APPLICATION OF NOISE SOURCE IDENTIFICATION USING EXTENDED CLEAN-SC AND A NEW DENOISING METHOD TO A TURBOFAN ENGINE MEASUREMENTS OUTDOORS

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ABSTRACT

Last few years, acoustic measurements of a turbofan engine, DGEN380, have been conducted in the open test site by JAXA and Brüel & Kjær.

The authors showed an ability of the extended CLEAN-SC which suggests a potential of evaluating directional contributions of jet noise sources in the paper presented at BeBeC 2018.

The previous paper described the extended CLEAN-SC using reference signals selected from the array microphones to obtain contribution of sources correlating to the reference signal. In this paper, to evaluate more about directional contributions practically, independent reference microphones were placed on the side-line on the ground parallel to the jet axis instead of using signals selected from the array microphones as reference signals.

In the case of measurements conducting outdoors or in a wind tunnel, flow-induced noise in microphones often becomes a problem.

Therefore, this paper also describes a new denoising method, Canonical Coherence Denoising (CCD), which was proposed by Hald, and tries it in the extended CLEAN-SC calculation in order to reduce flow-induced noise.

1 INTRODUCTION

Array based noise source identification (NSI) system is very useful to improve noise problems of products by knowing location of noise sources and strength of them.
Typically, a beamforming measurement system using with a relatively large diameter of array can be applied for measuring big structures like as cars, trains, aircrafts, jet engines, wind turbines and even scale model or full scale of rocket motors. One of the typical applications of the beamforming would be beamforming measurements conducted in wind tunnel in an

indoor facility. But many of beamforming measurements applied to big structures would be conducted outdoor.
Aerodynamic noise sources observed on a car in a wind tunnel, in the high-speed stream of jet engines or launch vehicle will be the main target in such beamforming measurements. And one of beamforming calculation methods to be used in such beamforming measurements is the CLEAN based on special source coherence (CLEAN-SC) method [1], which is used in this paper. This is because the aerodynamic noise sources are basically incoherent sources and CLEAN-SC is suitable for such incoherent sources. However, in both outdoor and wind tunnel measurements, incoherent noise in the individual microphones induced by airflow and turbulence would often be a problem. For such a problem, many denoising techniques have been developed and introduced. One of physical solutions is to use windscreen.
On the other hand, assuming stationary noises and a use of frequency-domain beamforming with a cross-spectrum matrix (CSM), some of denoising methods can be applied to beamforming calculations. Examples of such methods are the Diagonal Removal (DR) [2], the Diagonal Denoising (DD) [3] and the Canonical Coherence Denoising (CCD) [4]. In this paper, the CCD method will be described simply and applied with CLEAN-SC and extended CLEAN-SC for beamforming calculations.
In the previous paper [5], an array was applied to a turbofan engine, DGEN380, and beamforming results using CLEAN-SC and other methods were shown. And the extended CLEAN-SC, coupled with reference microphones, is introduced to predict the directional contribution of jet noise sources within certain emission angles. In this paper, the same array with the dedicated reference microphones is applied to the DGEN380 and the predicted results of the directional contribution within the wider angles will be shown.

2 THEORY

2.1 Cross-spectral matrix denoising

When a cross-spectral matrix (CSM) is contaminated by flow-induced noise like in a wind-tunnel measurement, the noise contamination will typically be concentrated on the diagonal of the CSM.
When M is the number of array microphones and G is the M x M cross-spectral matrix, the Diagonal Denoising (DD) method can subtract a noise-contaminated diagonal matrix diag(**d**) from G.

$$\mathbf{G}_{DD} = \mathbf{G} - \mathrm{diag}(\mathbf{d}) \quad (1)$$

Here, $\mathbf{G}_{DD}$ is the denoised matrix obtained by the DD method.
But there are some limitations in the DD method. One is that the number of incoherent target sources should not exceed approximately $M - \sqrt{2.5M}$.
The other limitation of the DD method is that remaining off-diagonal noise contributions will typically limit the noise power that can be removed from the diagonal before the smallest eigenvalue reaches zero. If a very long averaging time is applied, then the DD method will be effective, but with realistic averaging times, the benefit is limited.

