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Acoustic liner test of DGEN 380 turbofan engine

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ABSTRACT

Acoustic liner is one of the most effective devices for aero-engine noise suppression, especially for fan noise suppression. Its fundamental characteristics can be obtained by impedance tube measurements or by impedance eduction with grazing flow duct facilities, however in the product development stages it is necessary to evaluate its performance on large scale models, such as rotating fan rigs or real aero-engines. Japan Aerospace Exploration Agency (JAXA) introduced a small turbofan engine called DGEN380 for engine noise studies and has carried out outdoor tests since 2016. In this study, to achieve the fan noise reduction, the acoustic liners are designed. Then curved acoustic liner panels are fabricated by 3D printer and installed in an intake duct upstream of the fan blades. The acoustic performance of the liners is evaluated by two measurements. First, in-duct acoustic mode propagation is measured by the microphone array uniformly distributed both azimuthally and axially inside the duct surface at the upstream of the liner. In the other, sound radiation pattern from the engine is obtained by 20-meter arc microphone array measurement. From the results of both measurements, the noise reduction at the designed frequency bands is confirmed.

Keywords: Aircraft Noise, Turbofan Engine, Acoustic Liner, Acoustic Mode
I-INCE Classification of Subject Number: 34

1. INTRODUCTION

Significant reductions of aircraft noise have been realized in the past decades, mostly by reducing the jet noise. The continuously and rapidly growing air transportation demands further improvements for the noise problem. One of the most promising solutions is the Ultra-High Bypass-Ratio engine (UHBR), in which the fan diameter is increased. Consequently, fan noise is expected to become the main noise source of future aircrafts.

Acoustic liner is one of the most effective devices for aero-engine noise suppression, especially for fan noise reduction. Many worth studies on acoustic liners have been conducted up to now at the universities and the research institutes around the world [1,2]. The fundamental characteristics of acoustic liner can be obtained by impedance tube measurements or by impedance eduction techniques with grazing flow duct facilities, however in the product development stages, it is necessary to evaluate its performance on larger scale models, such as fan test facilities [3] or real aero-engines [4,5]. The effect of

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curved liner panel surface, the effect of rotating acoustic modes and sound emission from the engine intake are worth to investigate.

Japan Aerospace Exploration Agency (JAXA) has introduced a small turbofan engine, DGEN 380 for the noise reduction studies and has carried out outdoor engine tests since 2016. In the beginning year, studies are mainly focused on the jet noise reduction by the nozzle exhaust devices [6,7]. In the following years, fan noise measurement and fan noise reduction studies have been started.

The objective of this study is to verify the acoustic performance of liner installed on DGEN 380 engine. The preliminary acoustic liner test is conducted. Acoustic liner is designed to attenuate dominant fan tone noise and is fabricated with resin 3D printer. The performance of the acoustic liner is evaluated by in-duct mode analysis and far-field noise radiation measurement. This paper describes the result of these experiments.

2. DGEN 380, TURBOFAN ENGINE

DGEN380 is high-pressure ratio, two-spool geared turbofan engine. It is developed and built by Price Induction Company in France. This engine is small with fan diameter of 0.35m, 1.13m in length, 2580N of maximum thrust at sea level, dry weight of 130kg and bypass ratio of 7.6. A cutway view of DGEN 380 is shown in Figure 1.

One of the greatest features of this engine is easy operability, it can be started with a help of electric motor and it can be operated with a simple console. Engine parameters are monitored on a laptop PC. Automatic program operation based on the corrected engine speed is developed and available with a help of Price Induction Company.

3. LINER DESIGN

Figure 2 shows the narrow band spectrum of the radiated noise from DGEN 380 measured by the far field microphone. The rotation speed of low-pressure spool shaft is 90% of the maximum rate (max:43,600rpm), hereinafter this speed is called “90%NL”. From the result, the fundamental blade passing frequency (1BPF) tone of 2760 Hz is most dominant. Its second and third harmonic (2BPF & 3BPF) tone is observed at 5,500 Hz and 8,200Hz, respectively. Around 700 Hz, two discrete tones are observed, these tones are due to the shaft rotation speed of the low-pressure shaft (660Hz) and the high-pressure shaft (810Hz), respectively (Ω_{LPS}, Ω_{HPS}). Compressor tone noise is first appeared at 8,940Hz.

In this study, the liners are designed to attenuate the most dominant 1BPF tone (f = 2760 Hz) at 90%NL. Because the liner is fabricated by resin 3D printer and it is installed on the upstream of the rotor blades, the stiffness is the highest priority in the design process.

