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APPLICATION OF THE CLEANT METHODOLOGY TO FLYOVER NOISE MEASUREMENTS

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Abstract

The study of noise sources generated by aircraft flyovers in the vicinity of airports requires the deployment on the ground of large arrays of microphones, both in terms of the number of channels (typically several hundreds of microphones) and in terms of their span (several tens of meters). This type of test is in many ways similar to the pass-by noise antenna tests in the automotive, railway or maritime domains: the main difficulties consist in taking into account the trajectory of the source in a beamforming algorithm, in taking into account the frequency dispersions induced by the Doppler effect, and in evaluating the directivity of the source which is seen by the array under several angles of incidence. Deconvolution or identification techniques partially overcome beamforming drawbacks(poor resolution at low frequencies and side lobes), but have been developed for static sources, generally based on the estimation of averaged interspectra of stationary signals. The application to pass-by noise, which is transient by nature, is necessarily delicate and requires many compromises; the most advanced techniques to date are nevertheless based on this principle. An alternative has emerged in recent years, based on an iterative deconvolution processing in the time domain called CleanT. This method, inspired by the Clean method in the frequency domain, has the advantage of operating directly on the resampled signals in the time base of the source, correcting by construction the Doppler effect and allowing access to the information of directivity - at the expense of a significant computational cost. This method, recently proven on automotive and railway applications, is applied in this paper to the aeronautical case of flyover tests, first with simulated data and finally with *in situ* measurements.

1 INTRODUCTION

The application of beamforming techniques to moving sources is relatively simple in its formulation, when the kinematics of the target are known. It requires the application of variable delays to the microphone signals, through interpolation of these signals into a reception time base. The energy of the signals focused on a set of candidate sources allows the noise sources to be mapped in a moving frame of reference linked to the target [5]. The images obtained suffer, however, from the well-known downsides of beamforming, namely its limited resolution and its difficulty in quantifying the sources. In the aeronautical domain, for microphone array flyover tests, a great deal of work has been devoted to the deployment of deconvolution methods with the aim of improving resolution and obtaining quantitative results [2, 3, 7]. These methods are generally based on an assumption of source decorrelation, and aim to decompose the energy mapping from beamforming into a linear combination of frequency-dependent functions called PSFs (point spread functions) with positivity constraints. However, these methods come up against two main difficulties in the case of moving sources:

- PSFs vary with the relative position of the sources and the microphone array,
- PSFs undergo a frequency spread related to the Doppler effect.

These two difficulties generally lead to a splitting of the flyover into several short time windows, limiting the frequency resolution and leading to certain difficulties in case of tonal sources. An alternative to frequency deconvolution approaches for mobile sources has recently been proposed [1], based on a purely temporal approach. It is a matching pursuit type method, similar in principle to Clean deconvolution [6], but processed in the time domain (hence its name CleanT). This approach, initially developed for automotive pass-by noise applications, has also been tested on railway applications [4]. The objective of the present work is to propose first results in the aeronautical domain for microphone array flyover processing.
This paper is organised as follows: the main lines of the CleanT method are recalled in a first part, followed by a description of its adaptation to the flyover problem. Some method performance and validation are presented against simulated data. And first experimental results are finally proposed in a last section.

2 CLEANT METHOD PRINCIPLE

CleanT method is a Matching Pursuit (MP) type heuristic approach leading to sparse results. The principle is to iteratively focus the signals from a microphone array on a grid representing the candidate sources (which position moves relatively to the target), then to subtract at each iteration the contribution of the source maximising a given criterion.
The acoustic pressure generated at a given point by a moving point source is given by

$$p_i\left(t+\frac{r_{ij}(t)}{c}\right)=A_{ij}(t).q_j(t) \tag{1}$$

where $A_{ij}=[r_{ij}(t).(1-M.\cos(\theta_{ij}(t)))^2]^{-1}$ is the geometric attenuation for a source moving at Mach M, r_{ij} is the source-to-microphone distance, θ_{ij} is the angle between the direction of source motion and the source-to-microphone direction, and c is the velocity of the acoustic waves. For an antenna of m microphones, the least squares estimate of the source signal $q_j(t)$ is given by

$$q_j(t)=\frac{1}{\sum_{i=1}^{m}\left(A_{ij}(t)\right)^2}\sum_{i=1}^{m}A_{ij}(t).p_i\left(t+\frac{r_{ij}(t)}{c}\right) \tag{2}$$