The Canonical Coherence Denoising (CCD) method will overcome these limitations with the following main idea:

- The M array microphones are divided in two equally large groups, each with M/2 microphones, and the part of the signals which are coherent between the two groups is extracted. Effectively, the measured cross-spectral matrix **G** is divided into the coherent part $\mathbf{C}_1$ and the remaining residual $\mathbf{R}_1$:
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$$\mathbf{G} = \mathbf{C}_1 + \mathbf{R}_1 \tag{2}$$

- To overcome the M/2 limitation, a new and different grouping of the microphones is made, and the residual matrix $\mathbf{R}_1$ is split in the part which is coherent between the groups and a new residual $\mathbf{R}_2$:

$$\mathbf{R}_1 = \mathbf{C}_2 + \mathbf{R}_2 \tag{3}$$

This process can be repeated. Finally, the denoised matrix $\mathbf{G}_{\text{CCD}}$ is:

$$\mathbf{G}_{\text{CCD}} = \mathbf{C}_1 + \mathbf{C}_2 \ (+ \mathbf{C}_3 \ \ldots) \tag{4}$$

Details of the algorithm can be found in reference [4].

2.2 CLEAN-SC and Extended CLEAN-SC

The CLEAN algorithm based on spatial source coherence (CLEAN-SC) is useful to identify and map aerodynamic noise sources like in measurements in wind-tunnels, since the algorithm aims at detecting incoherent sources.

The Clean-SC method was introduced by Sijtsma, The algorithm iteratively allocates incoherent monopole point source on the focus plane. Together, these sources represent the measured CSM. Considering a single iteration, it begins with delay-and-sum (DAS) beamforming and identifies the peak position. Signal components in the CSM coherent with the beamformed signal at the peak are then allocated to a point source at the peak and subtracted from the CSM. The vector $\mathbf{p}_k$ of complex pressure contributions from the new point source across the array microphones can be expressed as follows:

$$\mathbf{p}_k = \frac{\mathbf{G}\mathbf{w}_k}{\sqrt{\mathbf{w}_k^H \mathbf{G}\mathbf{w}_k}} \tag{5}$$

Here, **G** is the CSM, $\mathbf{w}_k$ is the steering vector to focus at a position k, and ^{H} represents Hermitian (complex) conjugate of a vector or a matrix. Typically, the average contribution of each source $\|\mathbf{p}_k\|_2^2/M$ across the array microphones will be shown in a map.

The extended CLEAN-SC method was introduced by Hald [6], to estimate and map contributions from points or areas in a map to a reference microphone. With the point source positions identified exactly as in standard CLEAN-SC, the contribution from peak source number k to the reference signal can be expressed as:

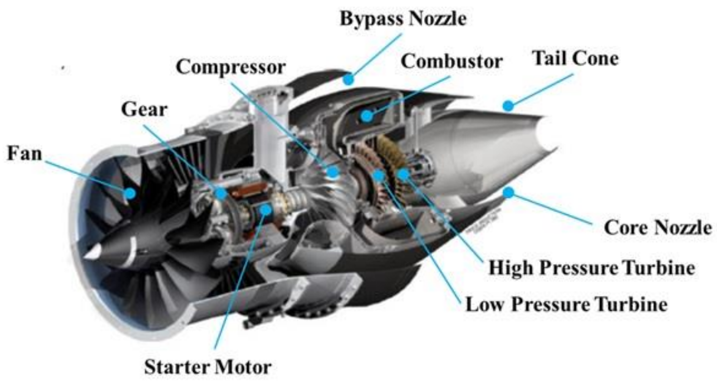
$$\mathbf{p}_{\mathbf{R,k}} = \frac{\mathbf{G}_{\mathbf{R}}^{\mathbf{H}} \mathbf{w}_{\mathbf{k}}}{\sqrt{\mathbf{w}_{\mathbf{k}}^{\mathbf{H}} \mathbf{G} \mathbf{w}_{\mathbf{k}}}} \tag{6}$$

where $\mathbf{G}_R$ is a vector containing the measured cross spectra between the reference signal and the array microphones. After each iteration, the coherent part must be subtracted from $\mathbf{G}_R$ as well as from $\mathbf{G}$. A map of $\left\|p_{\mathrm{R},k}\right\|_2^2$ across the focus plane will show the contributions of the identified sources to the reference signal. If the position of a reference microphone represents a radiation angle, P_{R} could suggest the directional contribution of the source map. Details of the algorithm can be found in reference [4].

