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ACOUSTIC IMAGING ON AIRCRAFT FLYOVER TESTS: COMPARING CLEAN-T TO DAMAS-MS

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ABSTRACT

This paper focuses on the localisation and characterisation of noise sources generated by aircraft flyovers near airports. Classical delay-and-sum beamforming algorithm has first been used to realise acoustic maps of sound sources, but the image resolution and the dynamic range of this technique are limited. To overcome these physical limitations, large arrays of microphones with many channels and a wide span are typically used. Deconvolution techniques have been developed these past two decades, first for static sources, then enlarged to moving sources. But applying them to flyover noise remain challenging due to the speed and distance of the aircraft, or the directivity of the sources. An alternative has emerged in recent years, based on an iterative deconvolution processing in the time domain called CLEAN-T. The performance of this method, inspired by the CLEAN method in the frequency domain and recently applied to this new field, is here compared to the widely used DAMAS-MS in the frame of simulations and on a real experimental case.

Keywords: *Noise source characterisation, aircraft fly-over, deconvolution techniques, time domain, signal processing*

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1. INTRODUCTION

Acoustic imaging is a powerful technique for identifying and localising noise sources in complex environments, such as aircraft fly-over tests. However, conventional beamforming methods suffer from low spatial resolution and high sidelobe levels, which limit their ability to resolve closely spaced or weak sources.

For over two decades, deconvolution techniques – introduced in optics with CLEAN method [1]– have been applied to acoustics and the aviation industrial applications in order to obtain more precise acoustic maps over aircraft, especially in low frequency, in wind tunnels [2] or during fly-over tests [3]. During the last decade, DAMAS-MS has become the industry standard for aviation [4, 5]. DAMAS-MS is a modified version of DAMAS that takes into account the moving aspects of the source. But the computation is hybrid, and merges the beamforming formulated in the time domain with the deconvolution at discrete frequencies. In recent years, Cousson *et al.* [6] proposed a time-domain version of CLEAN, extending the deconvolution techniques to the time-domain: CLEAN-T. The application to moving sources, and especially aircraft fly-over tests, has been done recently [7].

This paper aims at comparing CLEAN-T performances with regard to DAMAS-MS on simulated and experimental data from aircraft fly-over tests.

2. ARRAY PROCESSING

2.1 Direct model

In the following, all the coordinates vectors refer to the same static coordinate system on the ground. We consider an acoustic monopole moving at velocity $\mathbf{V}$ along an arbitrary trajectory. This trajectory is precisely known, with $\mathbf{r}_s(t_e)$ the coordinates at emission time t_e.

The sound propagation occurs in a medium at rest. Thus, a constant sound speed c_0 is considered. The monopole emits a signal $q_s(t_e)$ received at time $t = t_e + \tau_{ms}(t_e)$ by a static microphone located at $\mathbf{r}_m$. Note that the delay $\tau_{ms}(t_e) = R_{ms}(t_e)/c_0$ varies with the source, where $R_{ms}(t_e) = \|\mathbf{r}_m - \mathbf{r}_s(t_e)\|_2$ is the source-to-microphone distance. According [8], for the case of a moving monopole, the microphone output writes

$$y_m(t_e + \tau_{ms}(t_e)) = \frac{q_s(t_e)}{R_{ms}(t_e)\left[1 - M\cos\theta_{ms}(t_e)\right]^2} \quad (1)$$

with M is the norm of the Mach vector $\mathbf{M} = \mathbf{V}/c_0$. The quantity

$$M\cos\theta_{ms}(t_e) = \frac{< \mathbf{r}_m - \mathbf{r}_s(t_e), \mathbf{M} >}{R_{ms}(t_e)} \quad (2)$$

links to the orthogonal projection of $\mathbf{M}$ along the direction pointing towards the receiver. We note

$$A_{ms}(t_e) = \frac{1}{R_{ms}(t_e)\left[1 - M\cos\theta_{ms}(t_e)\right]^2} \quad (3)$$

for the rest of the paper.

