Use of a Model for Coherence Loss in the Context of Aircraft Fly-Over Measurements

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Introduction

Microphone arrays have been used extensively to measure aeroacoustic sources of aircraft in flight. The localization ability of microphone arrays allows a separation of the contribution of different components, i.e. the fuselage, engines and landing gear.

Fly-over measurements, which are typically done in the open, are subject to the meteorological conditions at the time they are conducted. For reproducible results, the encountered conditions must be considered when evaluating the measured data. The atmospheric turbulence and its causes have so far not been included in the algorithms evaluating microphone array measurements. The turbulence is responsible for the loss of coherence between microphones, which can have a significant impact on the quality of the results. Due to its random nature, it cannot be measured directly, and a model for is required.

This publication aims to present a possibility to include such a model of coherence loss in the source localization algorithms used by the DLR department for engine acoustics for fly-over measurements. The objective is to reduce the reproducibility across measurements under difference environmental conditions.

Methods

Model for Coherence Loss

In [1], Lincke et al. used an analytical model for coherence loss in the atmosphere to synthesize microphone array data. It is based on and extends works by Ostashev, Wilson, Kamrath et al. [2, 3, 4] and models the coherence loss due to variances of temperature σ_T^2, shear-produced wind velocity fluctuations $\sigma_{v,s}^2$ and buoyancy-produced wind velocity fluctuations $\sigma_{v,b}^2$, as well as their respective length scale of turbulences $L_T(z)$, $L_{v,s}(z)$ and $L_{v,b}(z)$.

As those quantities are not directly available they are parametrized based on the friction velocity u_*, surface heat flux Q_H and boundary layer height z_i.

To acquire a coherence factor $\lambda_{mn} \in [0, 1]$ between microphones m and n, their distance r_d, the height of the source h as well as a propagation angle θ is required. Together with the wave number k this results in λ being the function

$$\lambda(r_d, \theta, h; k; Q_H, u_*, z_i)$$

with the input parameters:

r_d	microphone distance
θ	source emission angle
h	source height
k	acoustical wave number
Q_H	surface heat flux
u_*	friction velocity
z_i	boundary layer height

Source Localization for Flyover Measurements

To evaluate the microphone array measurements of flyovers, the DLR department of engine acoustics uses the hybrid approach described by Guérin and Weckmüller [6, 7]. It consists of a conventional delay-and-sum beamforming (CTDBF) step which is, due to the motion of the sources, done in the time-domain. It is followed by a deconvolution step in the frequency domain similar to DAMAS to increase the spatial resolution and improve the source localization results.

DAMAS with Modified Point Spread Function

The Deconvolution Approach for the Mapping of Acoustic Sources (DAMAS) uses a model for the array response to a virtual unitary point source to find the source distribution that best reconstructs the delay-and-sum beamforming results [5]. This array response is called the point spread function (PSF). If expressed in the frequency domain it can be derived by the formulation for conventional beamforming

$$Y^{BF}(\vec{x}_f, \omega) = \mathbf{h}_f^H \mathbf{C} \mathbf{h}_f \quad ,$$

for a focus point $\vec{x}_f \in \mathbb{R}^3$. Here $\mathbf{C} \in \mathbb{C}^{M \times M}$ is the measured cross spectral matrix (CSM), $\mathbf{h}_j = (h_{j1}, h_{j2}, \ldots h_{jM})^T \in \mathbb{C}^M$ is called steering vector.

Different definitions of the steering vector are available in the literature [8]. Here, it is defined as $h_{jm} = w_m r_{jm} e^{-ikr_{jm}}$, which matches the transformed steering vectors of time-domain beamforming. w_m is a factor applied to the microphones signal called shading factor. It is used to adapt the array properties and allow the use of a single array for a broad frequency range. In this formulation the shading factors are expected to be normalized: $\sum_m^M w_m = 1$.

To derive the point spread function, the measured CSM is replaced with a modelled CSM, based on a (virtual) point source with unitary strength at position $\vec{x}_s$. Without coherence loss due to propagation, this can be expressed