Fig. 1 Cutway view of DGEN 380 engine.

Therefore, the thickness of the perforate plate and the perforation ratio are first determined, then the diameter of the perforation and length of the cavity are determined by the classic empirical formula [8-10] in order to attenuate 1BPF tone noise.

$$z = \frac{\sqrt{8\omega\upsilon}}{\sigma c}\left(t + \frac{t}{d}\right) + \frac{(k_0 d)^2}{8\sigma} + \frac{M_\infty}{\sigma(2 + 1.256\delta^*/d)} + i\frac{\omega}{\sigma c}(t + \delta_1) - i\cot(k_0 \ell) \qquad (1)$$

Here, z is the acoustic impedance of the liner, σ is the perforation ratio of the plate, t is the thickness of the plate, d is the diameter of perforation and ℓ is the length of the cavity. c is the speed of the sound, ω is the angular velocity, k_0 is the wave number, ν is the coefficient of viscosity and M_∞ is the Mach number of the uniform flow. δ^* is the displacement thickness of the boundary layer. δ_1 is derived in the reference [10].

Two liners were designed with the same perforation ratio but different perforation diameters and length of the cavity. The dimension of these liners are shown in Table 1. The sound absorption ratio for them are plotted in Figure 3. The result indicates that as the engine speed increases, the sound absorption frequency range is wider, the peak is shifted to higher frequency and its peak value increases. Liner 1 of smaller perforation diameter has slightly better performance than Liner 2.

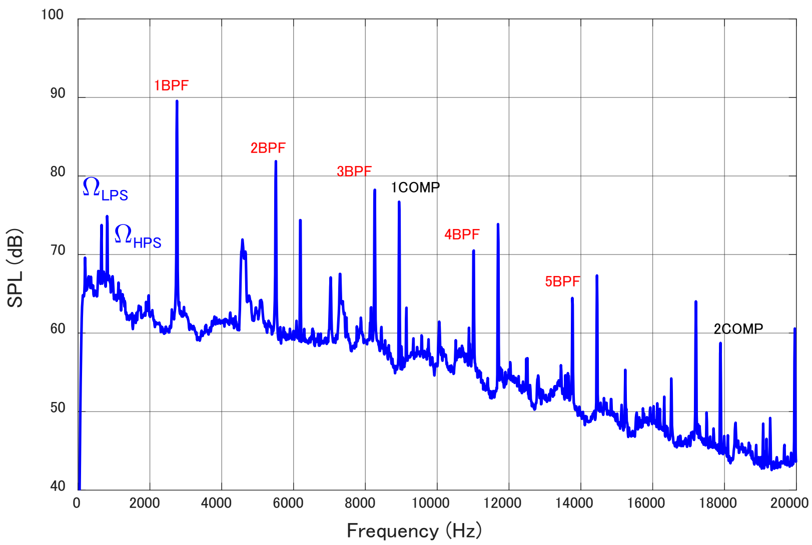

Fig.2 Narrowband spectrum at 45deg from inlet axis at 90% of max low spool shaft-speed.

Table. 1 Specification of designed liners

	Liner1	Liner2
Perforation Ratio, σ (%)	5.8	5.8
Perforation Diameter, *d* (mm)	1.0	1.6
Length of Cavity, ℓ (mm)	11.0	9.0
Plate Thickness, *t* (mm)	1.0	1.0
Axial Length (mm)	240	240

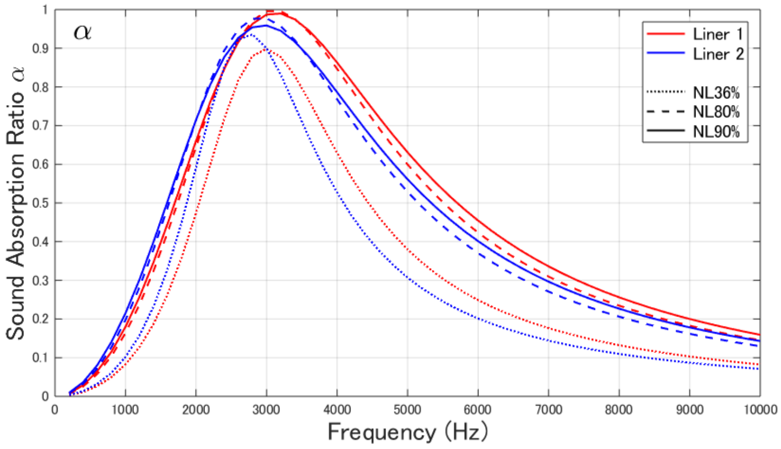

Fig.3 Predicted liner performances.

