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Using CLEAN-SC for determining the directivity of engine noise sources

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The deconvolution method CLEAN-SC is proposed as a tool for analysing engine static tests with far-field microphone arrays. Using measurements on a DGEN380 engine, it was demonstrated that CLEAN-SC is able to make a breakdown of the different engine noise sources (jet, core, bypass, intake) and to determine the far-field directivity of each source. Even the challenging task of separating core noise from jet noise was performed successfully, including the directivity.

Nomenclature

CSM	cross-spectral matrix	$g_{j,n}$	steering vector value
HPT	high-pressure turbine	\mathbf{h}_j	CLEAN-SC source component
LPT	low-pressure turbine	i	imaginary unit
SPL	sound pressure level	J	number of source areas
A_j	source power	j, k	source indices
\mathbf{C}	measured CSM	m, n	microphone indices
\mathbf{C}_{mod}	modelled CSM	\vec{x}_m	microphone position
C_{mn}	cross-spectrum	Δt	time delay
$D^{j,n}$	directivity factor	φ_j	CLEAN-SC loop gain
F	cost function	ξ_j	scan point
f	frequency		

I. Introduction

Important information to be obtained from engine static tests are the level and the directivity of the noise radiating into the far field, broken down into the contributions from the jet, the core, the bypass and the intake. Conventional beamforming¹ and integration² methods applied to far-field microphone arrays (linear or polar) are capable of making an “average level breakdown”, which means that the average level of the array microphones can be written as a summation over the different source contributions. But the directivities of the individual noise sources remain unknown with those methods. To obtain a breakdown *including* directivities, two inverse methods have been developed: SODIX³ and AFINDS⁴. As far as the author knows, there is no publication in which results of both methods were compared to each other.

As alternative to the above-mentioned methods, the present paper proposes the use of the deconvolution method CLEAN-SC⁵. A well-known feature of CLEAN-SC is that it does not make use of theoretical point spread functions. In other words, the directivities of the acoustic sources may be unknown. This property appears very useful for engine static tests, when source directivities are largely non-uniform.

Like other methods, CLEAN-SC can make a noise source breakdown of the average microphone levels. In this paper it is demonstrated that CLEAN-SC is also capable of determining the directivity of separate sources. Particularly, separation of core noise and jet noise appears feasible, by making use of the different source characteristics (compact vs distributed).

Although not an inverse method, CLEAN-SC has the same functionality as SODIX and AFINDS. The question if CLEAN-SC is better or worse than the other methods remains yet unanswered. But its added value is anyway in the ease of implementation. The other methods have in common that implementation into a numerical code is not straightforward.

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The capability of isolating the core noise contribution of the far-field noise is very useful for future studies on Ultra-High-Bypass Ratio (UHBR) engines, for which core noise is expected to be increasingly important. Development of methodology for understanding, predicting and reducing core noise for future UHBR developments is the topic of the CIRRUS project within the EU Clean Sky 2 Joint Undertaking. This topic was established by Safran Aircraft Engines.

In this paper, the new application of CLEAN-SC is demonstrated on sideline microphone array data measured in 2017 by NASA Glenn on a DGEN380 engine, within their DGEN Aero-propulsion Research Turbofan (DART) test bed⁶. Section II of this paper briefly discusses SODIX, AFINDS and CLEAN-SC. Section III outlines the DGEN tests. The CLEAN-SC results are presented in Section IV. The conclusions are summarised in Section V.

II. Methods

A. SODIX and AFINDS

The state-of-the-art models for analyzing far-field microphone array data of engine tests are SODIX³ and AFINDS⁴, both of which are still being improved and extended^{7,8}. Both methods solve the minimization problem

$$F = \|\mathbf{C} - \mathbf{C}_{\text{mod}}\|^2 = \sum_{m,n} |C_{mn} - (\mathbf{C}_{\text{mod}})_{mn}|^2, \quad (1)$$

in which \mathbf{C} is the measured cross-spectral matrix (CSM) and \mathbf{C}_{mod} a summation of model-CSMs due to different sources or source areas:

$$\mathbf{C}_{\text{mod}} = \sum_{j=1}^J \mathbf{C}_{\text{mod},j}. \quad (2)$$

This expression assumes that the separate contributions are incoherent. Recently, SODIX was extended with partially coherent sources⁷.

Within SODIX, the source directivities are included as unknowns in the minimization problem. The model-CSMs are expressed as:

$$(\mathbf{C}_{\text{mod},j})_{mn} = g_{j,m} D_{j,m} D_{j,n}^* g_{j,n}^*, \quad (3)$$

in which \mathbf{g}_j is the regular (monopole) acoustic transfer vector and $D_{j,m}$ are source- and microphone-dependent directivity factors. The asterisk denotes complex conjugation. To reduce the effective number of unknowns and to stabilize the solution, a regularization term is added to Eq. (1), which smooths the solution over neighboring microphones and neighboring (jet noise) sources.

In AFINDS, the number of source areas J is limited to 4: intake, bypass, core and jet mixing noise. For each of the source areas, maximum knowledge about the directivity is put into the model, for example the ‘‘GXMunt’’ Wiener-Hopf model for far-field radiation from an unflanged annular duct⁹. For jet noise, a semi-empirical directivity function with two unknown parameters is used and an empirical distribution of incoherent point sources¹⁰.

B. CLEAN-SC

CLEAN-SC⁵ was developed for wind tunnel measurements, when beamforming is usually done without the CSM-diagonal. For engine static tests diagonal removal is not needed, which makes the implementation easier. The method can then be summarized as follows.