2.2 Beamforming-MS

The conventional Delay-and-Sum (DAS) beamforming is expressed in the time-domain to follow the moving sources onto their trajectory [6]. Thus, it aims at back-propagating the signals received by a network of M microphones at $\mathbf{r}_m$ along a focusing grid of N candidate points at $\mathbf{r}_n(t_e)$. The estimation of the pressure signal q_n at the n^{th} point can be written as

$$q_n(t_e) = Q_{mn} \sum_{m=1}^{M} A_{mn}(t_e).y_m\left(t_e + \tau_{mn}(t_e)\right), \quad (4)$$

with the normalisation factor

$$Q_{mn} = \frac{1}{\sum_{m=1}^{M}\left(A_{mn}(t_e)\right)^2} \quad (5)$$

If the candidate point follows the trajectory of an emitted source ($\mathbf{r}_n(t_e) = \mathbf{r}_s(t_e)$), then the signal $q_s(t_e)$ is recovered for each time t_e.

2.3 CLEAN-T

First introduced by Cousson *et al.* [6], CLEAN-T method is a Matching Pursuit (MP) type heuristic approach leading to sparse results.

CLEAN-T is based on the use of DAS beamforming in time domain –using eq. (4). Then, iteratively, an indicator is maximized over the set of the s candidate sources, which allows selecting a source. The position and signal of this source are stored. The signal is propagated to the microphone –using eq. (1)– so that its contribution to the measured pressure is subtracted from the microphone data. The residual signals are used in the next iteration.

This imaging method has been adapted to aircraft flyover test cases in [7]: modifying the indicator to maximized and taking into account the trajectory of the source. The same approach is used in this paper.

2.4 DAMAS-MS

The DAMAS (Deconvolution Approach for the Mapping of Acoustic Sources) algorithm was introduced by Brooks and Humphreys [9] to overcome the spatial resolution limit of the DAS beamforming. It has been extended to the specific case of moving sources, in order to quantify noise from vehicles like aircraft [10] or ship [11].

The DAMAS-MS implemented in this paper is fully described in [4, 12]. As opposed to CLEAN-T, the deconvolution is formulated here in the frequency-domain. The DAMAS-MS assumes an uncorrelated distribution of candidate moving sources. The deconvolved source map $\mathbf{s}$ is solution of the linear system

$$\mathbf{Hs} = \mathbf{b} \quad (6)$$

under the positivity constraint $s_n \geq 0$ for $n = 1 \ldots N$. The power spectrum at the n^{th} grid point writes

$$b_n(\omega) = |\hat{q}_n(\omega)|^2, \quad (7)$$

with $\hat{q}_n$ the complex Fourier component of the beamforming output (4) at angular frequency ω. The n^{th} column of the matrix $\mathbf{H}$ is the point spread function (PSF) for source at $\mathbf{r}_n$ [13]. Like in [12], the inverse problem in (6) is solved using a gradient-based iterative procedure.

3. PERFORMANCE COMPARISON OVER SYNTHETIC DATA

3.1 Simulation

In this section, the performances of both DAMAS-MS and CLEAN-T techniques are investigated under a numerical flyover scenario. The Figure 1 shows the used microphone array. A total of 249 microphones along two lines form a cross-shaped distribution on ground. The aperture L_a equals the largest pairwise distance between these microphones, and defines the aperture of the array. The array is subdivided in sub-arrays to cover a large frequency range, and the microphones are evenly spaced. A similar design is described in [12].

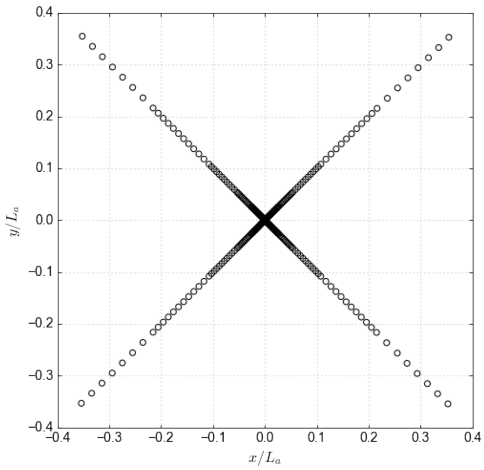


Figure 1: Geometry of the microphone array with aperture L_a

The simulation reproduces the noise emissions for a typical descending trajectory. When the aircraft is at emission angle $\theta = 90°$, the altitude above the array is around twice the aperture L_a. The propagation in the medium is supposed without wind, at constant sound speed $c_0 = 343 m.s^{-1}$.

