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QUANTIFYING THE EFFECT OF AN ACOUSTIC LINER FROM FAR-FIELD MEASUREMENTS IN STATIC ENGINE NOISE TESTS

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ABSTRACT

The evaluation of acoustic treatments of aero-engines in static noise tests requires advanced source localization techniques such as SODIX. The SODIX method is able to resolve the directivity of sound sources by fitting a model of the cross-spectral matrix to measured data from a microphone array. The localization method is now applied to new far-field measurements with a sparsely populated microphone array at a static engine noise test. The effect of an intake liner on the sound radiation from the intake and on the overall far-field levels is investigated by comparing different engine configurations with and without acoustic treatment. The localization results show that SODIX is able to quantify the impact of the intake liner from far-field measurements, even when the sound pressure level in the far-field is dominated by the contribution of other sources. In addition, the overall sound pressure levels calculated with SODIX agree well with the measured levels in the far-field. This shows that the application of the source localization method SODIX to a sparse far-field array in static engine noise tests is feasible.

1. INTRODUCTION

SODIX (*SOurce DIrectivity modeling in cross-spectral matriX*) is an acoustic source localization method that is able to determine the amplitudes and the directivities of sound sources. This feature is particularly useful for the investigation of the directional sound radiation from aero-engines in static noise tests.

The method has previously been applied to full-scale engine noise tests using densely populated microphone arrays with up to 250 microphones near the engine [1–3]. Recently, SODIX has also been applied to a sparse microphone array in the far-field with only 31 microphones [4]. Such a far-field arrangement promises benefits in terms of both, reduced computational time and complexity of the experimental setup. It has been shown that the source localization results with the far-field array are similar to those of a large microphone array despite spurious sound sources that occur due to the low spatial sampling of the microphones in the far-field array.

The SODIX method is now applied to new measurements with a similar far-field array at a static noise test of a short-cowl engine. The impact of an intake liner on the sound radiation from the intake and on the overall far-field levels is studied by comparing two engine configurations with and without acoustic treatment.

2. METHODOLOGY

The source localization method SODIX has been developed by Michel and Funke [1, 2] as an extension of the *Spectral Estimation Method* (SEM) by Blacodon and Élias [5, 6]. SODIX fits a model of the cross-spectral matrix to measured data from a microphone array. The model of the cross-spectral matrix consists of incoherent point sources D_{jm} with individual source amplitudes from all sources $j = 1, \ldots, J$ on a source grid to all microphones $m = 1, \ldots, M$ of the array:

$$C_{mn}^{\text{mod}} = \sum_{j=1}^{J} g_{jm} D_{jm} D_{jn} g_{jn}^{*} \ . \tag{1}$$

In Eqn. (1), g_{jm} is the steering vector that describes the sound propagation from the source j to the microphone m. Throughout this paper, free-field propagation is assumed with

$$g_{jm} = \frac{1}{r_{jm}} e^{-ikr_{jm}} \ , \tag{2}$$

where r_{jm} is the distance from the source j to the microphone m, and k is the wave number. The directive source amplitudes D_{jm} are determined by a least-squares fit between the measured and the modelled cross-spectral matrix:

$$F(D) = \sum_{m,n=1}^{M} \left| C_{mn} - C_{mn}^{\text{mod}}(D) \right|^2 + \sigma R(D) \ . \tag{3}$$

This optimization problem for the unknown source amplitudes D is solved by an iterative minimization procedure based on conjugate gradients, see also [7]. Eqn. (3) includes an additional regularization scheme R that can help to find stable solutions for ill-posed problems, i.e. the number of unknown source amplitudes is much higher than the number of known, independent entries in the measured cross-spectral matrix. The parameter σ is a weighting factor that controls the regularization against the raw fit of the cross-spectral matrix. The regularization used in SODIX is physically motivated and relies on the local smoothness of the source directivities, which is a good assumption for

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broadband noise sources of aero-engines in static noise tests. The regularization scheme sets a constraint on the amplitude changes from a single source to neighbouring microphones:

$$R(D) = \sum_{j=1}^{J} \sum_{m=1}^{M} \sum_{l=1}^{L(m)} \alpha_l \left(D_{jm} - D_{j,\Lambda(l)} \right)^2 \ , \qquad (4)$$

where the parameter L sets the number of microphones that are taken into account in the smoothing of the source directivities and α is a correction of the directivities with the corresponding distances from a source to different microphones, see also [3].