At each iteration of the CleanT method, an indicator is maximized over the set of n candidate sources, which allows selecting a source. The position and signal of this source are stored, and the contribution of this source to the microphone array is subtracted from the data. The residual signals are used in the next iteration.

The maximised indicator at each iteration can simply be an overall source signal level. However, this indicator is biased by the heterogeneity of the average distances of candidate sources to the antenna microphones: a source further away from the array will tend to be more energetic to compensate for the distance. An alternative indicator is given by:

$$\Lambda_j = \int_T w_j(t).(q_j(t))^2 \, dt \tag{3}$$

where $w_j(t) = \sum_{i=1}^{n} \left(A_{ij}(t)\right)^2$ corrects for distance bias.

3 APPLICATION OF CLEANT TO FLY-OVER

The simplistic principle of the CleanT method requires some adjustments related to the following difficulties

- the dominant source position depends on the frequency
- the source position depends on the angle of incidence (due to the source directivities)
- propagation being over a long distance, wind and temperature become sensitive parameters
- the sources can have a tonal aspect or be broadband

The answer to the first and second difficulties is to apply the method by partitioning the data by frequency bands and time windows.
The frequency band partitioning will adopt the partitioning used for the microphone array processing: the cross-shape array configuration used requires the definition of different sub-sets of microphones to optimise the array response per frequency band. However, bandpass filtering must be performed on dedopplerised signals, so that a given band is representative of the energy carried by the source and not the microphones. This dedopplerisation is done independently for each microphone, considering a source position at the centre of gravity of the target. The signals are then band-pass filtered and ”re-dopplerised” before the CleanT algorithm is applied. This step constitutes the pre-processing part described in the diagram 1.

In conventional array processing, the assumption of sparse distribution of omnidirectional sources is generally false, but the effect is limited by the fact that the source is seen from a limited solid angle (antenna aperture). In the case where the source is moving, it is seen over a much wider solid angle, which can create problems. For example, the main source in the approach phase (the target is approaching the array) is not necessarily the same as when the target is moving away. The CleanT algorithm must therefore be applied in chunks, each chunk corresponding to a certain angular interval of the source incidence. The part of the algorithm performed sequentially for each incidence interval is circled in blue dashed line in figure 1.