At each iteration step CLEAN-SC searches the maximum Conventional Beamforming¹ output for a set of steering vectors \mathbf{g}_j associated with scan points (potential noise sources) ξ_j :

$$A_j = \mathbf{g}_j^* \mathbf{C} \mathbf{g}_j. \quad (4)$$

After having found the maximum value A_j , the ‘‘dirty’’ CSM is updated by

$$\mathbf{C}^{\text{update}} = \mathbf{C} - \varphi A_j \mathbf{h}_j \mathbf{h}_j^*, \quad (5)$$

in which φ is the ‘‘loop gain’’, $0 < \varphi \leq 1$. The ‘‘source component’’ \mathbf{h}_j is defined by

$$\mathbf{h}_j = \frac{1}{A_j} \mathbf{C} \mathbf{g}_j, \quad (6)$$

After a complete deconvolution, the CSM can be written as

$$\mathbf{C} = \sum_k A_k \mathbf{h}_k \mathbf{h}_k^* . \quad (7)$$

Each iteration index k corresponds to a scan point $\vec{\xi}_j$ which was the peak location at that iteration step. Since the peak locations can be classified into separate source areas, we can reorganize Eq. (7) into

$$\mathbf{C} = \left(\sum_k A_k \mathbf{h}_k \mathbf{h}_k^* \right)_{\text{intake}} + \left(\sum_k A_k \mathbf{h}_k \mathbf{h}_k^* \right)_{\text{bypass}} + \left(\sum_k A_k \mathbf{h}_k \mathbf{h}_k^* \right)_{\text{core}} + \left(\sum_k A_k \mathbf{h}_k \mathbf{h}_k^* \right)_{\text{jet}} . \quad (8)$$

Thus, CLEAN-SC makes a decomposition of the CSM into summands that are due to separate source areas.

Normally, the average diagonal values of the separate matrices in the right-hand side of Eq. (8) are used to obtain integrated results of the different source areas. But information about the source directivity can be extracted as well, just by considering the individual diagonal elements. Thus, CLEAN-SC can provide directivity information about the separate source areas. This is the main message of this paper.

Note that Ishii et al.¹¹ already identified this potential of CLEAN-SC, although they used a special version of CLEAN-SC, in which a few microphones within the array were used as reference. The angular coverage of the array that they used (for DGEN380 measurements at an open test site) was too small for a full demonstration.

III. Measurements

CLEAN-SC was applied to measurements on a DGEN380 engine, which is a small high-bypass ratio geared turbofan. Its dimensions are shown in Figure 1. The engine has 14 fan blades, 11 compressor blades, 38 HPT blades and 38 LPT blades. The fan is connected with the LPT shaft by an 83/25 gear box. The HPT and the compressor are connected to the same shaft.

The tests took place in August 2017 in NASA Glenn's Aero-Acoustic Propulsion Laboratory (AAPL), which is in the anechoic dome shown in Figure 2. Measurements were done on both sides of the engine, both with a polar and a linear microphone array. The polar array consists of a forward and an aft part with a gap in between, which makes it less suitable for beamforming. Therefore, CLEAN-SC was applied to the linear array. This array consists of 30 equally spaced microphones, parallel to the engine axis at 88" distance, at the same height. The array length is 260". The forward most microphone is 87" from the engine intake plane. The acoustic measurements were done at several engine speeds, at 250 kHz sample rate and 10 s acquisition time. For more information about the tests and the facility the reader is referred to Sutliff⁶.



Figure 1 DGEN380 Dimensions (from AKIRA Technologies, France)

IV. Results

Results are discussed with the linear array on the right-hand side (starboard side) of the engine, at 70% speed. The RPM-values were 9329 for the fan, 43765 for the HPT and 30973 for the LPT.

A. Removal of tones

First, shaft order tones were subtracted from the microphone signals using the method of Rademaker et al.¹². Shaft order tones, especially fan tones, may radiate both from the intake and the bypass duct. Since a fixed-frequency tone is coherent, CLEAN-SC cannot provide a breakdown in that case.

The results of the subtraction, averaged over all array microphones, are shown in Figure 3. The spectra before and after filtering for tones ("Original" and "Filtered") are narrow-band results obtained with Welch's method (Hanning window and 50% overlapping snapshots). The FFT blocksize is 4096, implying a frequency bandwidth of 61 Hz.

The tones are presented as shaft order spectra (without windowing). The blade-passing frequencies of the fan (2177 Hz) and the compressor (8024 Hz) are clearly visible. The blade-passing frequencies of HPT and LPT are outside the plot range of Figure 3. No effort was undertaken to subtract interaction tones, although these are present as well¹². The impact of not subtracting interaction tones is assumed to be limited.



Figure 2 Aero-Acoustic Propulsion Laboratory (from NASA GRC photo C94-2204)