4. TEST FACILITY AND ACOUSTIC MEASUREMENTS

DGEN 380 engine and its test devices are shown in Figure 4. In the upstream of the engine, a lined duct is connected. There are 8 squared-pockets around the duct and acoustic liner panels can be mounted to these pockets. Also, a set of hard-walled panel was made for the comparison.

Next to the lined duct, microphone array duct is connected. In order to detect the acoustic modes propagation inside the duct, an array of 36-azimuthal and 4-axial equal interval microphones are installed. Azimuthal interval is 10 degree and axial interval is 50 mm. 1/4” GRAS 40PH CCP Free-field array microphones are used for the measurement. Acoustic data is stored with 102.4kHz sampling rate by 24bit ΔΣ ADCs.

Test piece of acoustic liner panel is shown in the left picture of Figure 6. This panel is made by resin 3D printer. The right picture of Figure 6 is a mounting device for the liner panel. The liner panel is attached to this device and it is extruded to the duct pockets by the lever. Calking compound is applied to seal the clearance between the duct and liner panels.

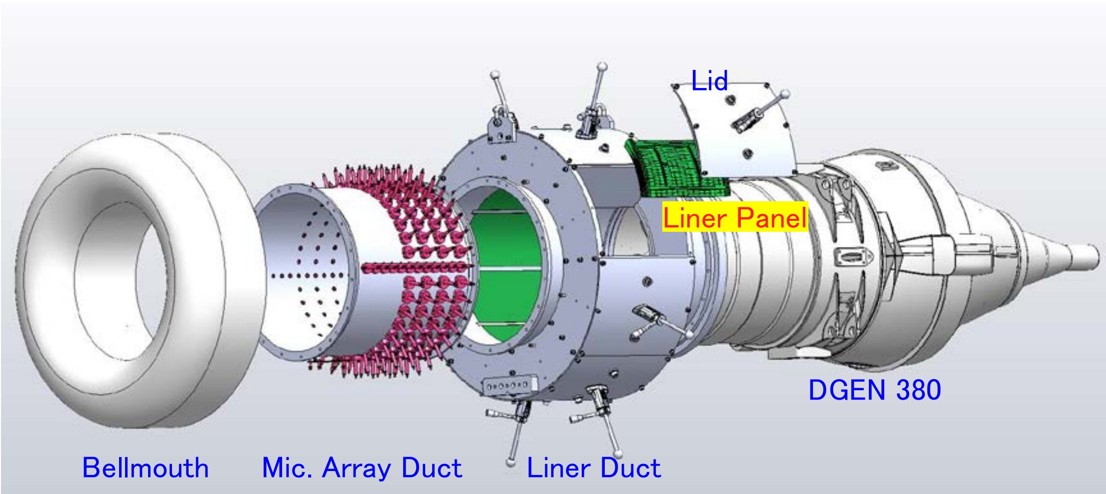

Fig.4 DGEN 380 liner testing configuration diagram

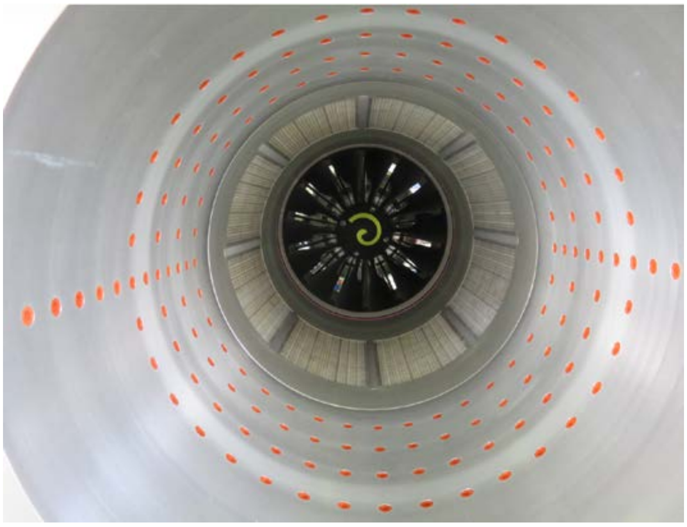

Fig. 5 Acoustic liners and microphone array installed on DGEN fan duct.