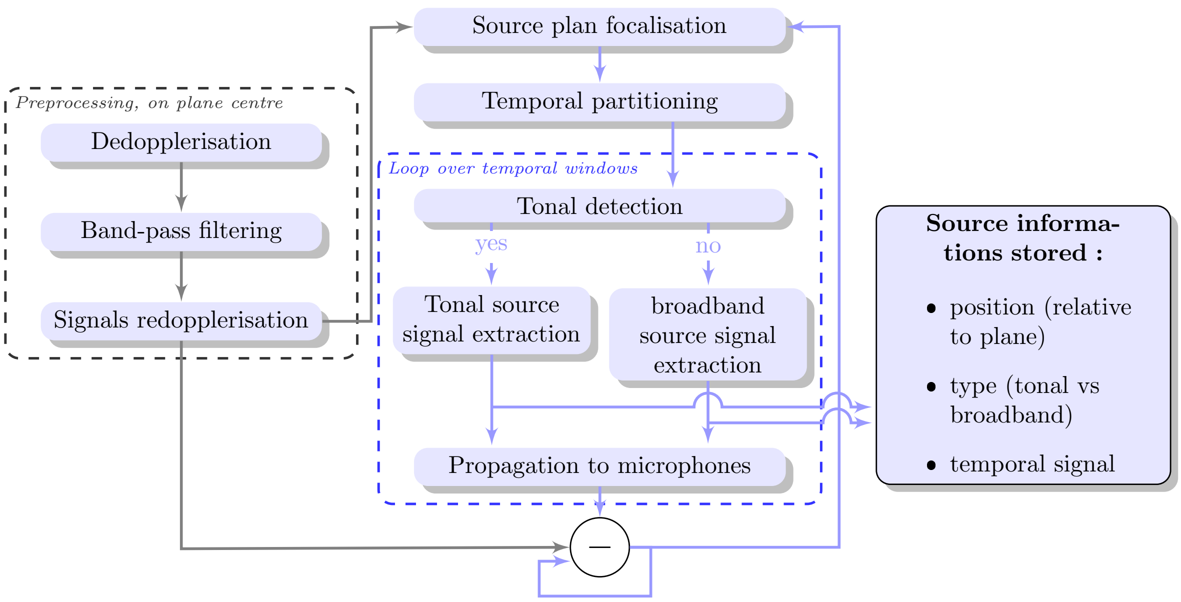


Figure 1: CleanT algorithm applied to the flyover antenna. Black arrows are executed at startup only, blue arrows are borrowed at each iteration.

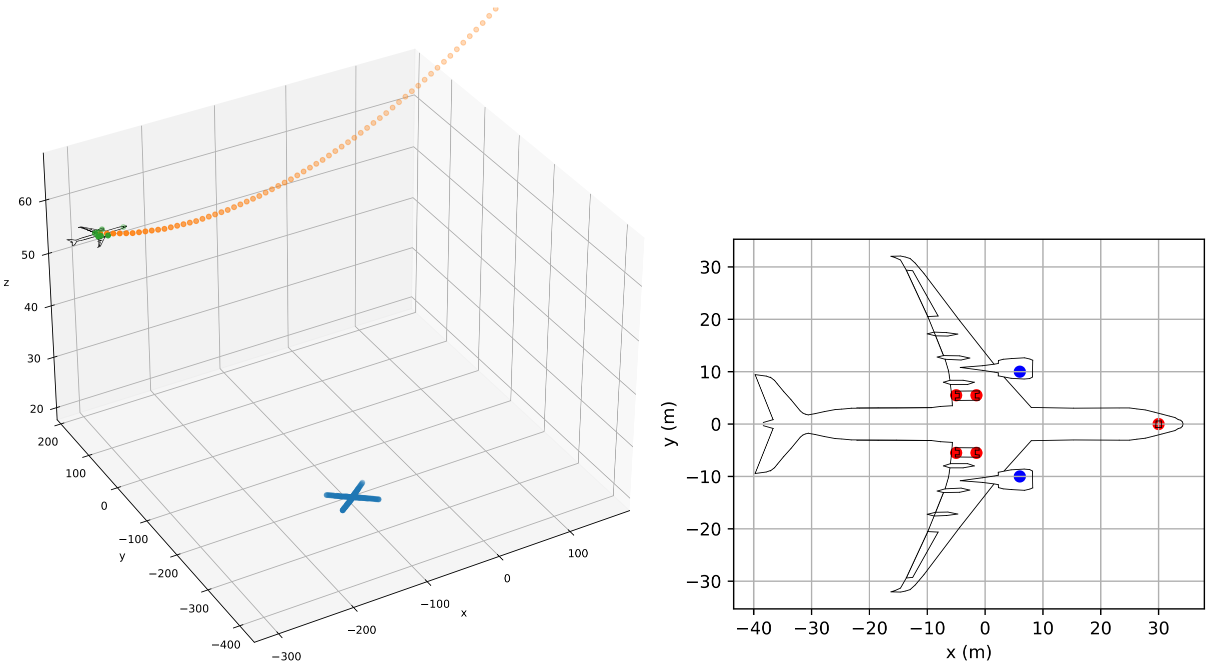
Concerning the difficulty linked to the uncertainties on the environmental data (wind, temperature), average values are inferred here by trial and error with the objective of repositioning the acoustic image in the mobile reference frame linked to the source.
The presence of tonal components in addition to broadband noise also represents a certain difficulty. They can be significant while having a lower level than the broadband components, and therefore not necessarily a priority according to the quadratic level maximisation indicator as defined in Eq. (3). It may however be advantageous to extract them as a priority. A specific treatment is taken into account, based on the calculation of a tonality indicator (not detailed in this paper). If a tonal character is detected in the source signals, the source signal maximising the tonal indicator is narrowband filtered and subsequently processed as a tonal type source signal (see fig. 1).