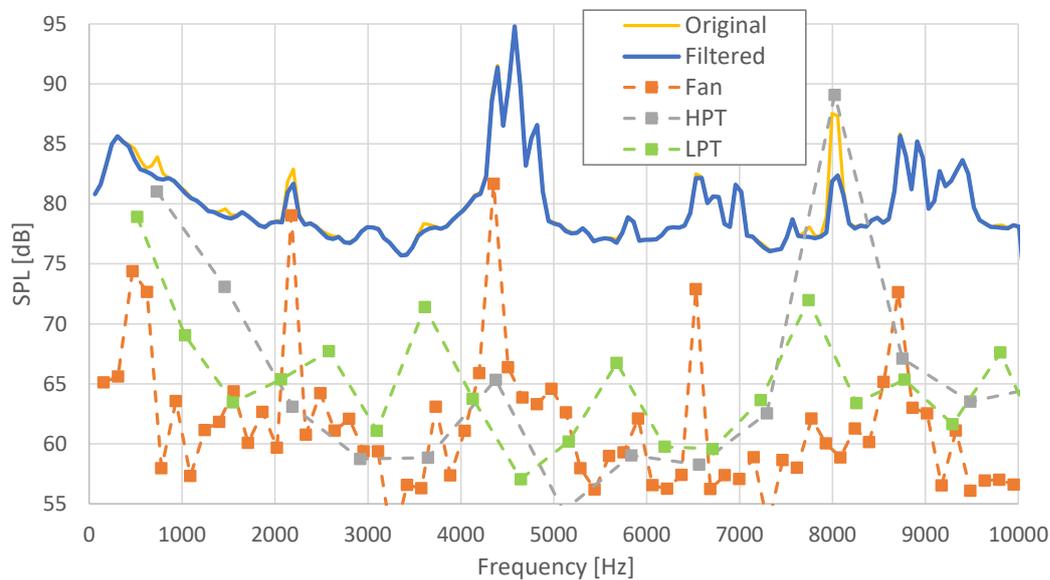


Figure 3 Subtraction of shaft order tones, average array SPL

B. Beamforming

For determining the engine noise source breakdown, the steering vector can be defined by

$$g_{j,m} = \exp\left(-2\pi i f \Delta t \left(\bar{x}_m, \bar{\xi}_j\right)\right), \quad (9)$$

where i is the imaginary unit, f the frequency, \bar{x}_m a microphone position, $\bar{\xi}_j$ a potential point source location (scan point) and Δt the time delay between these points. Eq. (9) does not contain a correction for distance between source and microphone. Therefore, beamforming and integration results must be interpreted as the average array

SPL due to a particular engine noise source. Thus, a direct comparison can be made between beamforming results and the measured average SPL.

The beamforming scan grid is on the engine axis, ranging from 3 m downstream of the intake to 1 m upstream. The grid resolution is 2 cm. The fact that sources are actually off-axis is neglected.

Narrow-band beamforming up to 10 kHz was done with three different methods:

- Conventional Beamforming¹,
- DAMAS¹³, with 20000 iterations,
- CLEAN-SC, with loop gain 0.5.

The respective results are shown in Figure 4 to Figure 6. The vertical dashed lines in the images denote, from left to right, the positions of the core exhaust, the bypass and the intake. The CLEAN-SC image was not blurred with “clean beams”.

The Conventional Beamforming image (Figure 4) is heavily contaminated by aliasing lobes (the curved lines), but the physical sources can be recognized. The DAMAS-images are much cleaner, although aliasing lobes are still present. At low frequencies (< 2 kHz) DAMAS detects the distributed jet noise sources. In the CLEAN-SC image, the aliasing lobes disappeared. Low-frequency jet noise appears as a “cloud” of isolated points. The locations, levels and number of these points depend on the loop gain.