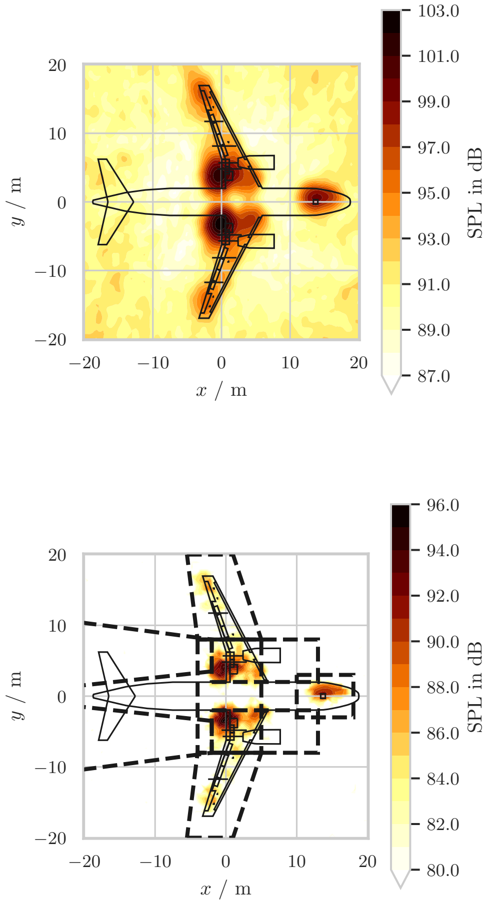

Figure 1: The evaluation of fly-over microphone array data consists of a conventional delay-and-sum beamforming step in the time domain (top). Additionally, a deconvolution step in the frequency domain can be applied, and source regions integrated (bottom).

by $\mathbf{C}_s^{\mathrm{mod}} = \mathbf{g}_s \mathbf{g}_s^H$, where $\mathbf{g}_s = (g_{s1}, g_{s2}, \dots g_{sM})^T \in \mathbb{C}^M$ contains the Greens Function, with $g_{jm} = \frac{1}{r_{jm}} e^{-ikr_{jm}}$.

This results in the definition as used in DAMAS [5]

$$
\begin{aligned}
A_{fs} &= \mathbf{h}_f^H \mathbf{C}_s^{\mathrm{coh}} \mathbf{h}_f = \mathbf{h}_f^H \mathbf{g}_s \mathbf{g}_s^H \mathbf{h}_f = \left| \mathbf{h}_f^H \mathbf{g}_s \right|^2 \\
&= \left| \sum_m^M h_{fm}^* g_{sm} \right|^2 = \left| \sum_m^M w_m \frac{r_{fm}}{r_{sm}} e^{ik(r_{fm} - r_{sm})} \right|^2
\end{aligned}
$$

Note that this PSF-definition yields $A_{fs} = 1$ when the focus equals the modelled source location $\vec{x}_s = \vec{x}_f$, e.g. the amplitude of a point source at $\vec{x}_s$ gets correctly reconstructed.

For a PSF to consider coherent loss, it must be included in the modelled CSM. By multiplying each element of the unattenuated CSM with the corresponding coherence factor γ_{mn} for the coherence between microphone m and n, such a CSM can be defined as $\tilde{\mathbf{C}}_s^{\mathrm{mod}} = \mathbf{\Gamma} \circ \mathbf{C}_s^{\mathrm{mod}}$, where $(\cdot \circ \cdot)$ is the elementwise matrix multiplication (Hadamard product). The PSF then becomes this adapted PSF

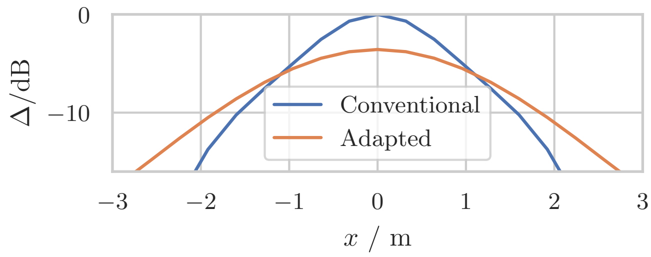

Figure 2: The conventional and the adapted point spread function as used for Record 110, cut along the x-axis. Including the modelled coherence loss lowers the reconstructed amplitude and increases the beamwidth.

$$
\begin{aligned}
\tilde{A}_{fs} &= \mathbf{h}_f^H \tilde{\mathbf{C}}_s^{\mathrm{mod}} \mathbf{h}_f = \mathbf{h}_f^H (\mathbf{\Gamma} \circ \mathbf{g}_s \mathbf{g}_s^H) \mathbf{h}_f \\
&= \sum_m^M \sum_n^M h_{fm}^* w_m g_{sm} \gamma_{mn} g_{sn}^* w_n h_{fn} \quad .
\end{aligned}
$$

Note that for the case of $\vec{x}_s = \vec{x}_f$ this results in $\sum_m^M \sum_n^M w_m \gamma_{mn} w_n < 1$. This shows that a microphone array measurement with coherence loss is expected to underestimate the true source levels (see also figure).