This approach will be first applied to simulated data in section 3.1 in order to validate the computation with homogeneous media and no wind. Then, section 3.2 will present the first results obtained with experimental data.

3.1 Method validation

In this section, we investigate the performance CleanT methodology over a large propagation path using simulated data.
In this simulation, we used the aircraft trajectory recorded in the test campaign, referred as ”Configuration 1” in section 3.2, and presented in fig. 2(a). Using Eq. (1) and 7 noise sources, we generate the simulated signals over the same microphone array as the one used in section 3.2. Note that an homogeneous media, no wind and no reflections are considered for now in this work. Fig. 2(b) shows that two types of noises sources have been considered: two tonal

sources simulating the fans and five broadband sources simulating the aerodynamic sources due to the flow around the landing gears. The five broadband noise sources are implemented as white noises emitted at 94 dB SPL while the two tonal sources are modelled with pure sinus emitted at 78.9 dB SPL. The one located at $y = 10$ m is centred on 440 Hz while the one at $y = -10$ m is at 880 Hz.



(a) Sources (in green) and aircraft at $t = 0$, its trajectory (in orange) and the microphone array (in blue)

(b) Source distribution over the simulated aircraft. Blue: tonal sources, Red: broadband sources.

Figure 2: Source and microphone configuration used for the simulation.

The CleanT is then applied to the data obtained with this simulation. Fig. 3 presents the results of the computation integrated for an angle of incidence varying between 75 and 105° over the octave band centred on 200, 400 and 800 Hz. Sources of tonal character have been shown in a different colour scale, also on 30 dB range, to illustrate one of the advantages of the CleanT method. We can see that the source locations are very well localised, so as the nature of the sources. Nevertheless, we can notice that we detect some extra sources on the symmetry axis of the aircraft. These are probably due to the constructive interactions of the side lobes of the microphone array PSF. Other array designs should probably avoid these artefacts. Note that the resolution of the sources is not influenced by the frequency (for the tonal sources) or the broad or narrowband aspect of the sources.

We can see on the source spectra that the two types of sources are well separated with a good suppression of the tonal components on the broadband source reconstructed signals and *vice versa*. The black dashed line and black markers indicating the magnitude of noise sources at source position shows that CleanT estimates well the source magnitudes in this simulation.