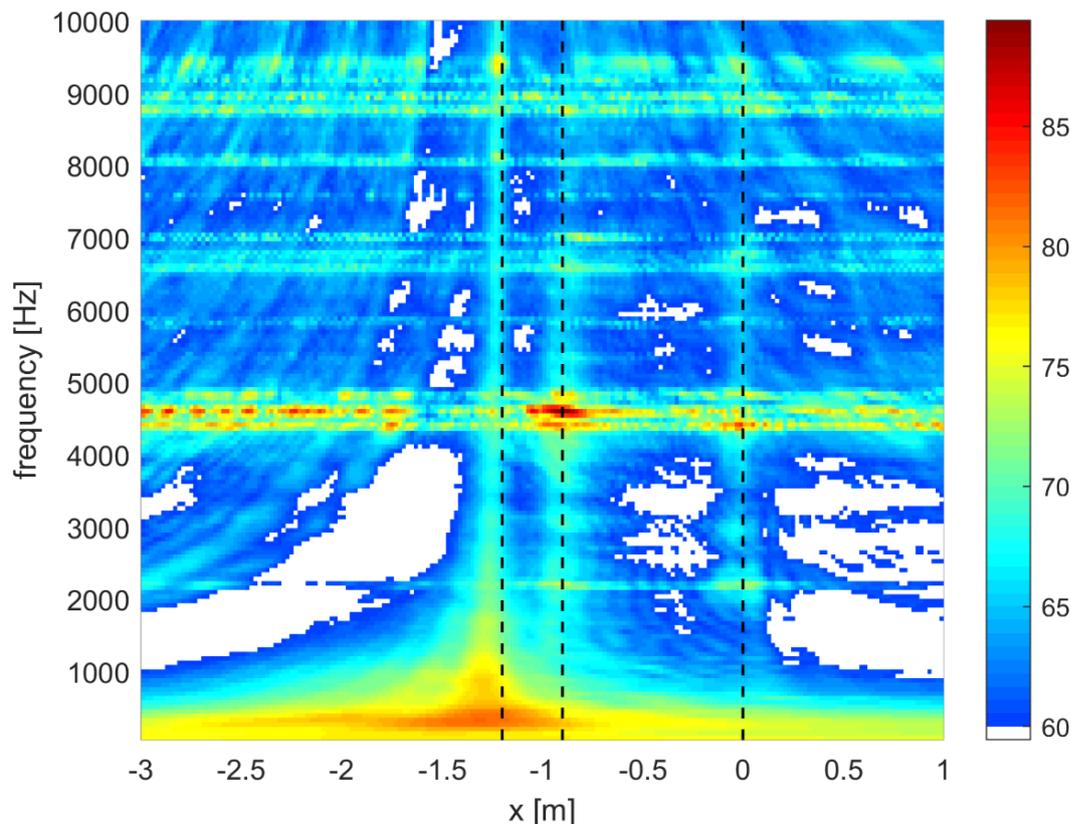


Figure 4 Results of Conventional Beamforming

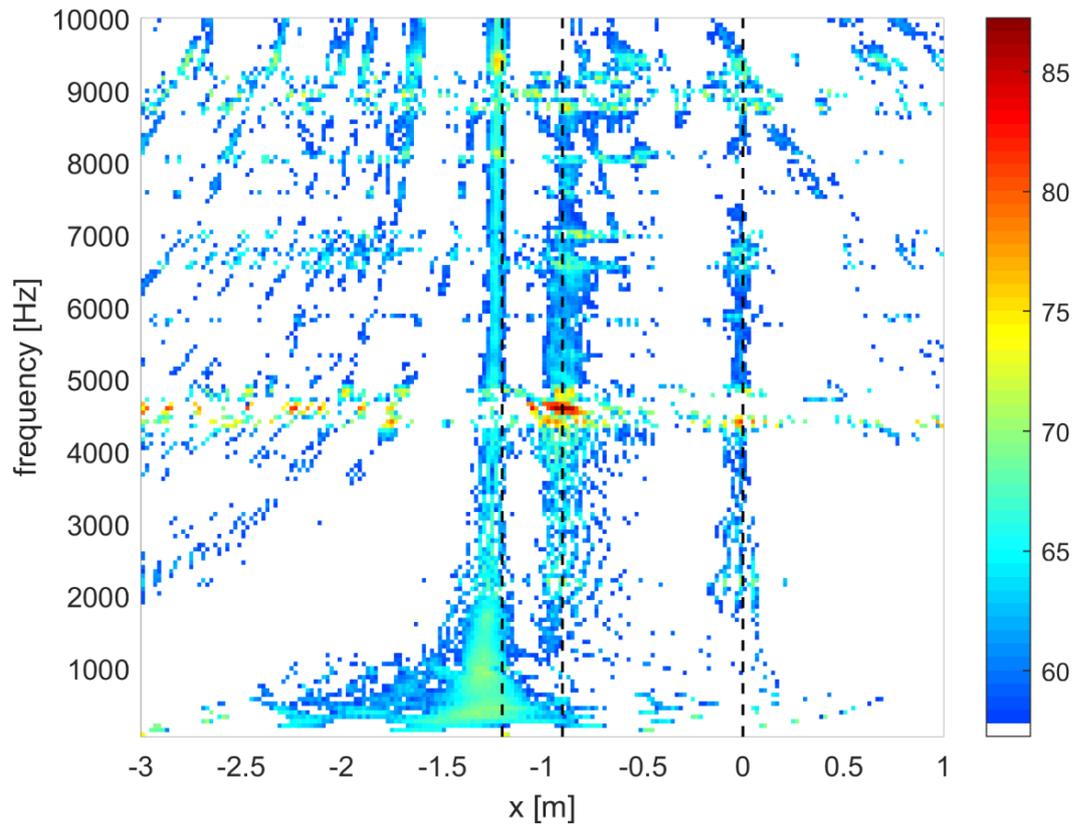


Figure 5 Results of DAMAS beamforming

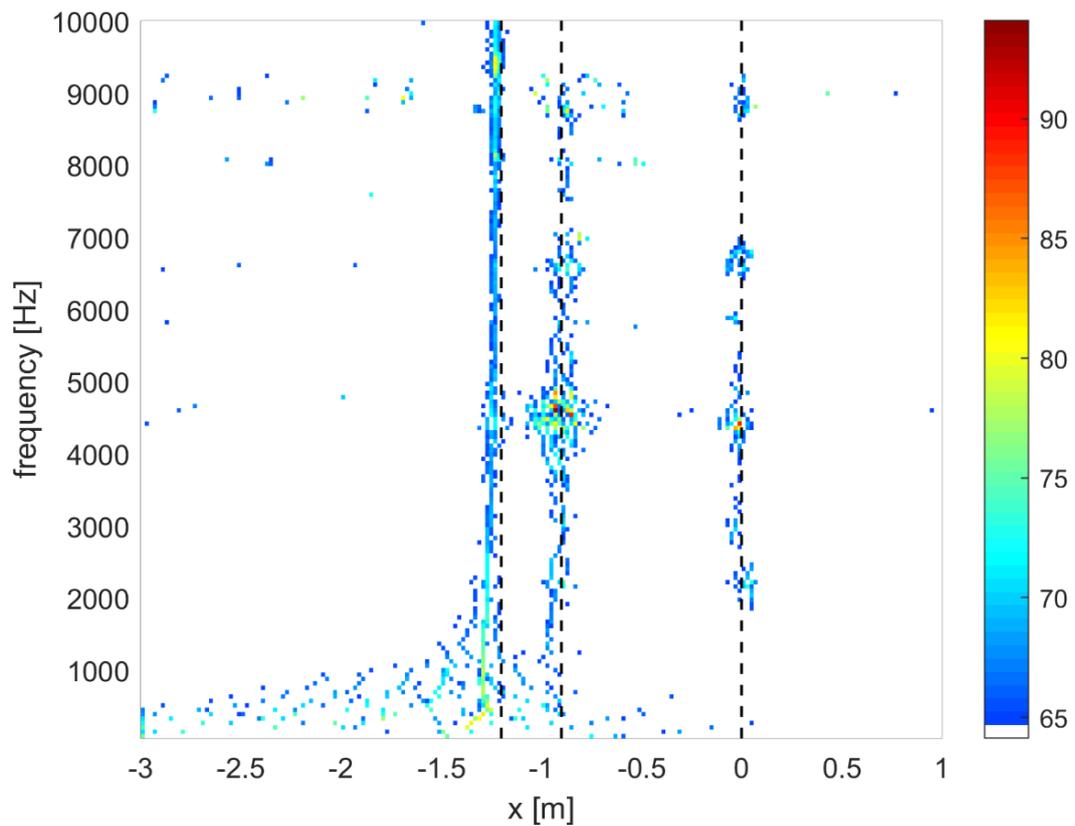


Figure 6 Results of CLEAN-SC beamforming

C. Source power integration

For making a noise source breakdown, source areas were defined as shown in Figure 7. The “aft” area comprises both jet noise and core noise. Source power integration was done with DAMAS and CLEAN-SC. The results are shown in Figure 8. The integrated levels from the “other” areas are small and therefore omitted. The “Summation” results are the summations over all integration areas. The integrated results are compared to the average SPL of the array microphones (filtered for tones).

The following observations are made:

- The CLEAN-SC summation level is almost the same as the average SPL. The solid red line is therefore not visible.
- Below 4 kHz, the DAMAS summation level is a little lower (up to 1.5 dB).
- At most frequencies, the highest integrated levels are found for the aft area.
- The integrated CLEAN-SC levels of the aft area agree well with the DAMAS results, however with the following exceptions:
 - Below 3200 Hz, the DAMAS aft levels are a little lower, which is in line with the summation levels.
 - Between 4300 and 4900 Hz, the DAMAS aft levels are much higher since they include aliasing lobes from intake and bypass sources (see Figure 5).

