even though the extent is slight at most 0.5 dB. This result agrees with the source maps observed at a rear angle of nozzle. The serrated nozzle also reduced the jet noise more than the notched nozzle at frequencies lower than 500 Hz band. However, it deteriorates noise reduction at higher frequencies. This is partly because of the additional noise caused by the mixing process of serrations. The limited overall sound pressure levels, as seen in the bottom right, indicate that the notched nozzle as well as the serrated nozzle reduced the jet noise over wide radiation angles.

3.3 Noise Reduction by Bypass Notched Nozzle

The acoustic results are presented in Fig. 9 when the baseline conical, notched and serrated nozzles were attached to the bypass end. The definitions of the figures are same as Fig. 8. As compared to the core nozzles, the end of the bypass nozzle was extended

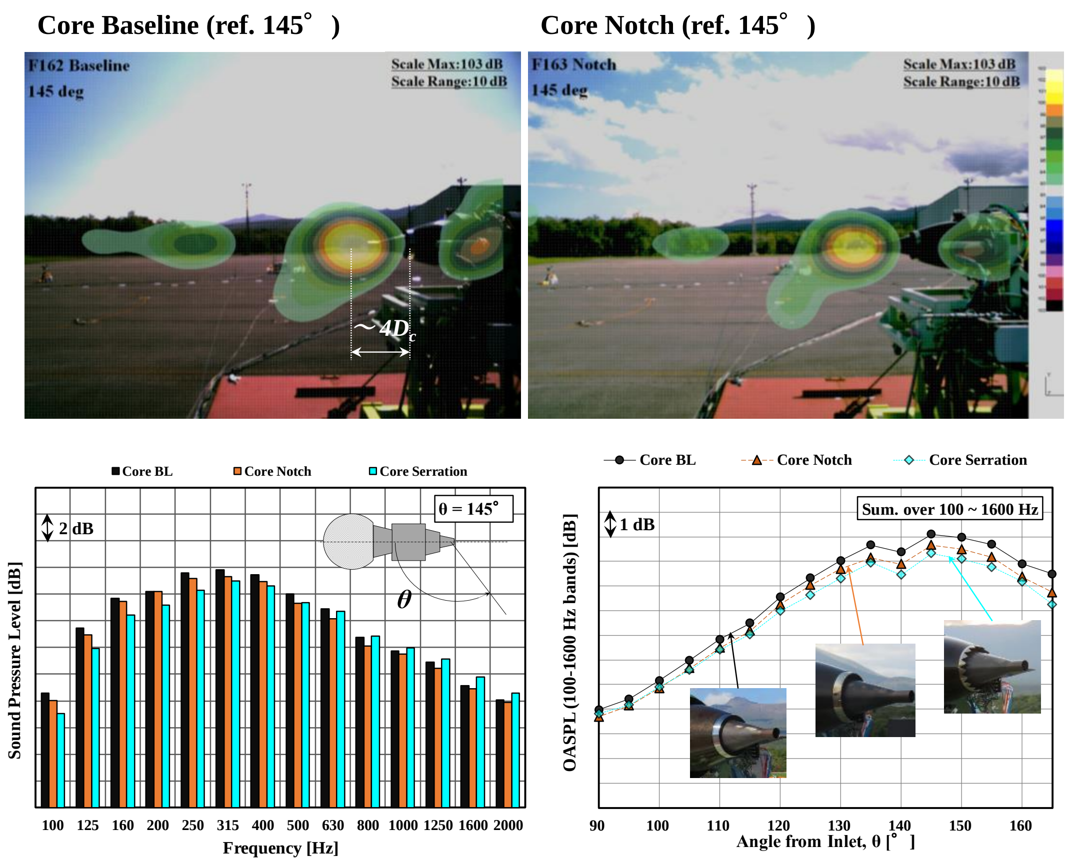


Fig. 8 Results with regard to core nozzles. Power setting is 95% of N_L. Top figures are source maps contributed to a refererential rear angle. Bottom figures are one third spectra in the farfield, at 145° from inlet and overall sound pressure levels over 100 Hz - 1600 Hz bands.

axially and the sound pressure level of the baseline case was different from the core nozzle. Although the maximum level of the source maps is higher on the baseline case, the notched nozzle reduced the area where sound sources excessed the threshold level. This fact suggests that the notched bypass nozzle reduced jet mixing noise relative to the baseline nozzle.