3 EXPERIMENT

3.1 Turbofan Engine for Noise Tests

A small turbofan engine, the DGEN 380, is composed of a 350 mm - diameter fan, a centrifugal compressor, a reversed-type annular combustor, a single-stage high-pressure turbine and a single-stage low-pressure turbine. The inner structure of the engine and the representative specifications of the DGEN 380 are shown in Fig. 1



Structure	Twin Spool with Gear
Length	1130 mm
Diameter	550 mm
Fan	14 Blades and 40 vanes
Fan Diameter	350 mm
Compressor Centrifugal	11 blades
Combustor	Reversed Annular
High-pressure Turbine	Single Stage 38 Blades
Low-pressure Turbine	Single Stage 38 Blades
Fuel	Kerosene
High-pressure Spool Speed	51,400 rpm
Low-pressure Spool Speed	43,400 rpm
Thrust	250 daN
Exhaust Gass Temperature	630℃

Fig. 1. Inner structure and specifications of DGEN380 engine

The exhaust nozzles are short-cowl nozzles containing a tail-cone that extends out of it, and diameter of the core nozzle and the bypass nozzle are 200 mm and 460 mm respectively. Figure. 2 shows example nozzles used in a series of the engine test campaign.

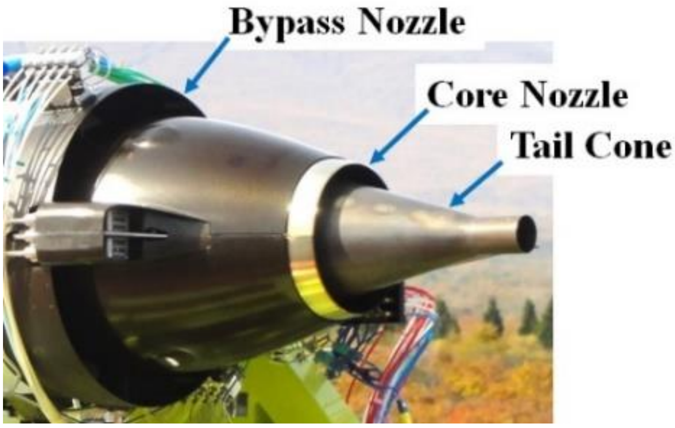


Fig. 2. Example of core (primary) and bypass (secondary) nozzles used in tests

The DGEN 380 was installed on a mechanically floating stand placed on a rigid plate in an apron zone of Shikabe airfield located in the southern part of Hokkaido, Japan. An overall view of the noise test is shown in Fig. 3.

Fig. 3 View of test site in Hokkaido

3.2 Canonical Coherence Denoising (CCD)

The Diagonal Removal (DR) applied with Non-negative Least Squares (NNLS) is effective to suppress flow-induced noise, but producing underestimated map as described in reference [7]. The Canonical Coherence Denoising (CCD) method is implemented in the PULSE Beamforming software. Furthermore, the CLEAN-SC calculation with DD and the NNLS calculation with DR are also available in the PULSE Beamforming software. Fig. 4 shows comparison of CLEAN-SC CCD with CLEAN-SC DD and NNLS DR. The averaged wind speed during the measurement was 7.8 m/s. The display range is 20 dB. The CCD map seems to have slightly better noise suppression than the DD map while The NNLS map seems to underestimate the level of the strong source. It might be lower wind speed to confirm the effect of the CCD. However, since it is desirable to conduct noise measurements under low wind conditions, there was almost no data measured under windy conditions in the series of engine noise tests. All the subsequent CLEAN-SC calculations and extended CLEAN-SC calculations have applied CCD.