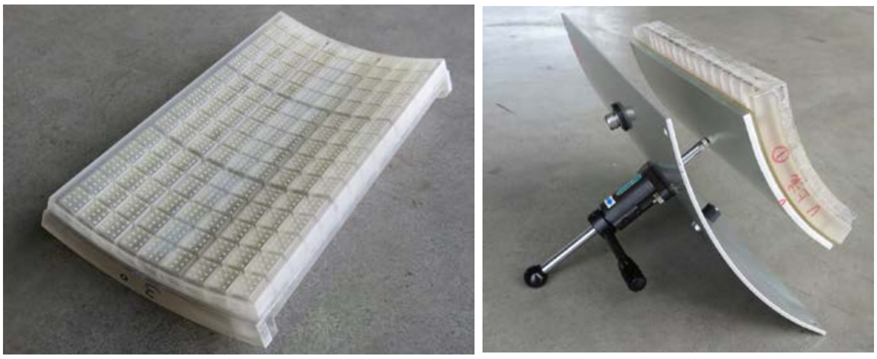

Fig. 6 Acoustic liner panel and its mounting device.

Fig.7 DGEN 380 and inflow control device on the outdoor engine test stand.

As shown in Figure 7, DGEN380 is mounted 2 meters high above the ground to avoid the suction of debris and ground vortex. In the front of the engine, an inflow control device (ICD) is installed to reduce the inflow disturbance.

Sound radiation pattern from DGEN 380 is obtained by 20-meter arc microphone array as shown in Figure 8. Both one-third octave band spectrum and narrow band spectrum are measured by the microphones located at 27 radiation angles from 5 to 160 degree

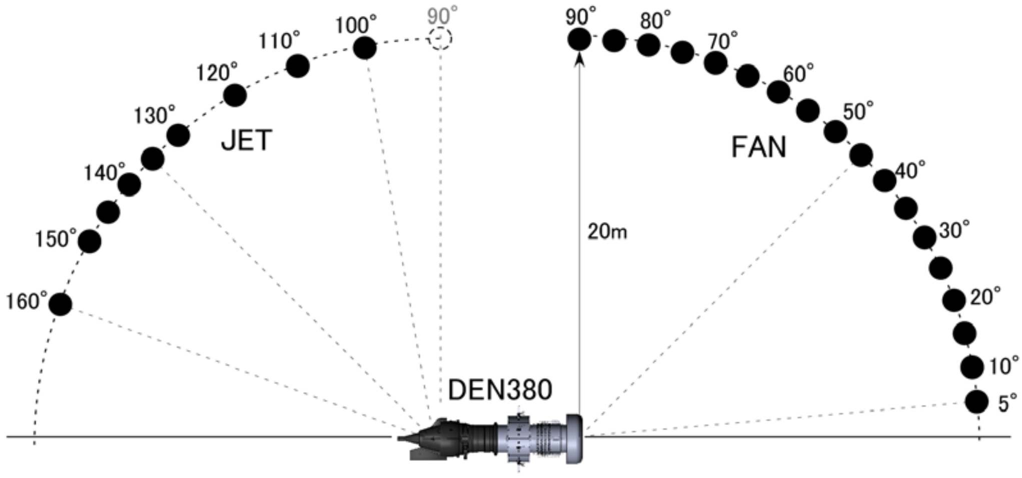

Fig. 8 Sensor position of 20-meter arc microphone array.

relative to the engine inlet axis. 1/4” condenser microphones are used. To reduce the low frequency wind noise, 50Hz-hi-pass filters are used.

Noise measurements were made at Shikabe Airport in Hokkaido, northern island of Japan.

5. RESULTS AND DISCUSSIONS

5.1 In-duct microphone measurement

First, narrow band spectrum measured by in-duct microphones is shown in Figure 9. This is the averaged spectrum of an array of 36 azimuthal microphones closest to the engine inlet. The engine speed is NL90%. Compared with the hard-wall result, the first BPF tone of 2800 Hz is reduced by 10 dB with Liner 1 and by 15 dB with Liner 2. As for the 2nd BPF tone, about 5 dB attenuation is achieved by each liner. As the result of large attenuation on 1BPF, Liner 1 has largest peak at 2nd BPF while Liner 2 has largest peak at 3rd BPF. Regarding to the broadband noise, up to 5 dB reduction is obtained in a wide range of from 1 kHz to 8 kHz. Although two liners have almost the same for broadband noise attenuation, Liner 1 has better attenuation on the broadband noise of 6 kHz or higher.

The difference between hard-wall SPL and liner-treated SPL is defined as “liner attenuation” and is plotted in Figure 10. Both liners have attenuation peak at the design frequency about 2.8kHz. As the engine speed increases, the amount of attenuation increases. This agrees with the result derived by the empirical formula as shown in Figure 3.

Figure 11 is the comparison in attenuation of Liner 1 and Liner 2 at each engine speed. At any engine speed, the Liner 1 of smaller perforation has good performance, especially in the range of 4 kHz or higher.