The application of other regularization strategies such as ℓ_1 and ℓ_2 schemes that are commonly used in the source localization community has been studied currently [8]. It has been shown that these regularization techniques can reduce the impact of noise on the source localization with SODIX.

3. EXPERIMENTAL SETUP AND DATA PROCESSING

Fig. 1 shows the microphone setup used for far-field measurements in a static engine noise test. The microphone array is sparsely populated and consists of only 31 microphones that are arranged in a polar arc at a distance of 150 ft (45.72 m) from the engine. The far-field array provides a polar resolution of 5° between 10° (forward arc) and 160° (rearward arc) relative to the flight direction. Such a microphone setup in the far-field is commonly used for certification purposes of aero-engines, see [9]. The engine was mounted with the centerline approximately 6 m above the ground plane.

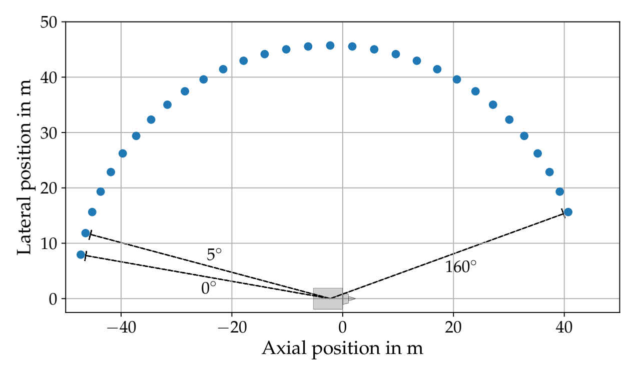


Figure 1: Experimental setup with a far-field array at a static engine noise test. The far-field array consists of 31 microphones on a 150 ft arc with a polar resolution of 5°. The engine is not to scale.

In the data pre-processing, cross-spectral matrices with a frequency resolution of 4 Hz were calculated on the basis of calibrated time signals. Tones were removed from all auto-power and cross-power spectra before applying the source localization method SODIX. For the tonal removal, the spectra were convolved with a Gaussian function that removed strong peaks from the spectra. An interpolation of the phase and the magnitude was performed for the removed frequency lines from neighbouring frequencies in order to recover the broadband noise at those frequencies. However, the SODIX method might only yield limited results for these few frequencies due to the interpolation of the phase spectra.

The SODIX method was then used to calculate equivalent source amplitudes for a distribution of sources along the engine axis in the direction of every array microphone. Fig. 2 shows the source grid for different one-third octave bands. A linear source grid on the engine axis with constant spatial resolution was used. The grid is constructed in such a way that there is one source located exactly at the position of the inlet, the bypass, and the core nozzle exit, respectively. These positions are indicated by the vertical blue lines in Fig. 2. The spacing of the sources is adapted to the wavelength by using a different set of source positions in every one-third octave band such that the source grid has a spatial resolution of at least four sources per wavelength. For low frequencies under 200 Hz, the spatial resolution was increased so that there is at least one source between bypass and core nozzle exit. The source number increases from 69 sources in the lowest one-third octave band to 352 sources in the highest one-third octave band of 2 kHz.

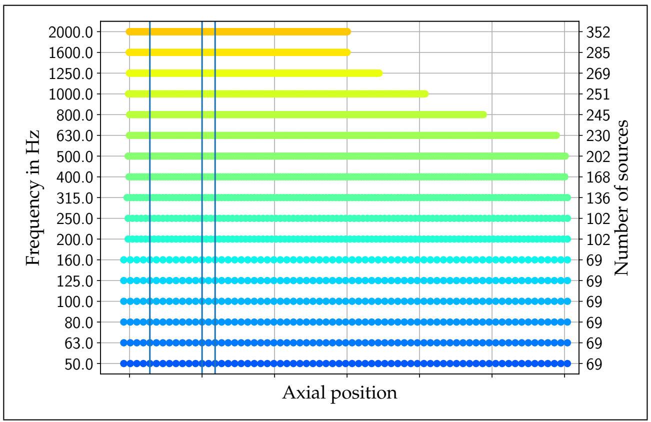


Figure 2: Source grid on the engine axis that is used for the source localization with SODIX. The source positions are adapted to the engine geometry, the frequency, and the expected source distributions as e.g. the jet. The source separation is approximately one quarter of the corresponding wavelength.