The Figure 2 shows the positions and types of the simulated sources linked to the aircraft : two pure tones on the engines (blue dots) at respectively 440 Hz and 880 Hz, and five broadband sources on the landing gears (red dots). All the sources are monopolar, and generate on the microphones a pressure signal synchronized with the trajectory.

3.2 Results

The identification of the emitted equivalent sources on the aircraft is done using DAMAS-MS and CLEAN-T. The sources are sought along a regular cartesian grid of $N_s = 2601$ focal points. The grid delimits an area of $D \times D$ meters where D is the wingspan of the aircraft. The discrete time signals are estimated first with (4) for each point of the grid, and used in a second step as input of each deconvolution technique. The analysis is carried out at emission angle $\theta = 90°$.

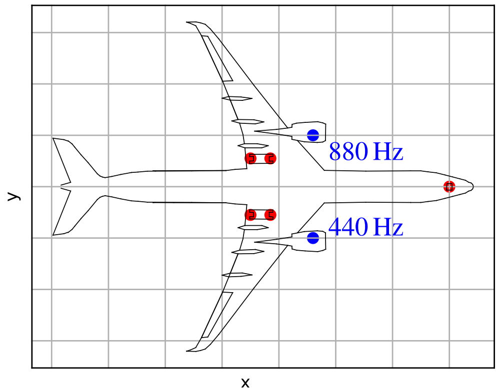


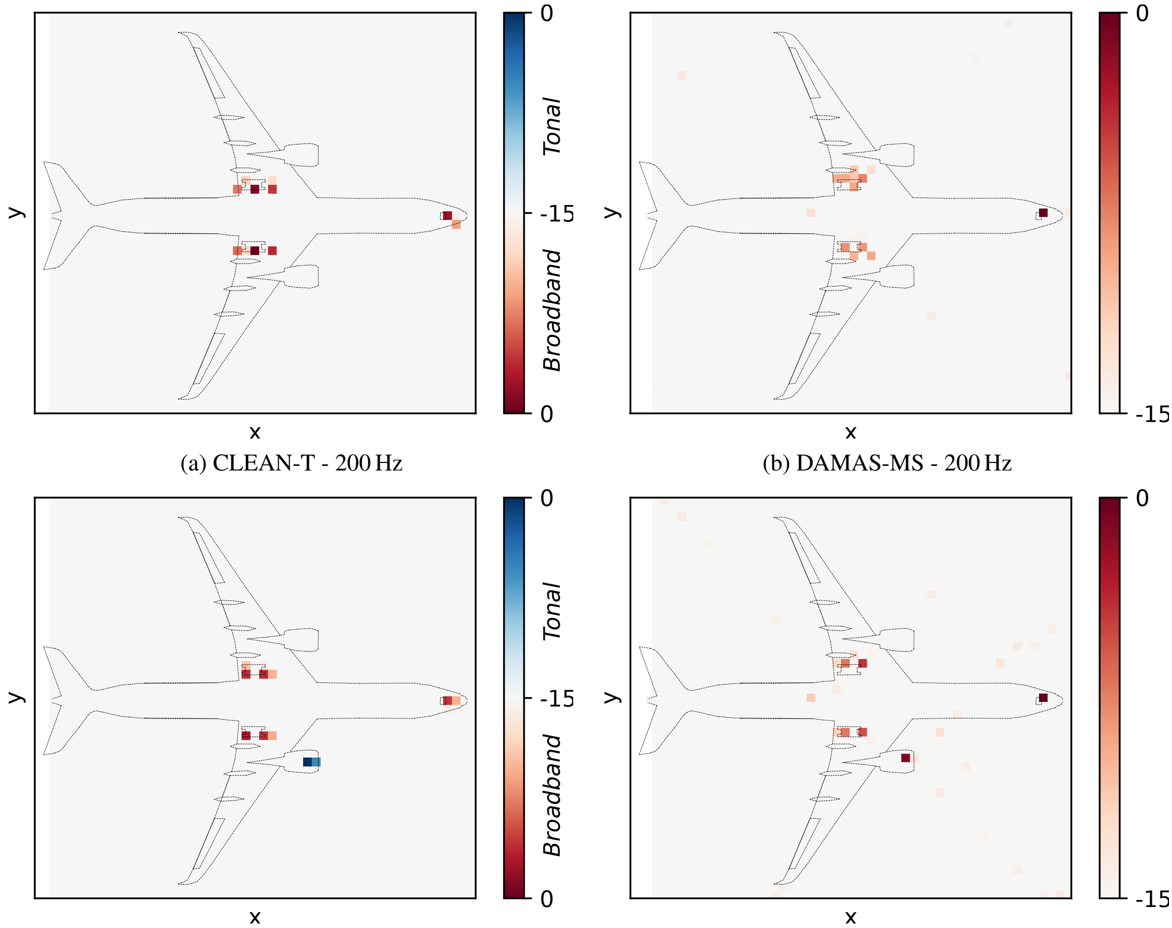
Figure 2: Simulated sources - Blue: tonal, Red: broadband