Results

The deconvolution scheme was applied to data acquired in 2019 for the LNATRA project. The measured aircraft is an Airbus 320. The configuration presented here is a approach with the landing gear down (see fig. 3). Seven runs were recorded in total, at three different time windows. The environmental data is taken from the ERA5 Database [9] as shown in table 1 and based on measurements and meteorological models. It significantly differs between the time windows. While the reproducibility was good, some scattering was registered in the levels of the deconvolution results.

Rec.	$\lvert\vec{v}\rvert/\mathrm{m\,s^{-1}}$	h_0/m	$T/{}^\circ\mathrm{C}$	$\lvert\vec{u}\rvert/\mathrm{m\,s^{-1}}$
63	82.72	109.88	15.60	4.70
64	83.91	116.30	15.70	3.70
65	84.02	134.35	15.20	5.20
110	86.06	121.57	25.10	4.80
111	86.55	121.73	24.90	3.90
136	85.41	91.85	22.40	1.70
137	88.37	133.48	22.10	0.90

Table 1: The environmental conditions of the evaluated recordings as required by the model for coherence loss as provided by the ERA5 Database[9].

In figure 3 the results of the deconvolution using the conventional definition are compared to the results using the adapted formulation of the PSF. The source regions are reconstructed at the same locations. The calculated levels are however higher when the adapted PSF is used. This is to be expected, since more source power is needed

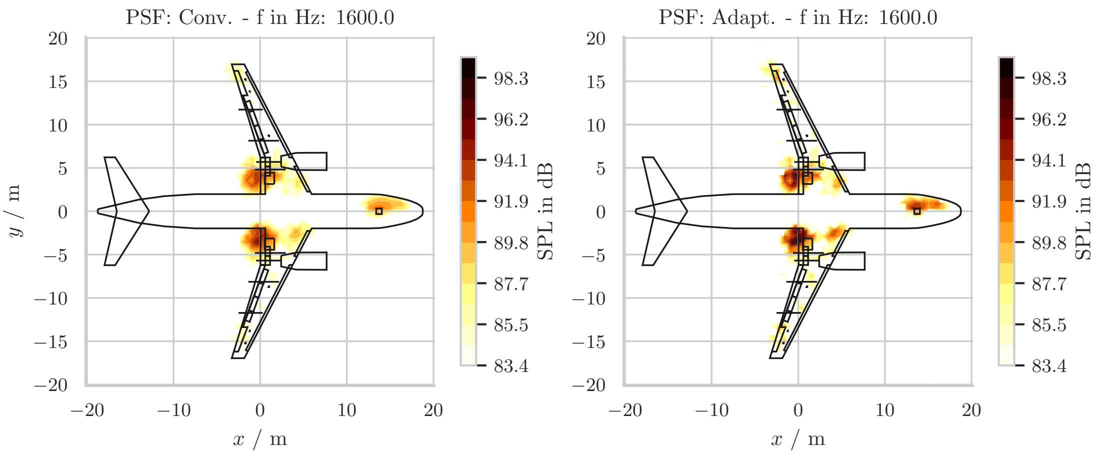

Figure 3: Deconvolution results for record 110 using the conventional point spread function (left) and the adapted point spread function (right). The sources are detected at the same locations: The nose and main landing gear. The calculated levels are increased however when using the adapted PSF.

to yield the same map of the conventional beamforming results.

These elevated levels can also be observed when the total power of the sources on the aircraft are compared (fig. 4). For this, the source strength of all sources which fall on or close to the aircraft are added. The considered region is illustrated in fig. 1.

Conclusion

In this contribution a new formulation for the point spread function was presented. It is based on the conventional definition of the PSF but altered to consider coherence loss. This allows the integration of a model for coherence loss due to atmospheric turbulence directly in the deconvolution step.

Using this new model, the levels of the deconvolution results were increased. The variance between the records and especially between the observed time windows could not be improved, hinting at it being caused by different underlying causes.

Further research is required, using a source with known noise levels to show if the increased source levels are a more accurate representation of the true source levels.

References

[1] D. Lincke, T. Schumacher, and R. Pieren, "Synthesizing coherence loss by atmospheric turbulence in virtual microphone array signals," The Journal of the Acoustical Society of America, vol. 153, pp. 456–466, 2023, doi: 10.1121/10.0016847.

[2] V. E. Ostashev and D. K. Wilson, "Acoustics in moving inhomogeneous media." CRC Press, Taylor and Francis Group, Boca Raton, 2016.

[3] V. E. Ostashev, M. J. Kamrath, D. K. Wilson, M. J. White, C. R. Hart, and A. Finn, "Vertical and slanted sound propagation in the near-ground atmosphere: Coherence and distributions," The Journal of the Acoustical Society of America, vol. 150, no. 4. pp. 3109–3126, Oct. 01, 2021. doi: 10.1121/10.0006737.