The source localization with SODIX was performed individually for every narrow-band frequency up to the one-third octave band of 2 kHz. In the post-processing of the SODIX method, a geometrical source breakdown was applied to the localization results that separates the source contributions from the intake, the nozzle, the bypass, and the jet. The source breakdown also accounts for parallax effects that can occur because the actual sources radiate off-axis at radial positions different from the engine centerline. The separated source spectra were extrapolated to reference positions in the far-field including corrections of the atmospheric attenuation.

4. RESULTS

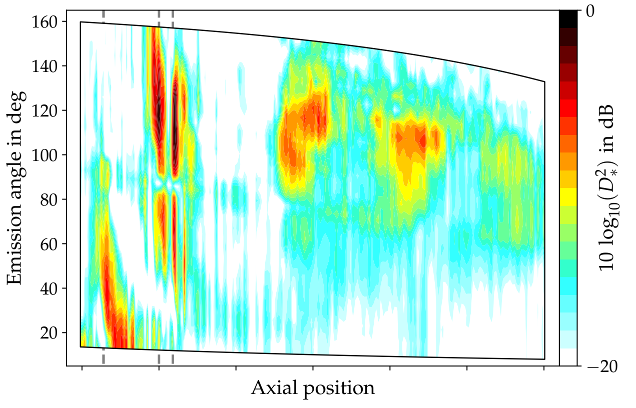
4.1 Source localization results

Fig. 3 and 4 compare the source localization results of the far-field array for both engine configurations with and without intake liner, respectively for two different one-third octave bands. These source maps show the directive source amplitudes derived with SODIX over the axial source position on the horizontal axis and over the local emission angle on the vertical axis. The emission angle is defined as the angle between the engine axis and the connecting line from a source point to a microphone. Flight coordinates are used so that an emission angle of $0°$ stands for radiation in the direction of flight and $180°$ to the rear into the jet. The gray dashed lines mark the axial positions of the intake, the bypass exit, and the core nozzle exit from left to right. The narrow-band results are integrated in standard one-third octave bands for better visualization. All source maps have a dynamic range of $20\,\mathrm{dB}$ that is scaled to the same maximum source amplitude.

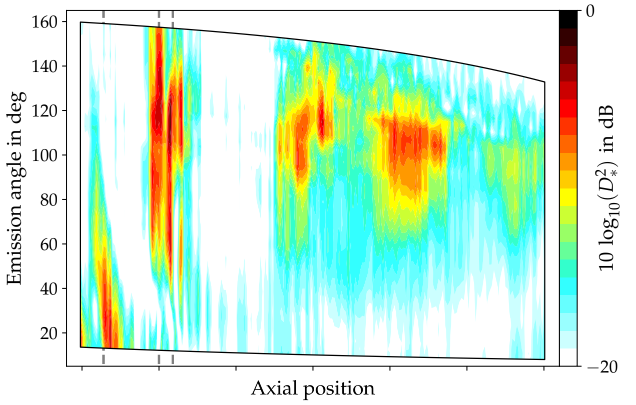
The localization results show that SODIX can be applied to data from a sparse far-field array with good results. Sound sources at the position of the intake, the bypass, and the core are well localized and the source solution has a dynamic range that is more than $20\,\mathrm{dB}$. The sources at the relatively large intake and bypass are distributed around their true axial positions due to a parallax effect that occurs for the one-dimensional source grid. The actual sources at intake and bypass radiate at radial positions different from the engine centerline which causes an axial shift of these sources for observer angles other than $90°$.

One particularity is the appearance of spurious sound sources in the downstream area of the source maps. These secondary sources cannot be related to actual noise sources and have already been observed for a different application of SODIX to a similar far-field array, see [4]. The spurious sources are known to occur due to the low spatial sampling of the microphone array for higher frequencies, e.g. the microphone separation in the far-field array is $4\,\mathrm{m}$, whereas the average wavelength in the $400\,\mathrm{Hz}$ one-third octave band is less than $1\,\mathrm{m}$. The secondary sound sources depend on the length of the source grid and on the actual source distributions.

The balance of the individual source areas in the two frequencies bands can also be compared with Fig. 3 and 4. In the mid one-third octave band, strong sources that even radiate into the forward arc are localized at the bypass and the core position. The contribution of these sources is smaller for the higher frequency band and the sound radiation from the intake dominates in the forward arc.