Figure 3 presents the results of the two methods integrated over octave bands centred on 200 Hz and 400 Hz. First, it can be seen that DAMAS-MS and CLEAN-T provide similar performances in general.

Focusing the analysis first on the lower frequency band, we can see that the two sources simulating the rear landing gears are too close to be separated with both methods. CLEAN-T finds a source at the middle position and sub-sources on each side, while DAMAS-MS finds a cloud of sources in this region. Thus, we see here the major difference between the two methods: they don't provide the same source separation in low frequency (in cases of bad resolution with DAS beamforming).

In the higher frequency band, for which a more diverse sound scene is simulated, we can see that the broadband sources at the landing gears level (both rear and front) are well positioned for both methods. Note that, CLEAN-T analyses properly the tonal characteristic of the source at 440 Hz accounting for the engine.

It has to be noted a higher number of ghost sources in DAMAS-MS results (mostly at the front of the acoustic scene) compared to CLEAN-T. This is probably related to the Doppler effect on the tonal source(s). Indeed, as the DAMAS-MS method is done for discrete values of frequency, the frequency-domain beamforming (and so DAMAS-MS) will find ghost sources along the Point Spread Function (PSF) ahead of the source in higher frequencies and downstream of the source in lower frequencies [13].



(a) CLEAN-T - 200 Hz

(b) DAMAS-MS - 200 Hz

(c) CLEAN-T - 400 Hz

(d) DAMAS-MS - 400 Hz

Figure 3: Sound source localisation comparison between CLEAN-T and DAMAS-MS (on 15 dB scales). Aircraft above the microphone array : $\theta = 90°$. Simulation test case. CLEAN-T: same reference used for tonal and broadband scale.

4. PERFORMANCE COMPARISON OVER EXPERIMENTAL DATA

Performance comparison of the two deconvolution methods is now investigated over experimental data provided by Airbus. A similar array as the one presented in Figure 1 is deployed.

Figure 4 presents the comparison between DAMAS-MS and CLEAN-T on the experimental data. The sources are sought along a regular cartesian grid of $N_s = 5776$ focal points. Note that CLEAN-T results have been reprocessed since their first presentation in [14].

As an initial observation, one might note that CLEAN-T offers a more sparse result, as fewer sources are found by the method compared to DAMAS-MS.

Throughout the frequency range, CLEAN-T also seems to avoid more ghost source detections, such as the ones DAMAS-MS detects upstream the engines for octave bands centred on f_1, f_2 and f_3. The amount of sources localised downstream the wings are also significantly reduced compared to DAMAS-MS.

For the central frequencies f_3 and f_4, CLEAN-T allows distinguishing the noise sources at the front of the engine (tonal fan noise) and the ones at the back (broadband jet noise).

