Beamforming of aeroacoustic sources in the time domain

Jeoffrey FISCHER[1]; Vincent VALEAU[1]; Laurent-Emmanuel BRIZZI[1]

[1] Institut PPRIME UPR 3346
CNRS - Université de Poitiers - ENSMA
86022 Poitiers Cedex, France

ABSTRACT

A classical array processing technique used for the analysis of aeroacoustic sources is the frequency-domain beamforming technique. The use of this technique requires an assumption on the stationarity of the sources as it works with a time-averaged estimate of the cross-spectral matrix. As a consequence this technique provides an estimation of the average position (in space and time) of an aeroacoustic source. However, some studies, focusing in particular on jet noise, have shown the intermittent nature of some aeroacoustic sources. The aim of this paper is then to show that the time-domain beamforming technique allows assessing the intermittent nature of aeroacoustic sources, and makes possible a space-time tracking of short duration acoustic events occurring in the flow. The method is applied to experimental wind-tunnel measurements. The noise produced by the flow over a forward-facing step is analyzed by using both frequency-domain and time-domain beamforming, and the intermittent structure of such an aeroacoustic source is investigated.

Keywords: Aeroacoustics, Beamforming. I-INCE Classification of Subjects Number(s): 21.6

1. INTRODUCTION

A classical array processing technique used for the analysis of aeroacoustic sources is the delay-and-sum beamforming (DSB) technique (1, 2). This technique is most of the time calculated in the frequency domain, et it makes possible, from a set of data measured with an array of microphones, to perform sound maps in a given frequency band. Further developments were made in the last decade concerning the deconvolution of the array response, in order to overcome the dependency of the latter to frequency. One robust algorithm to perform this deconvolution is the DAMAS technique (3). The frequency-domain DSB technique lies on the calculation of the Cross-Spectral Matrix (CSM) of the array data; this matrix is calculated by performing time averages, so that the obtained sound maps represent an estimate of the average sources of sound in the flow.

However, some studies were focused on the intermittent character of areoacoustic sources, and in particular of jet noise (4, 5, 6), observing that the greater part of the energy is localized in short intermittent events. For studying such property of aeroacoustic noise, and more generally the fluctuations of aeroacoustic noise occurring at short time scales, the classical techniques for sound source localization (frequency-domaine DSB, DAMAS) are not adapted, as they rely on time-averages. In this paper, it is shown how to develop an imaging method for studying the intermittency of aeroacoustic sound sources.

Recently, imaging method were proposed for studying aeroacoustic sources, relying on the time-reversal principle (7, 8, 9). These imaging technique were applied both to numerical and experimental data. They rely on a time-domain numerical computation of the waves through the flow, but most of the results were equivalent to averaged frequency-domain results. The present study proposes a method of time-domain imaging based on the DSB technique. This technique can be seen as a time-reversal-based method, as the equivalence between time-reversal and DSB is often assumed, at least implicitly in the literature (10). However, the algorithm of time-domain DSB is rather simple compared to techniques based on a numerical computation; on the other hand, time-domain DSB can only deal with simple flow profiles such as shear flows. In the present study, it is then shown how this technique can be applied to an experimental case in order to perform an analysis for assessing the intermittent nature of the source. The energetic events detected in the flow are then detected both in the time and space domains.

[1] jeoffrey.fischer@etu.univ-poitiers.fr
[2] vincent.valeau@univ-poitiers.fr
[3] laurent.brizzi@univ-poitiers.fr

The experimental application is the noise generated by a forward-facing step in a flow. There exists a considerable amount of published data for flows over three-dimensional or two-dimensional geometries such as the forward-facing step (11, 12). Even if these studies demonstrate that for a fixed obstacle geometry, this flow is mainly influenced by numerous geometrical (height, relative, spanwise, ...) and dynamical parameters (Reynolds number, boundary layer thickness, turbulence intensity,...), a common behavior can be observed for most of the configurations : Unsteady 3D vortical structures are generated in the vicinity of such obstacles (13). This behavior may induce a natural trend for the flows over steps to generate noise, although the intermittent character of their sound radiation has not been assessed in the literature.

This paper starts with the description of the experimental setup in Section 2. Some averaged frequency-domain results are then provided in terms of spectra and sound maps (Section 3). The method for the detection of intermittent events in space and time is then explained in Section 4, and the results for the experimental data are given lastly in Section 5, before the conclusions.