Noise reduction is confirmed in the spectra, presented in the bottom left of Fig. 9. The notched nozzle reduced jet noise similar to the serrated nozzle until the 400 Hz band. The amount of noise reduction is increased relative to the core nozzle application. This is accounted for the velocity difference of the jet and the surrounding flow. In the present cases, the mean jet velocities of core nozzle and bypass nozzle were estimated 295 m/s and 175 m/s. Finally, the overall sound pressure levels, plotted on the bottom right of Fig. 9, summarize the bypass nozzle cases. The notched nozzle as well as the serrated nozzle attained jet noise reduction by approximately 1 dB.

4. SUMMARY

This paper overviewed the recently conducted engine noise tests regarding the notched nozzle. JAXA and IHI have studied the notched nozzle as a simple jet noise reduction device, and found that the finer notched nozzle has a potential of competing with existing mixer nozzles. For practical application, it was necessary to evaluate acoustic and engine performances of the notched nozzle under practical nozzle configuration as seen in high bypass ratio engines. Notched nozzles were designed and mounted on the small turbofan

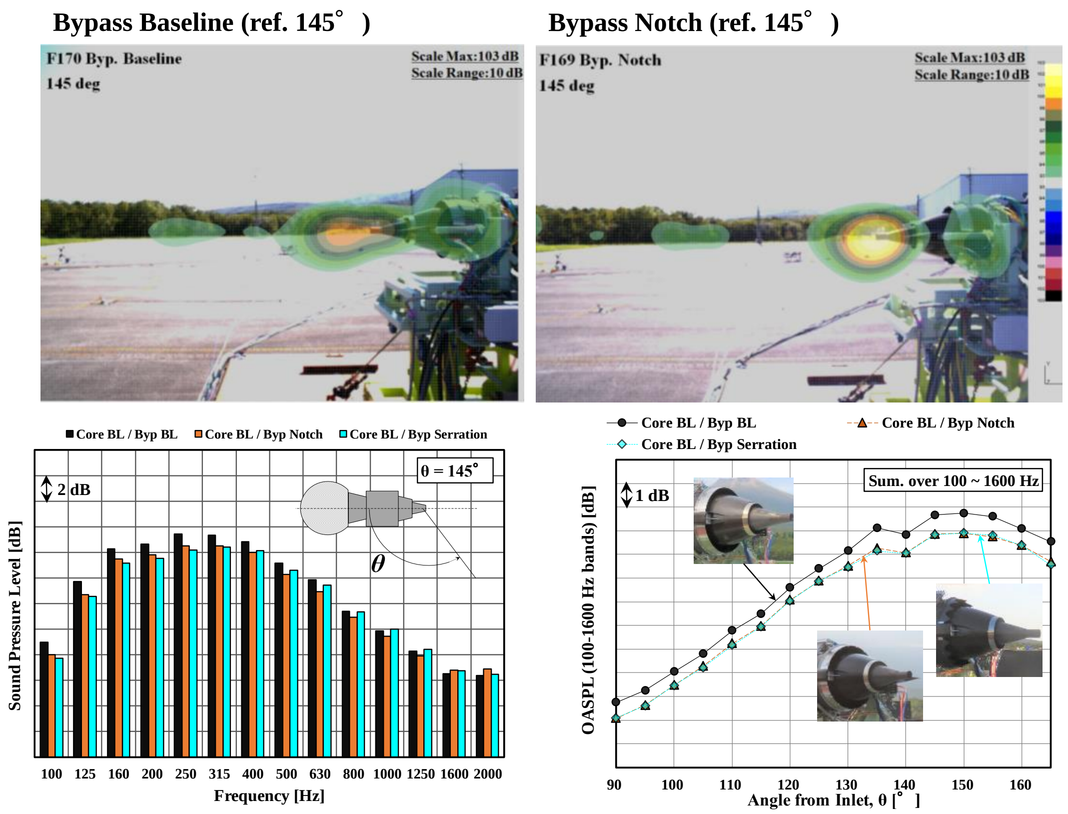


Fig. 9 Results with regard to bypass nozzles. Details of figures are same as Fig.8.

engine, DGEN380. According to the noise tests, it is concluded that the notched nozzle, if the corrected thrust and other engine parameters were well adjusted to the baseline nozzle, would have a slight noise margin up to 1 dB. Considering the superiority of notched nozzle in its simple structure, lighter weight, and less impact on engine performances, the notched nozzle has a potential of application to the existing engines as well as the new types of engines in order to gain more noise margin with minimizing the impact on engine performances.

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