5.2 Modal analysis with in-duct array microphones

According to the reference [12], 4 axial microphone array arrangement can mathematically provide a solution of both upstream and downstream propagating waves of 0^{th} and 1^{st} radial modes. However only 0^{th} axial mode with both upstream and downstream propagating waves are derived on this discussion because of the poor resolution of radial modes. Here, the modal analysis for the hard-wall configuration at the high pressure shaft rotation frequency (Ω_{HPS}) and the first and the second blade passing frequency tones (1BPF, 2BPF) are shown in Figure 12. As the engine speed increases,

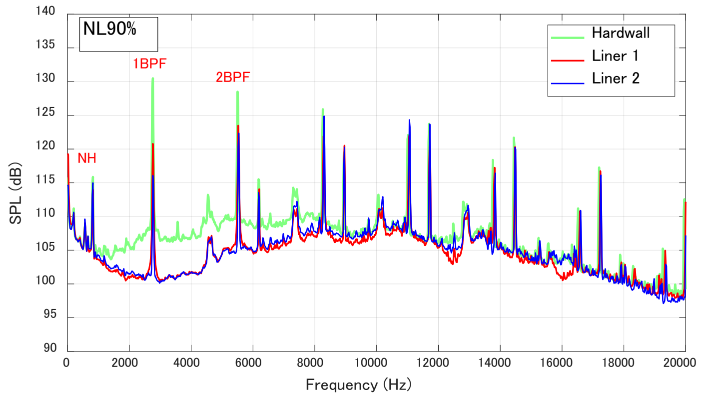

Fig. 9 Averaged sound spectrum of 36 azimuthal in-duct microphones at 90% of max low spool shaft-speed.

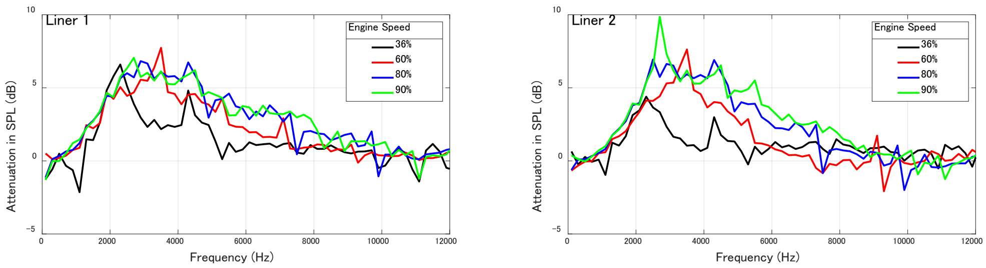

Fig. 10 Attenuation of each liner at different engine speeds.

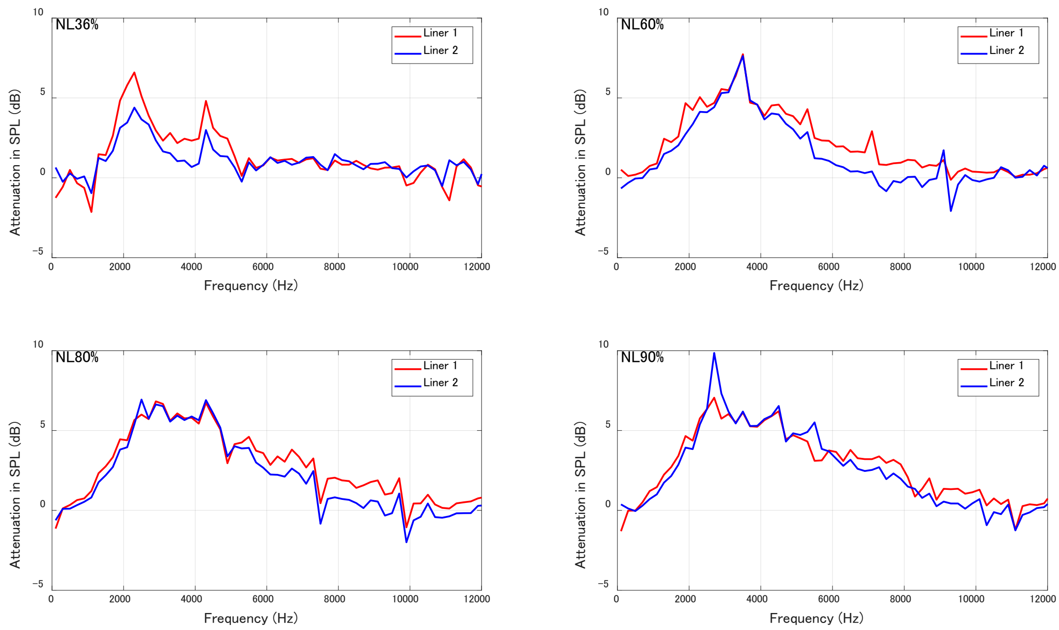

Fig. 11 Comparison in attenuation level for both liners.

the frequencies of these tones are higher, then the number of “cut-on modes” (propagating in the duct without decay) increases.