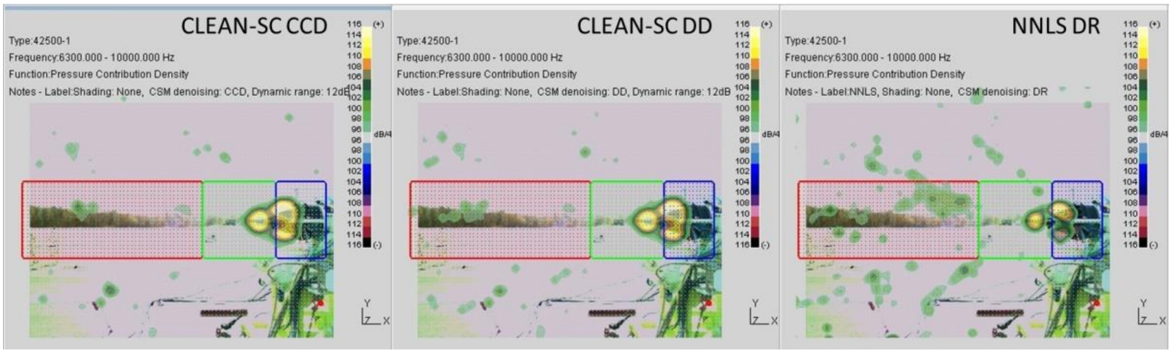


Fig. 4. Maps of CLEAN-SC applied with CCD (left), CD (middle) and Shading function (right)

3.3 Beamforming measurements in engine noise tests

Beamforming measurements were carried out in the series of engine noise tests in 2017 following 2016. The results from 2016 has already been presented in BeBeC 2018 [5].
The measurements in 2017 were done with a 2.5 m diameter planar array consisting of 9 arms with 6 microphones spaced logarithmically from the center of the array which was the same array used in 2016. And all microphones including reference microphones placed on the ground were fitted with windscreens. The center of the array was focused on the point on the jet axis approximately 1 m behind the core nozzle, and to avoid the exposure to jet plume, the array plane was aligned to the parallel line 3.3 m away from the jet axis.

As shown in Fig. 5 and Fig. 6, the layout of the array, the engine and other stuff in the test campaigns in 2017 is almost the same as in 2016 except the layout of the reference microphones. To estimate the directional contribution of the sound source maps, the reference microphones were placed in a line on the ground parallel with the jet axis in the measurements in 2017.