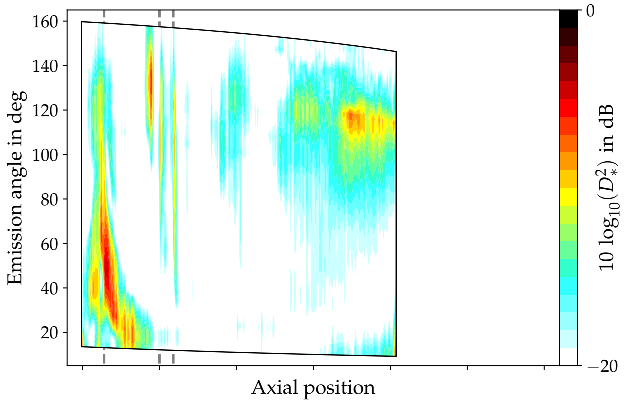


(a) Engine configuration without intake liner

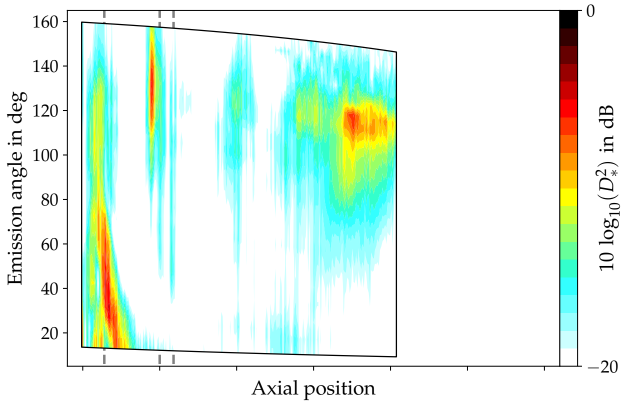


(b) Engine configuration with intake liner

Figure 3: Source localization results for two engine configurations without (top) and with intake liner (bottom) in a mid one-third octave band.



(a) Engine configuration without intake liner



(b) Engine configuration with intake liner

Figure 4: Source localization results for two engine configurations without (top) and with intake liner (bottom) in a high one-third octave band.

4.2 Far-field extrapolation

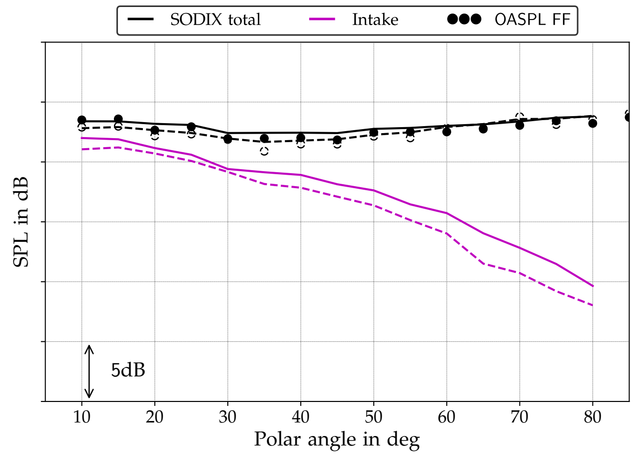
A direct comparison of both engine configurations can be achieved by the extrapolation of the SODIX results to the far-field. Fig. 5 shows such a far-field extrapolation of the sources radiating from the intake (purple line) for both engine configurations without (solid) and with intake liner (dashed). The spectra were derived from a geometrical source breakdown that was applied on the source localization results from Fig. 3 and 4. In addition, the overall sound pressure level calculated with SODIX (black line) can be compared to the measured far-field levels (black circles).

The extrapolated spectra show that the liner reduces the broadband noise radiated from the intake. In both one-third octave bands, a reduction of the sound pressure level by 1 dB to 2 dB is visible. The SODIX method is able to determine the noise reduction due to the acoustic treatment, even when the overall sound pressure levels (black circles) are dominated by other source areas, as shown for the mid frequency band at high polar angles. In this case, the contribution of bypass and core to the sound radiation into the forward arc is relatively high. For the higher one-third octave band, the positive effect of the intake liner is mainly visible for polar angles larger than 30°. In general, the overall sound pressure levels calculated with SODIX (black lines) agree very well with the measured data in the far-field (black circles). These results show that the application of SODIX to data from a sparse far-field array in static engine noise tests is feasible.