In Ω_{HPS}, azimuthal mode m = 1 is dominant, the possible noise source is rotating with the hi-pressure shaft rotation. For 1BPF, the number of rotor blades is 14 and the number of stator vanes is 40, then blade-stator interaction is always cut-off (decaying in the duct),

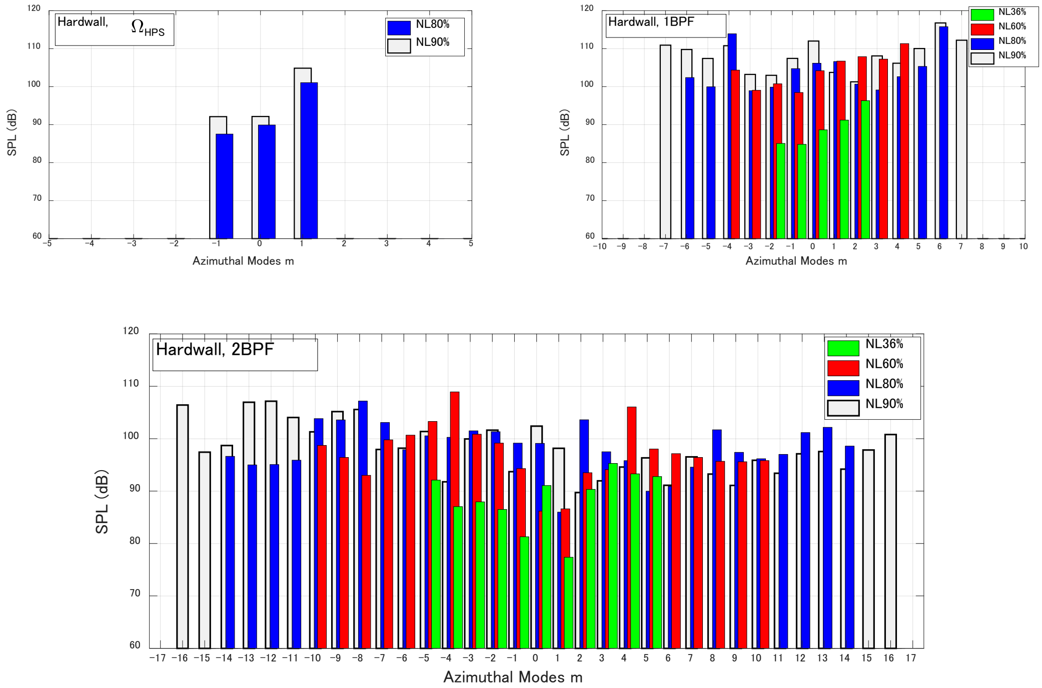

Fig.12. Distribution of azimuthal modes at each engine speed with hardwall configuration.