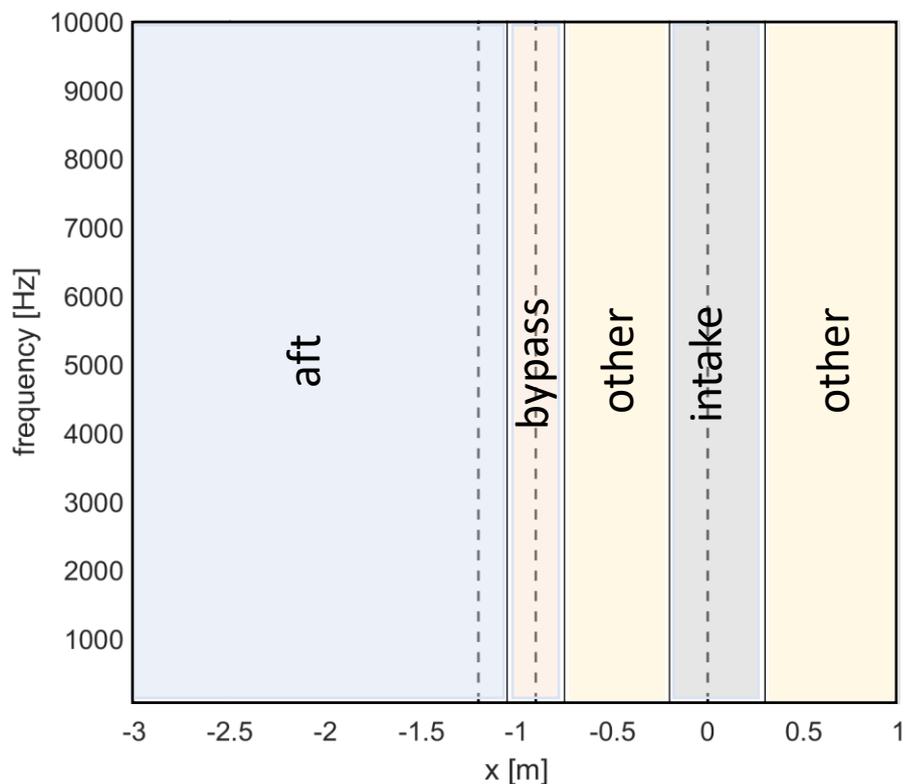


Figure 7 Noise source areas

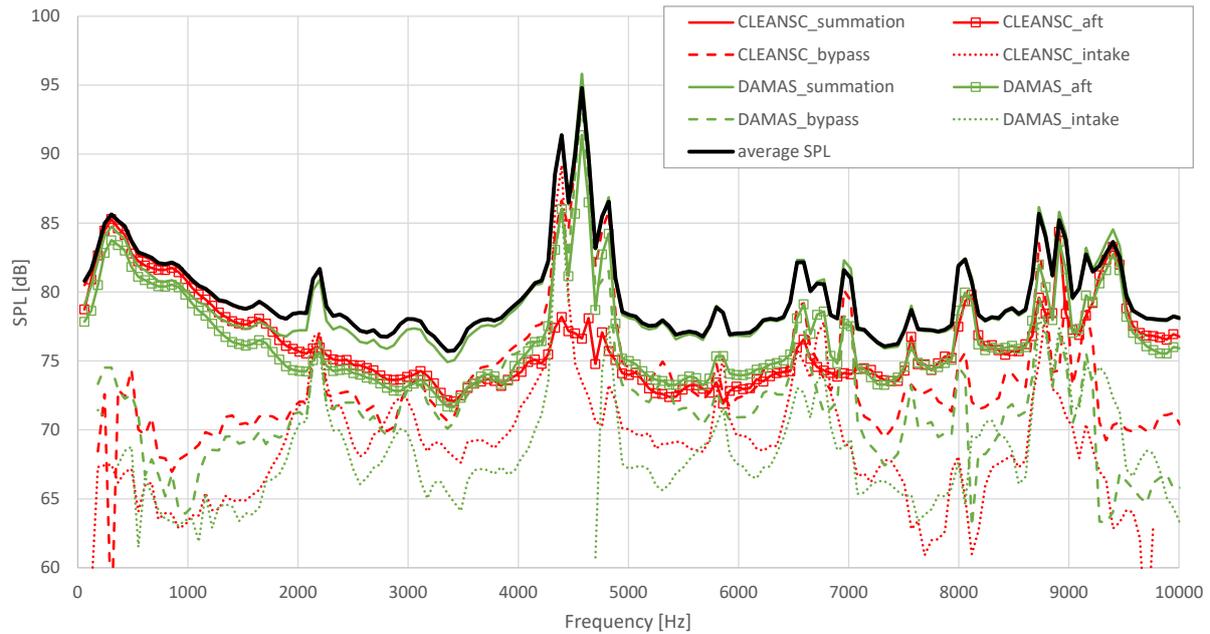


Figure 8 CLEAN-SC and DAMAS noise source area breakdown

D. Directivity

As mentioned in Section II.B, CLEAN-SC should be able to provide the directivities of the noise from the different source areas. This feature gives most added value when levels from several integration areas are comparable. That is, for example, the case for frequencies within the 3150 Hz (1/3 octave) frequency band. The results, summed over the narrow-band frequencies, are shown in Figure 9, together with the microphone levels. The directivity breakdown is in line with expectations.

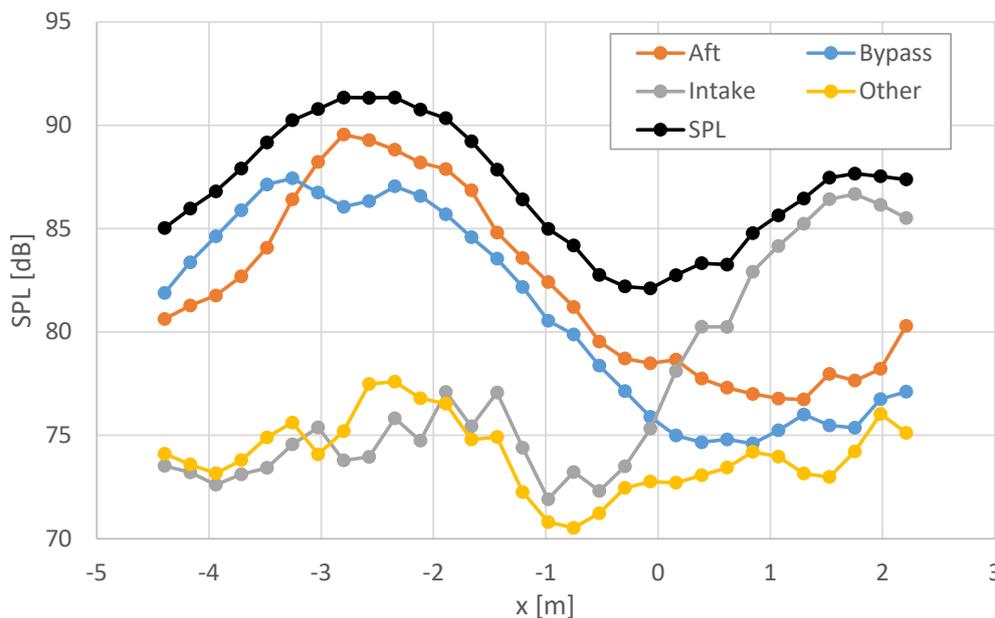


Figure 9 CLEAN-SC directivity breakdown, 3150 Hz (1/3 octave)