[4] M. J. Kamrath, V. E. Ostashev, D. K. Wilson, M. J. White, C. R. Hart, and A. Finn, "Vertical and slanted sound propagation in the near-ground atmosphere: Amplitude and phase fluctuations," The Journal of the Acoustical Society of America, vol. 149, no. 3, pp. 2055–2071, Mar. 2021, doi: 10.1121/10.0003820.

[5] T. F. Brooks and W. M. Humphreys, "A Deconvolution Approach for the Mapping of Acoustic Sources (damas) Determined from Phased Microphone Arrays," Journal of Sound and Vibration, vol. 294, no. 4–5, pp. 856–879, 2006, doi: 10.1016/j.jsv.2005.12.046.

[6] S. Guérin, C. Weckmüller, and U. Michel, "Beamforming and deconvolution for aerodynamic sound sources in motion," in 1st Berlin Beamforming Conference, 21-22 November, 2006, Berlin, 2006. doi: stefan.

[7] S. Guérin and C. Weckmüller, "Frequency-domain reconstruction of the point-spread function for moving sources," in 2nd Berlin Beamforming Conference, 19-20 February, 2008, Berlin, 2008. doi: stefan.

[8] E. Sarradj, "Three-Dimensional Acoustic Source Mapping with Different Beamforming Steering Vector Formulations," Advances in Acoustics and Vibration, vol. 2012, pp. 1–12, Jun. 2012, doi: 10.1155/2012/292695.

[9] Hersbach, H., Bell, B., Berrisford, P., Biavati, G., Horányi, A., Muñoz Sabater, J., Nicolas, J., Peubey, C., Radu, R., Rozum, I., Schepers, D., Simmons, A., Soci, C., Dee, D., Thépaut, J-N. "ERA5 hourly data on single levels from 1940 to present", Copernicus Climate Change Service (C3S) Climate Data Store (CDS), 2023 DOI: 10.24381/cds.adbb2d47

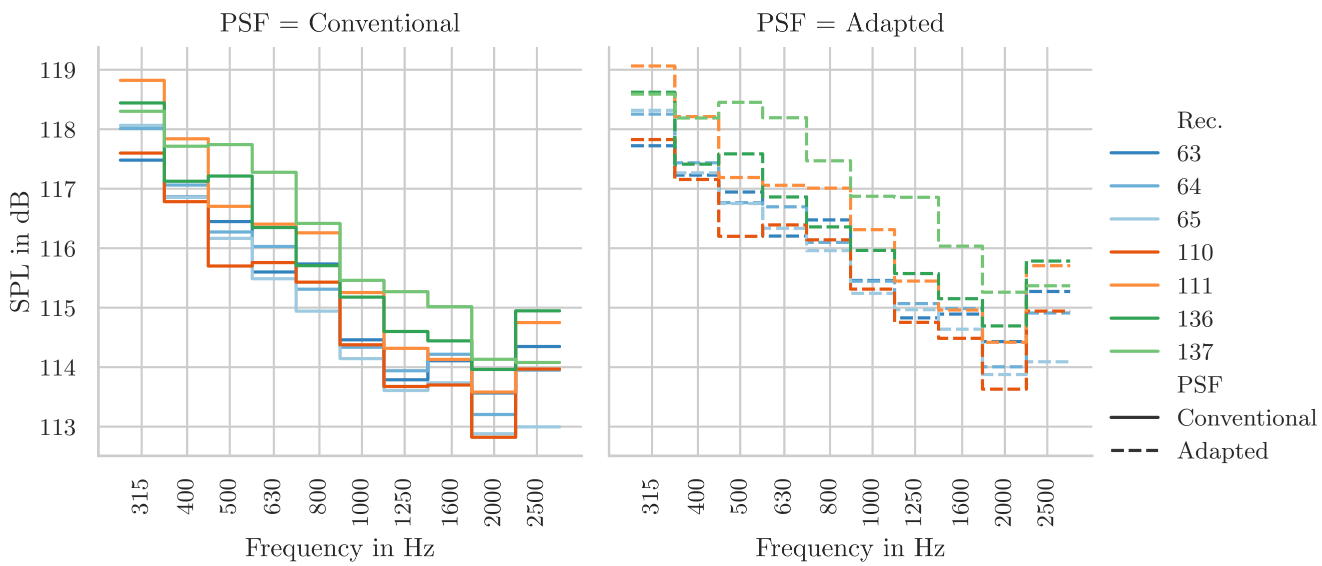

Figure 4: The calculated levels of the total sources located on the aircraft. The results using the conventional are generally within 1.5 dB. When using the adapted point spread function, the levels where increased, especially for $f \geq 800$ Hz. The reproducibility however was not improved.