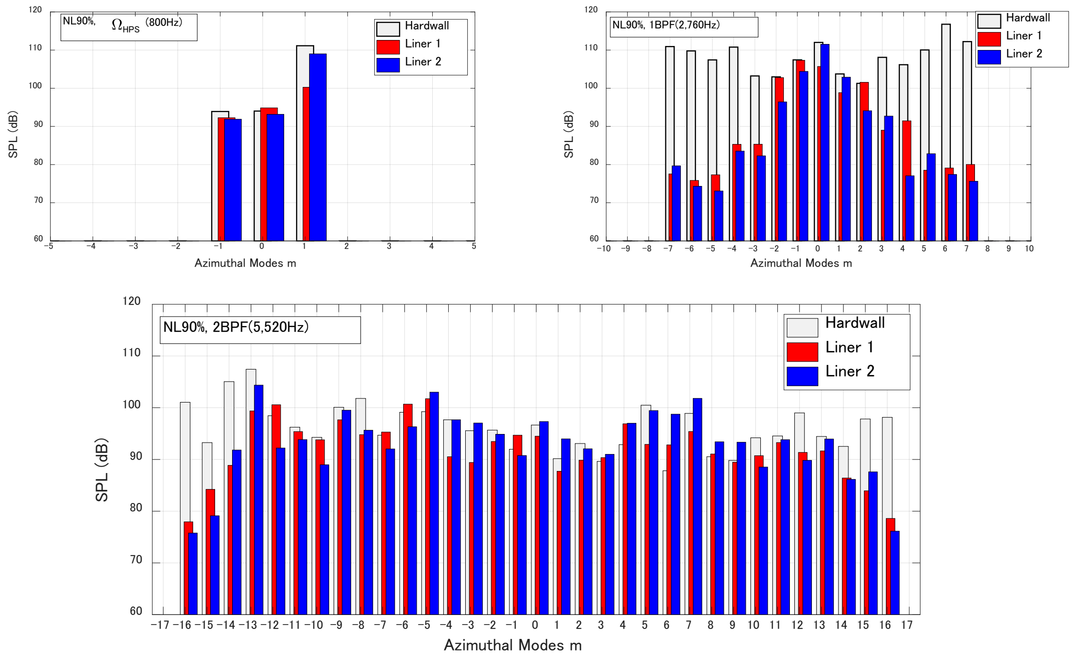

Fig.13 Distribution of sound pressure level in azimuthal modes for hardwall, Liner 1 and Liner 2 at engine speed NL90%.

$m = -26\ (14 - 40)$ is the minimum azimuthal mode order. $m = 6$ is large at 80%NL and 90%NL. The blade (14) and strut (4) interaction $(14 - 2 \times 4)$or blade-liner pocket (8) interaction $(14 - 8)$ are the possible sources. For 2BPF, blade-stator interaction will be cut on for $m = -12\ (2 \times 14 - 40)$ above 80%NL and this mode is strongly appeared at NL90%.

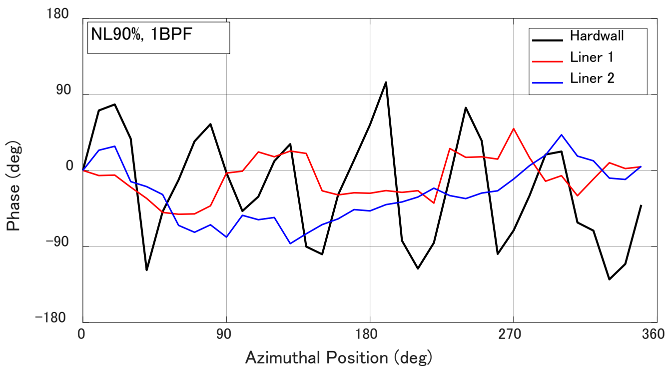

Fig.14 Distribution of phase angle of azimuthal microphones. (1BPF at engine speed NL90%)

Mode distributions of the hard-wall, Liner 1 and Liner 2 are compared in Figure 13. First, at the high pressure shaft rotation speed frequency (Ω_{HPS}), m = 1 mode is dominant. This mode is reduced by more than 10dB with Liner 1 but only 2dB with Liner 2. In the results of 1BPF and 2BPF, large attenuation at higher order modes is observed. Focusing on the result of 1BPF, the phase differences between the azimuthal array microphones are shown in Figure 14. For the hard-wall case 6 cyclic phase variation is observed along the azimuthal microphones and this must be the reason that m=6 mode is one of the largest modes in Figure 13. However, this cyclic phase variation is disappeared by installation of each liner. Therefore, the installation of liner is effective for the dissipation of high order azimuthal modes.

5.3 Sound radiation from DGEN 380

Sound radiation from DGEN 380 is measured by 20-meter arc microphone array and 1/3- octave band analysis is performed for comparison. The attenuation by each liner with respect to the hard-wall are plotted in Figure 15. Three centre band frequencies of 2.5kHz, 3.15kHz and 4kHz and overall SPL are shown. First, at overall SPL plot, noise reduction of 1-2 dB was confirmed in a wide range arc angles of from 5 to 90 degrees. At center frequencies of 2.5kHz and 3.15kHz, around the liner design frequency, 3 dB or more reduction is obtained in the angles of from 30 to 60 degrees of forward arc array, while at 4kHz, the attenuation is relatively small. In comparison of two liners, the superiority of Liner 1 as seen in in-duct microphone measurements is not confirmed in this radiation results.

The 1/3-octave band spectrum at arc angle of 45 degrees is shown in Figure 16. An attenuation of 5 dB or more is limited only at the frequency bands of 2.5kHz and 3.15kHz, while noise increase is observed at higher frequencies such as 8 kHz or 10 kHz for Liner 2.