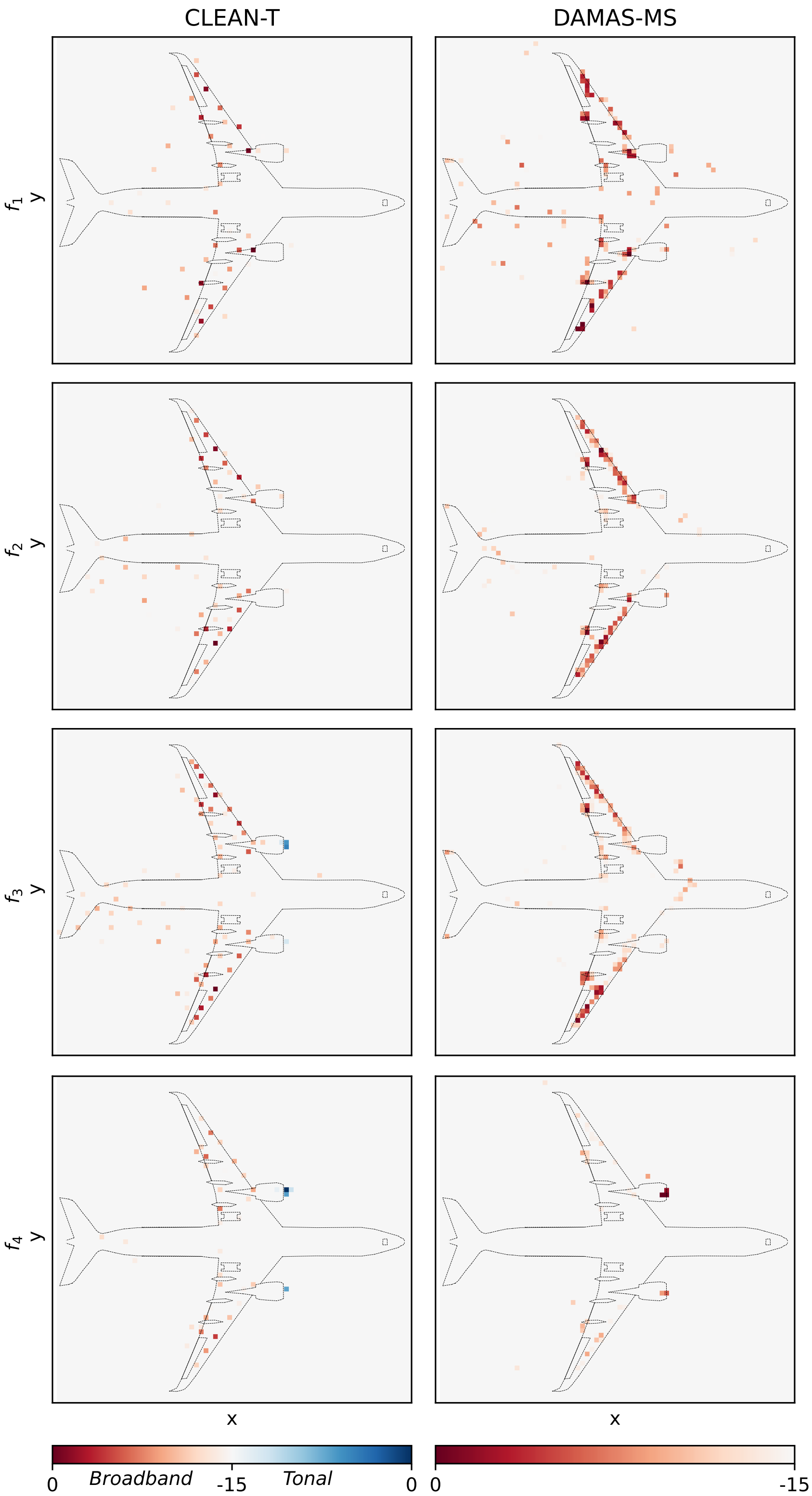


Figure 4: Sound source localisation comparison between CLEAN-T and DAMAS-MS (on 15 dB scales). Aircraft above the microphone array : $\theta = 90°$. Experimental test case. Results integrated over octave bands with central frequency f_i with $f_1 < f_2 < f_3 < f_4$. CLEAN-T: same reference used for tonal and broadband scale.

It can be noted that actual sources could be missed by CLEAN-T around the rear tail tips for f_1, f_2 and f_3. For all other aeroacoustic sources, the sources localisation and quantification performance of both techniques seems quite similar.

5. CONCLUSION

In this paper, CLEAN-T performances have been compared to the existing deconvolution method DAMAS-MS dedicated to the moving sources. This comparison was carried out in the context of flyover noise measurements. The two methods were first applied on synthetic data from a ground-truth simulated scenario, and then on real experimental data from aircraft fly-over tests.

The CLEAN-T method has shown good localisation and quantification performances, even with complex *in situ* situations, such as fly-over test cases. In lower frequencies, the two methods give similar performances, but in higher frequency CLEAN-T seems to realise a cleaner map. This is probably due to the fact that the PSF of each source is subtracted in time domain, thus inducing a broadband computation.

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