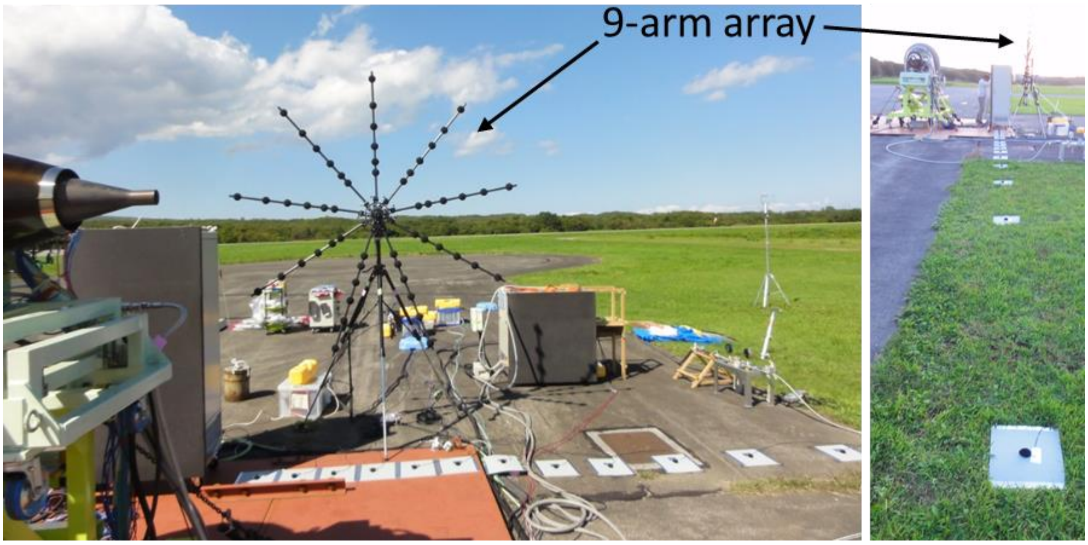
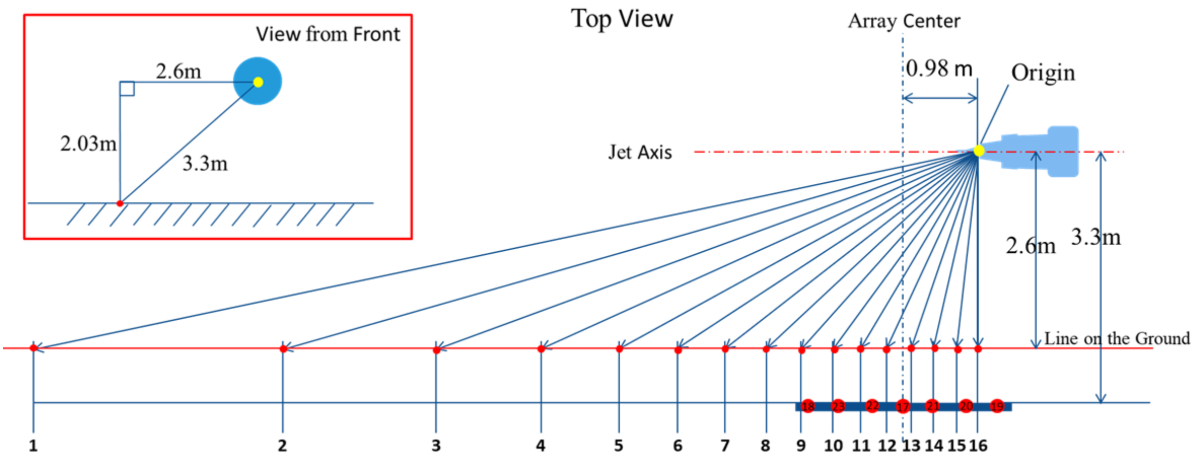


Fig. 5. Layout of the 9-arm array



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)	-11.336	-8.087	-6.097	-4.736	-3.733	-2.953	-2.32	-1.789	-1.331	-0.925	-0.559	-0.221	0.096	0.398	0.691	0.98

Fig. 6. Layout of reference microphones

The measured data presented in the paper were obtained from serial number F162 and F164 in the test campaign in 2017. The core nozzle used in F162 (Core nozzle A) and F164 (Core nozzle B) is different but the bypass nozzle is the same.

Figure. 7 shows the maps of linear overall results for the 100 Hz to 1600 Hz 1/3-octave bands obtained by CLEAN-SC from F162 and F164 at 95% of the engine power setting. The display range is 15 dB. In both maps, the intensive noise source is observed near the core nozzle and levels of the noise sources within the downstream area enclosed by red line are much smaller than the peak level. And the colored values represent sound pressure contribution at array center from the areas enclosed by each color respectively.

Fig. 7 Maps obtained by CLEAN-SC with different nozzles

Figure. 8 and Fig. 9 contain the directional contribution maps obtained by Extended CLEAN-SC from F162 and F164 respectively. The power setting of the engine is 95 %. Both maps show linear overall results for the 100 Hz to 1600 Hz 1/3-octave bands. The area integrated sound pressure levels contributing at position of each reference microphone corresponding to the radiation angle from the engine inlet are shown on the maps. When comparing the downstream area (enclosed by red line) and the core nozzle area (enclosed by green line) from lower radiation angle to higher radiation angle, the relative difference of the level of the contribution is gradually decreased and eventually reversed.

These maps suggest that the contribution of the downstream area is bigger than the contribution of the core nozzle at the higher radiation angles even though the contribution of the core nozzle area is bigger than the downstream area, as shown in Fig. 7.

Fig. 8 Maps of contribution at each reference microphones corresponding to the emission angles. Serial number is F162. Frequency range is 100 – 1600 Hz.