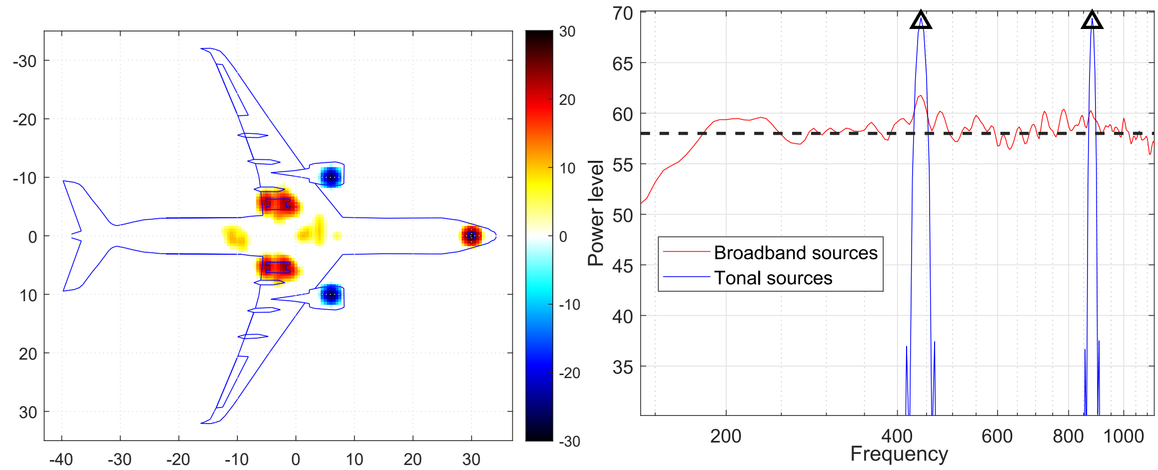


Figure 3: Source map (left) and source spectra (right) recovered from simulated pressure signals. Left: Red scale is used for broadband sources, blue scale for tonal sources. Each scale have 30 dB of dynamic range. Right: black dashed line (or broadband sources) and black markers (for the tonal sources) indicate the magnitude of source spectral components before propagation.

3.2 Experimental results

First experimental results of flyover application cases are proposed in this section. The microphone antenna used is a 249-microphone cross antenna. Two aircraft configurations are presented with and without landing gear extended, the broadband imaging results are plotted in fig. 4(a), 4(b) and 4(c) (configuration 1: landing gear retracted) and fig. 4(d), 4(e) and 4(f) (configuration 2: landing gear extended), for different incidence angles. On the figures, the tonal sources related to the fans are clearly identified and correctly positioned. They are no longer significant in the second configuration because of the predominance of the landing gear.
We can also see the effect of the environmental conditions with an offset of the sources when the aircraft is at 60 and 120°. This shows that the consideration of these factors can still be improved.

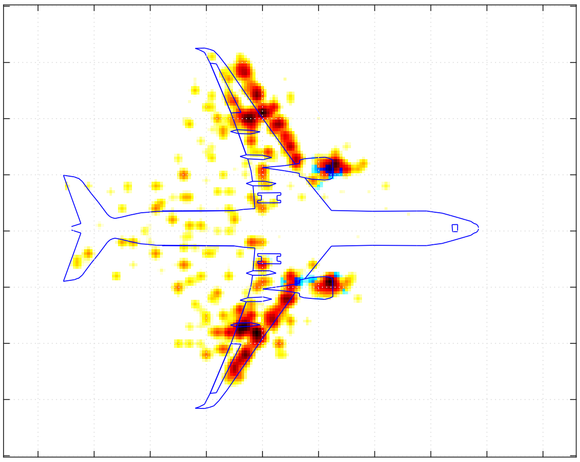
An advantage of the CleanT approach is that it provides source signals in time domain, allowing to analyse the temporal variations, use them for psychoacoustic tests or plot narrowband source spectra as presented in fig. 5. The power spectrum of the sources is plotted and compared to the average spectrum of the microphones array. Tones, absent from the microphone spectra due to the Doppler effect, emerge significantly in the source power spectra.

Note that in this section all the magnitudes, frequencies and dimensions were removed for confidentiality reasons.

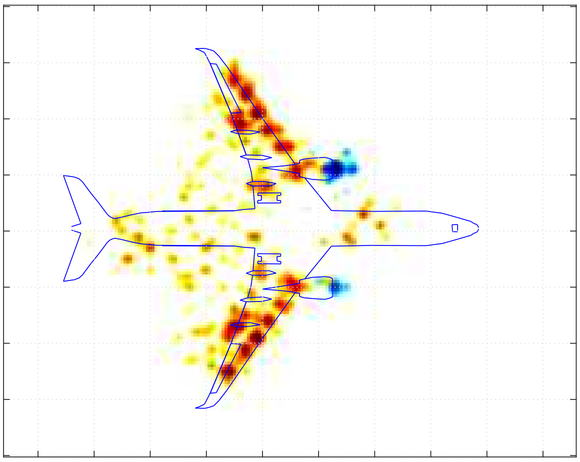
4 CONCLUSIONS

The aim of this work was to demonstrate the possibility of implementing the CleanT methodology for flyover noise measurements.