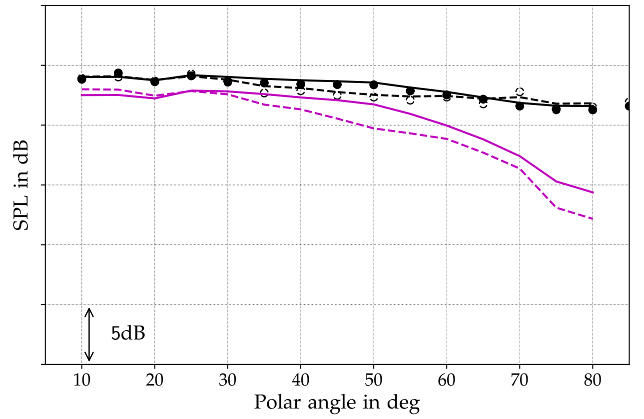
4.3 Computational performance

Fig. 6 shows the computational performance of the source localization with SODIX for the sparse far-field array. The top figure shows the value of the cost function before (solid line) and after the minimization process (dotted line) and the bottom figure shows the mean error between measured and modelled auto-power spectra.

The value of the cost function is reduced within the optimization between one and two orders of magnitude which is in the expected range. The reduction of the cost function is decreasing for higher frequencies due to the low spatial

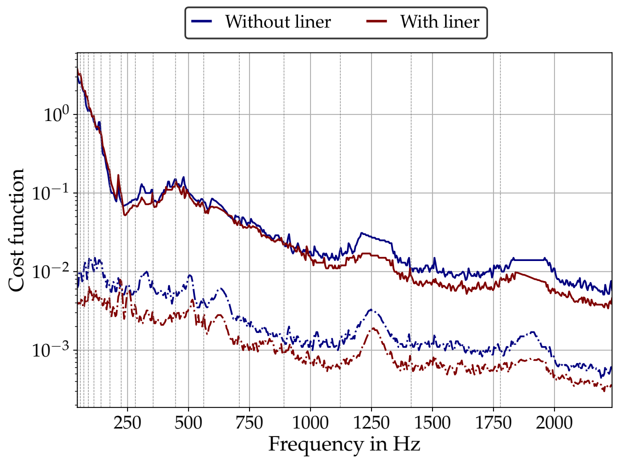


(a) Spectra for a mid one-third octave band

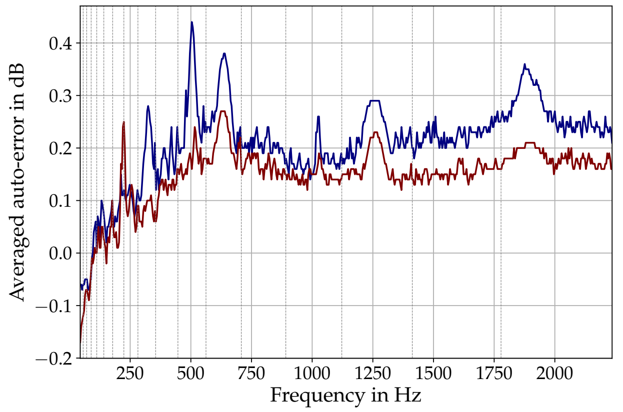


(b) Spectra for a high one-third octave band

Figure 5: Extrapolated far-field spectra for the sources radiating from the intake (purple line) and the overall SODIX spectra (black line) for two engine configurations without (solid) and with intake liner (dashed). The measured levels in the far-field are indicated by black circles.



(a) Cost function before and after minimization



(b) Error in fitting the cross-spectral matrix

Figure 6: Computational performance of the source localization with SODIX for the sparse far-field array. The reduction of the cost function during the minimization procedure and the error in the modelled auto-power spectra are within the expected range.

sampling in the far-field array. The error in the modelled auto-power spectra is less than $0.3\,\mathrm{dB}$ for a wide frequency range. This coincides with the good agreement of the total SODIX spectra and the measured far-field levels from Fig. 5. The computational error increases for higher frequencies because of the spurious, secondary sources. The computation of the SODIX results (without pre- and post-processing) for 550 frequencies up to $2\,\mathrm{kHz}$ took approximately five minutes on a standard PC.

5. CONCLUSIONS

The source localization method SODIX has been applied to new far-field measurements in a static engine noise test. The localization results have shown that the method is able to detect the sound sources at their expected positions and to resolve their individual directivity. However, spurious sound sources in the downstream area appear in the source maps due to the low spatial sampling of the sound field by the reduced number of microphones in the far-field array. The SODIX method was used to quantify the effect of an intake liner on the radiated sound field in the forward arc by comparing two engine configurations with and without acoustic treatment. It has been shown that SODIX is able to quantify the noise reduction due to the liner in a full-scale engine test, even when the overall sound pressure levels are dominated by other sources so that the contribution of the sources radiating from the intake is relatively low. The results confirm previous findings that the application of SODIX to a sparse far-field array is in general feasible.

6. ACKNOWLEDGMENTS

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