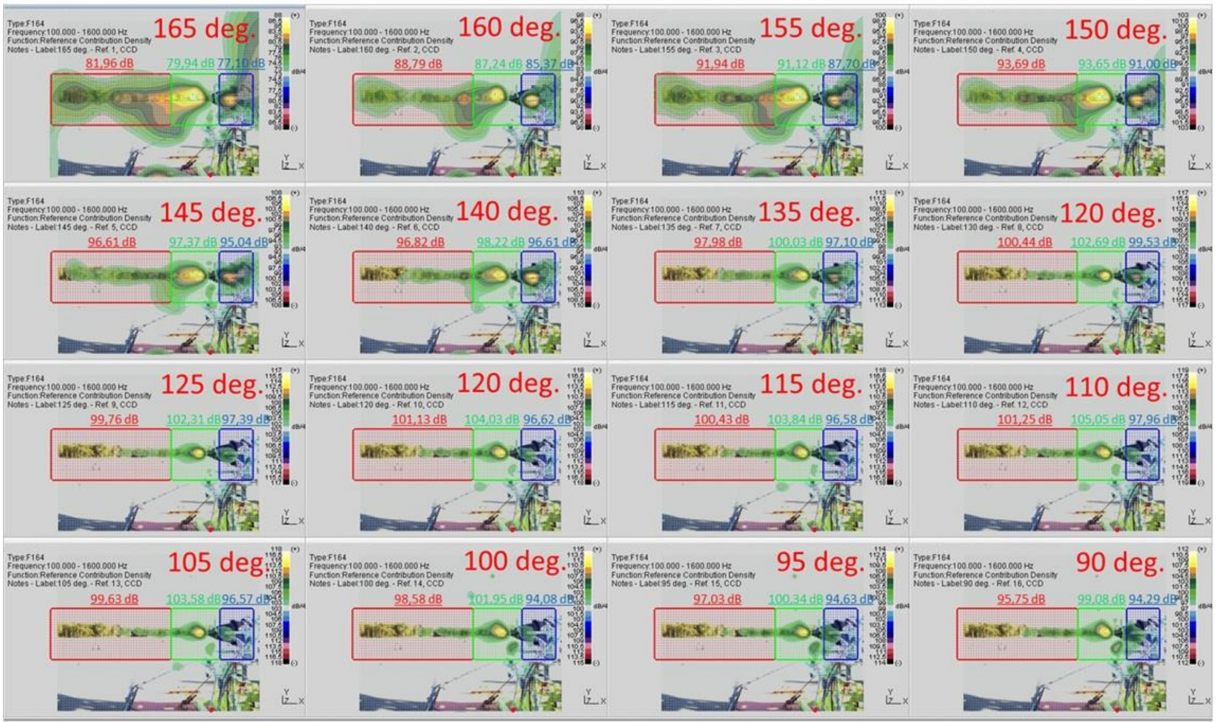


Fig. 9 Maps of contribution at each reference microphones corresponding to the emission angles. Serial number is F164. Frequency range is 100 – 1600 Hz.

4 SUMMARY

Array measurements have been applied in engine noise tests performed in the open test site at Shikabe airfield. In this paper, the CCD method introduced by Hald was simply described contrasted with the DD method. Thereafter, the CCD was applied with the CLEAN-SC calculation and the extended CLEAN-SC calculation to confirm the performance of the CCD. But the differences did not appear clearly from the comparison with the CLEAN-SC DD and NNLS DR. The data used in the comparison might have not been appropriate, since the data were taken under low wind conditions.

As mentioned in reference [5], it would be useful to be able to know the directional contribution of noise emitted by an engine by noise source identification measurements with an array placed on the beside of the engine, since it would be avoided the damages from the exposure to jet plume. In this paper, the independent reference microphones were employed for the extended CLEAN-SC measurements, in order to extend the range of angles for predicting the directional contribution of jet noise. As a result, maps of relative directional contribution were obtained from the extended CLEAN-SC with the independent reference microphone, corresponding to the radiation angle, placed along on the side line parallel to the jet axis.

Finally, the authors would like to thank people who have been involved in the noise tests using DGEN380

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