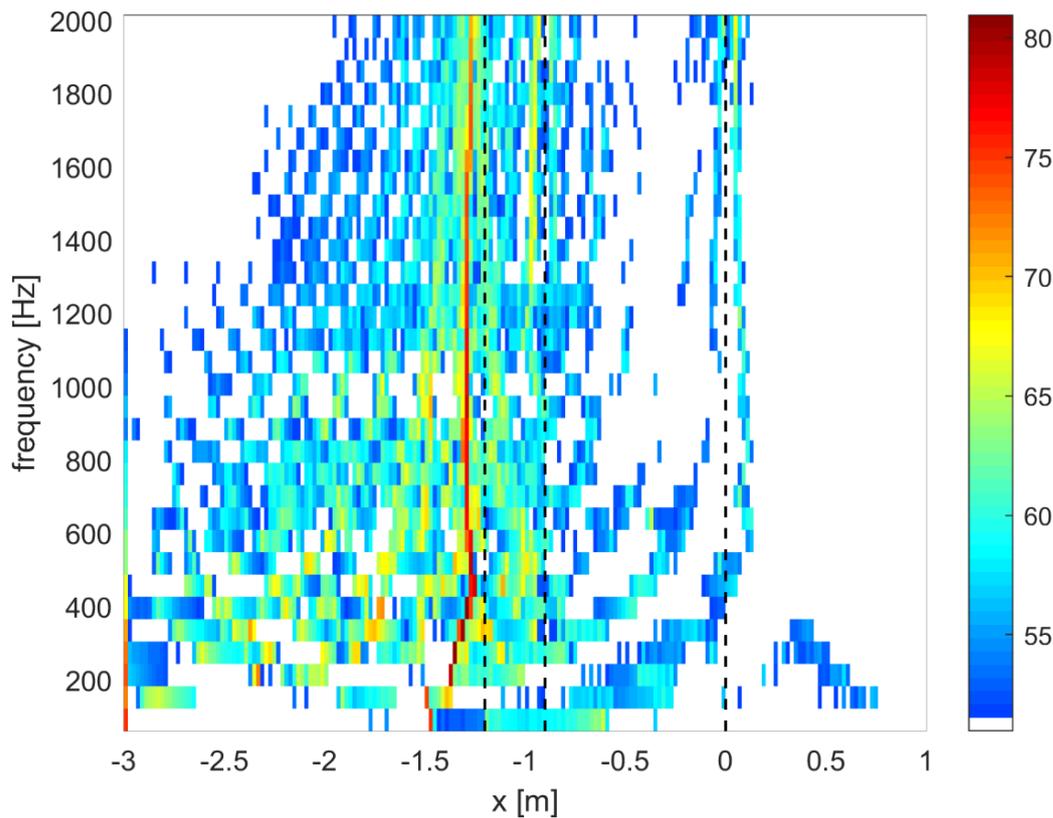


Figure 10 Results of CLEAN-SC beamforming up to 2 kHz with loop gain 0.001

E. Separating jet noise and core noise

A particular challenge is the separation of core noise and jet noise, which co-exist at low frequencies and originate from the same direction. We can exploit an essential difference of the two sources, namely the fact that core noise is localized at the exhaust of the core duct, while jet noise sources are distributed. Using a very small loop gain (and, consequently, many CLEAN-SC iterations), core noise appears as a localized peak amidst of distributed sources. This is illustrated in Figure 10, which was obtained with loop gain $\varphi = 0.001$. A cross-section of Figure 10 at 793 Hz is shown in Figure 11.

Between 600 and 1600 Hz, the peak is located almost at a single scan grid point, $x = -1.3$ m. This single point, together with its two neighbor points, were defined as an extra “core noise” source area, in addition to the areas depicted in Figure 7. Thus, core noise and jet noise were considered separately. For 800 Hz (1/3 octave band) the directivity breakdown is shown in Figure 12.

This figure shows a clear difference between the directivities of jet noise and core noise, which agrees with the model directivities that Tester et al.⁸ used for the same engine. The difference in directivity between core noise and jet noise is confirmed at other frequencies in Figure 13.

Likewise, an update was made of Figure 9, which is shown in Figure 14. At this frequency (3150 Hz), each engine noise source appears to have directivity angles where they prevail.

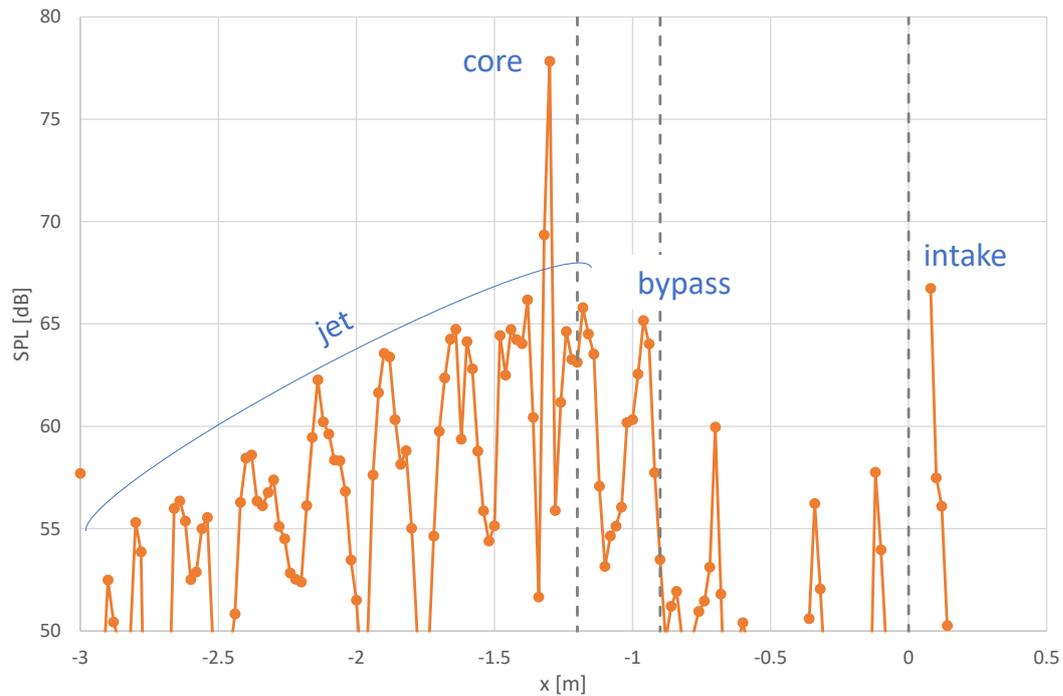


Figure 11 Results of CLEAN-SC beamforming at 793 Hz with loop gain 0.001 (typical cross-section of Figure 10)