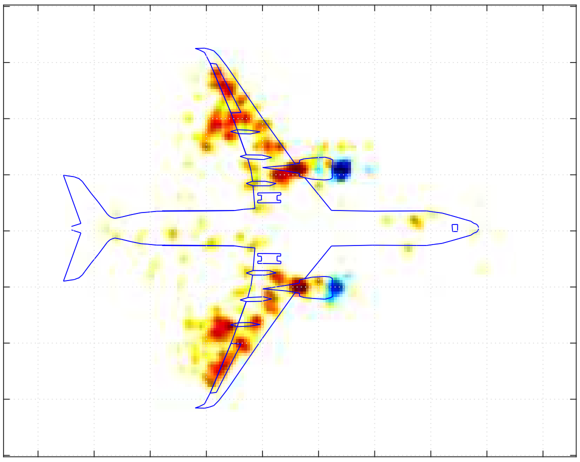
CleanT applied to simulations allowed us to validate the implementation and the interest of



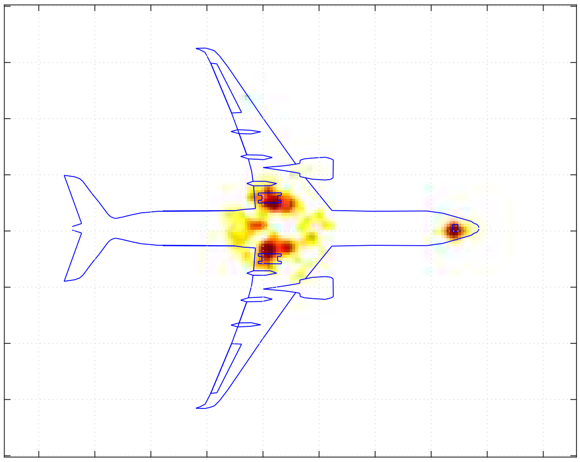
(a) Configuration 1 - 60°



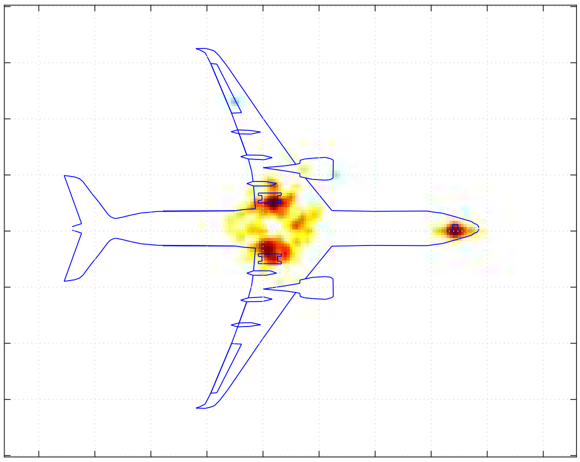
(b) Configuration 1 - 90°



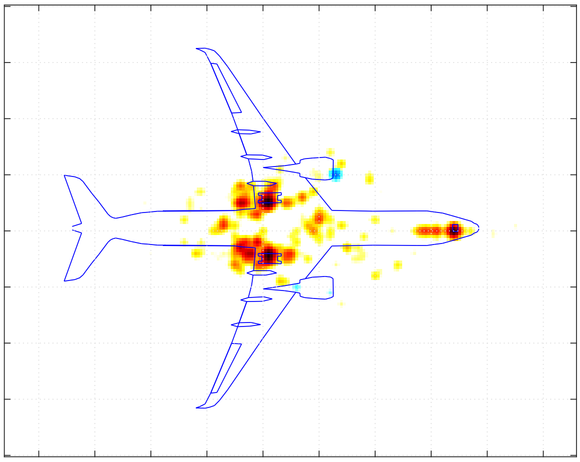
(c) Configuration 1 - 120°



(d) Configuration 2 - 60°



(e) Configuration 2 - 90°



(f) Configuration 2 - 120°

Figure 4: Broadband acoustic imaging results for different incidence angles using CleanT method. Red scale is used for broadband sources, blue scale for tonal ones.