Figure 17 shows the noise attenuation in SPL at 2,500 Hz at each engine speed. In consistent with the in-duct measurement results, as the engine speed increases larger noise attenuation is obtained.

Further studies are required to predict the radiation field in conjugation with the in-duct propagation modes analysis.

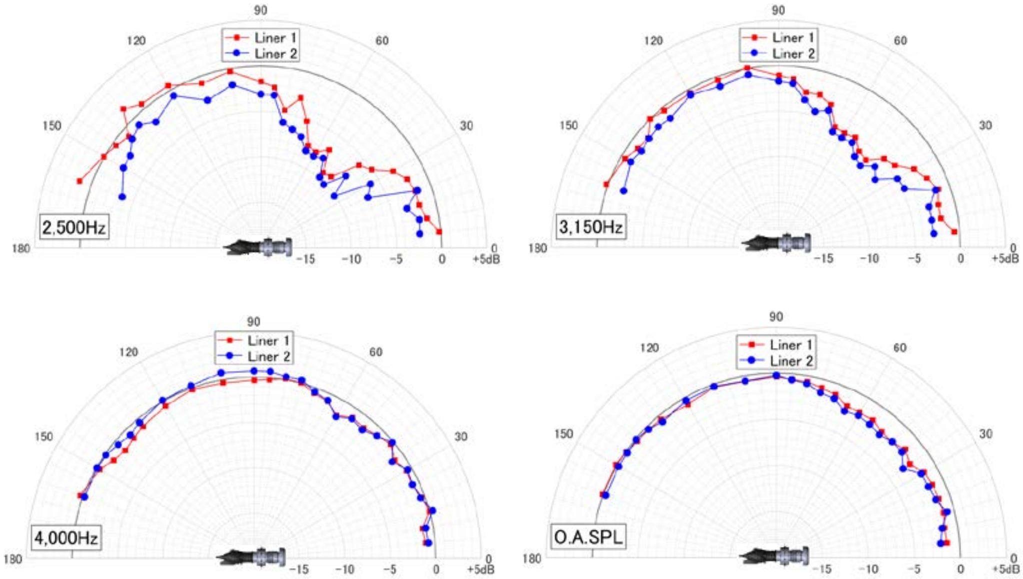

Fig.15 Noise attemuation directivity pattern of acoustic liners by 20m-arc microphone array at engine speed NL90%. (One-third-octave bands center frequencies.)

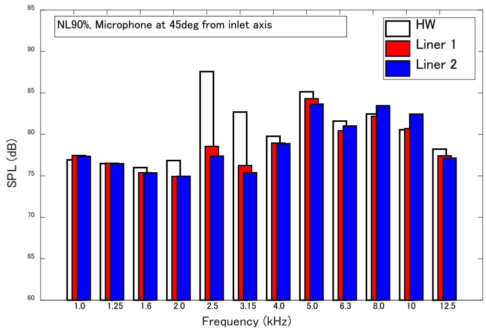

Fig.16 One-third octave bands spectrum of arc microphone at 45deg from inlet axis.

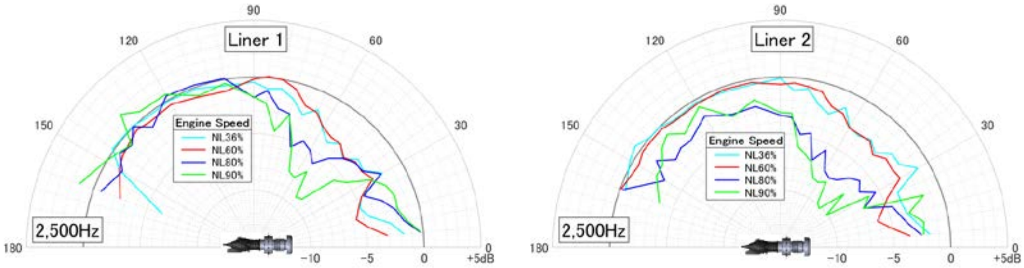

Fig.17 Noise reduction directivity pattern of acoustic liners by arc microphone array at different engine speeds. (one-third-octave bands center frequency f=2,500Hz.)

6. CONCLUSIONS

This paper describes preliminary acoustic liner test on small turbofan engine, DGEN 380. Acoustic liner panels are designed to reduce the first blade passing frequency (1BPF) tone noise and are fabricated by 3D printer. The attenuation characteristics was evaluated by in-duct and far-field acoustic measurements. Their attenuation performances are good agreement with the conventional prediction formula. Based on these preliminary results, further studies on optimization of the liner panels, detailed analysis of the duct propagating modes and prediction of radiation field by those modes have to be addressed soon.

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