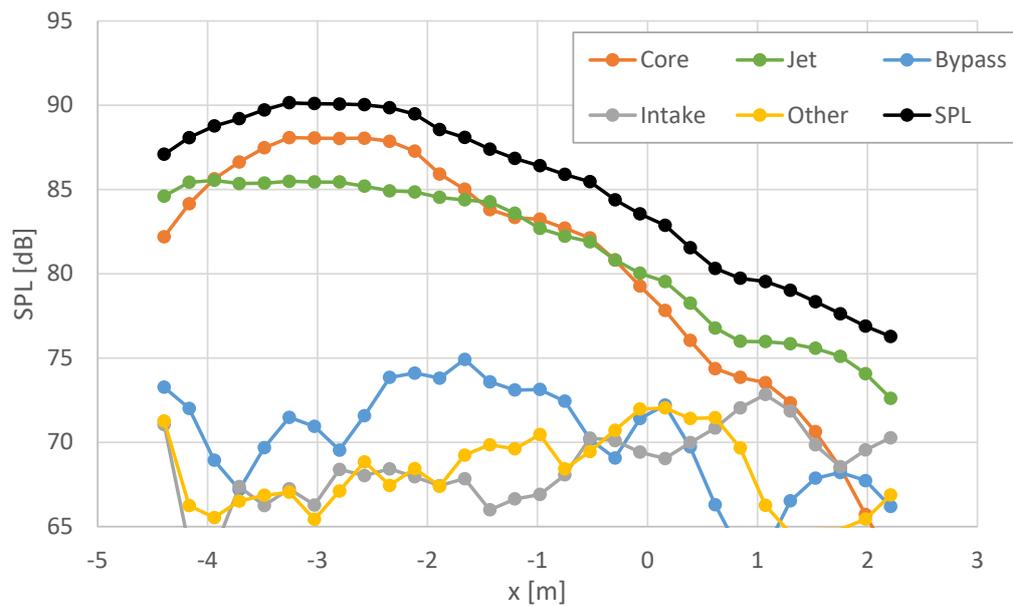


Figure 12 CLEAN-SC directivity breakdown, 800 Hz (1/3 octave)

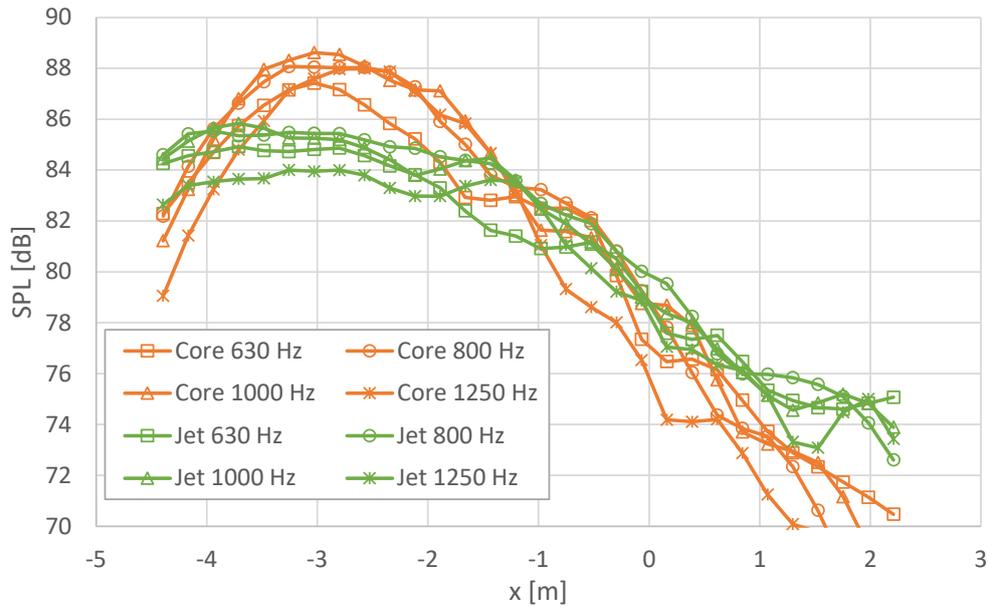


Figure 13 Core and jet noise directivity at several 1/3 octave frequency bands

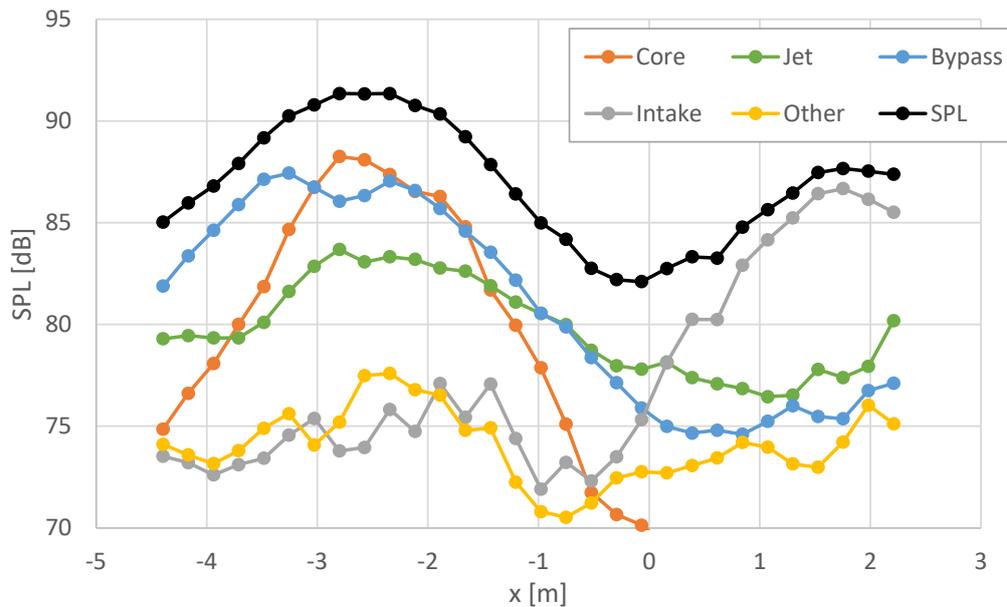


Figure 14 CLEAN-SC updated directivity breakdown, 3150 Hz (1/3 octave)

V. Conclusions

Using far-field measurements with a linear or polar microphone array, CLEAN-SC can make a decomposition of engine broadband noise into contributions from intake, jet, bypass and core. For each of these noise sources, the directivity is retrieved as well. The directivity results are plausible and in line with theoretical models. CLEAN-SC is easy to implement and can therefore be an interesting addition to existing methods like SODIX and AFINDS.

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