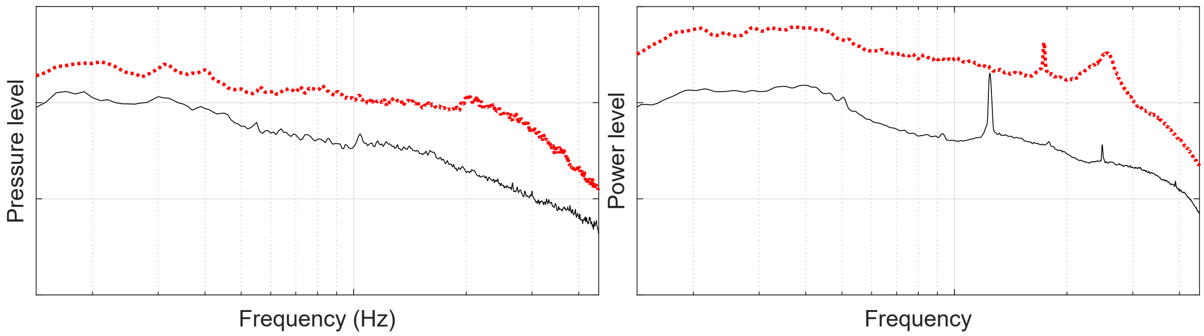


Figure 5: Comparison of microphone signal spectra (left) and reconstructed source power (right) for configurations 1 (black line) and 2 (red dotted line)

the method in ideal situation. The results obtained with *in situ* data are encouraging, and allow the possibility of numerous post-processing operations that would enhance the interest of the approach in relation to existing tools.

That said, the comparison in terms of performance with these existing tools remains to be done. The CleanT method suffers from a significant disadvantage: its calculation cost. It will be necessary to demonstrate that the benefits of the approach are worth the extra processing time.

REFERENCES

[1] R. Cousson, Q. Leclère, M.-A. Pallas, and M. Bérengier. "A time domain clean approach for the identification of acoustic moving sources." *Journal of Sound and Vibration*, 443, 47–62, 2019. ISSN 0022-460X. doi:https://doi.org/10.1016/j.jsv.2018.11.026. URL `https://www.sciencedirect.com/science/article/pii/S0022460X18307880`.

[2] V. Fleury and J. Bulté. "Extension of deconvolution algorithms for the mapping of moving acoustic sources." *The Journal of the Acoustical Society of America*, 129(3), 1417–1428, 2011. doi:10.1121/1.3531939. URL `https://doi.org/10.1121/1.3531939`.

[3] Guérin and Weckmüller. "Frequency-domain reconstruction of the point-spread function for moving sources." In *Proceedings on CD of the 2nd Berlin Beamforming Conference, 19-20 February, 2008*. GFaI, Gesellschaft zu Förderung angewandter Informatik e.V., Berlin, 2008. ISBN 978-3-00-023849-9. URL `http://www.bebec.eu/Downloads/BeBeC2008/Papers/BeBeC-2008-14_Guerin_Weckmueller.pdf`.

[4] Kujawski and Sarradj. "Application of the cleant method for high speed railway train measurements." In *Proceedings of the 9th Berlin Beamforming Conference, 2020*. 2020.

[5] U. Michel, J. Helbig, B. Barsikow, M. Hellmig, and M. Schuettpelz. *Flyover noise measurements on landing aircraft with a microphone array*. doi:10.2514/6.1998-2336. URL `https://arc.aiaa.org/doi/abs/10.2514/6.1998-2336`.

[6] P. Sijtsma. "CLEAN based on spatial source coherence." *International Journal of Aeroacoustics*, 6, 357–374, 2007. doi:10.1260/147547207783359459.

[7] Siller. “Localisation of sound sources on aircraft in flight.” In *Proceedings on CD of the 4th Berlin Beamforming Conference, 22-23 February 2012*. GFaI, Gesellschaft zu Förderung angewandter Informatik e.V., Berlin, 2012. ISBN 978-3-942709-04-0. URL `http://bebec.eu/Downloads/BeBeC2012/Papers/BeBeC-2012-01.pdf`.