2. EXPERIMENTAL SETUP

The experimental configuration under study is the aeroacoustic noise radiated by a forward-facing step in a flow. Some measurements were carried out in the anechoic wind-tunnel of the Institute PPRIME in Poitiers. The cutoff frequency of the anechoic measurement chamber is 300 Hz. The upstream nozzle has a cross-section of (0.46×0.46) m^2, and the streamwise length of the test section, located between the nozzle and the collector, is 1.39 m. The flow is bounded on its lower part by a flat wall with a forward-facing step, whose height is 30 mm. The edge of the step is located 285 mm downstream the nozzle. Measurements were carried out at a mean flow velocity of U=50 m/s, corresponding to a Reynolds number of 10^5, based on the step height. A general scheme of the configuration under study is proposed in Figure 1. The coordinate system is also indicated: x and y are the streamwise and spanwise directions, while z is the vertical axis.

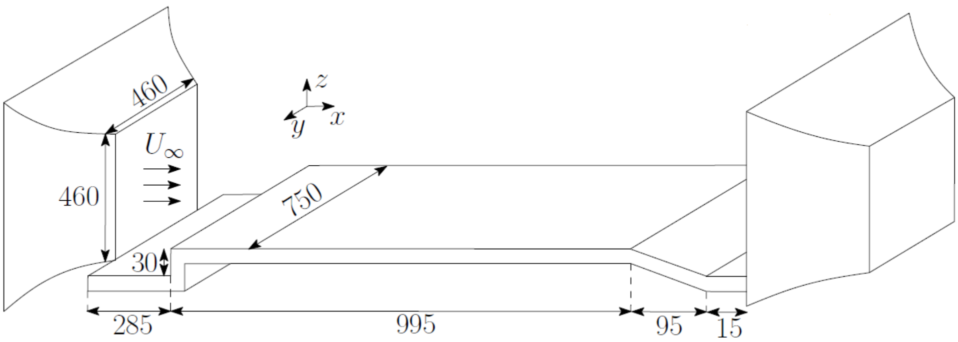

Figure 1 – Scheme of the test-section of the anechoic wind-tunnel, including the nozzle (left), the forward-facing step and the collector (right).

An array of 30 phased microphones (B&K type 4957) was set up for measuring the far-field acoustic field radiated by the step. The geometry of the array is a spiral made of 5 logarithmic branches of 6 microphones, inspired by the works of Underbrink (14). The geometrical center of the array is located horizontally outside the flow, 0.88 m above the step and 15 cm downstream the edge of the step. At this height it was checked that the microphones signals are not perturbed by the hydrodynamic pressure fluctuations of the wind tunnel flow. Concerning the array, some experiments using a well-controlled acoustic source showed that its operating frequency range ranges in the interval [500;7000] Hz. The acquisition system used for the array measurements is a 32-channel *ETEP* system operating at a 50 kHz sampling frequency.

3. FREQUENCY-DOMAIN RESULTS

In the following, the frequency spectra were computed by using time-average with the following parameters: the FFT were calculated by using 4096 points, and were averaged over a total acquisition duration of 20 s (244 averages). The CSMs used for producing the beamforming sound maps were also calculated following the same averaging process.

The spectrum of the aerodynamic noise radiated by the step was computed. The signals measured by the array were beamformed in order to obtain a temporal signal focused on the step edge; in this way the array acts as a spatial filter, keeping in the energy the contributions of the waves coming from the step. The corresponding Power Spectral Density (PSD) of the noise measured in the wind tunnel with and without flow are plotted in

Figure 2. The spectral content of the noise radiated by the step is seen to lie well above the ambient noise level of the wind-tunnel: about 15 dB above for frequencies lower than 3 kHz, and less than 10 dB otherwise.

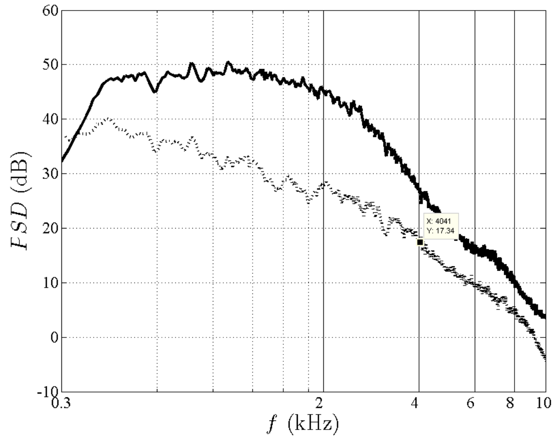

Figure 2 – PSD of a the acoustic far field measured at 50 m/s. Plain line: step noise; dotted line: wind-tunnel (background) noise.

The frequency-domain Delay-and-Sum Beamforming technique is then applied to the array data in order to obtain sound maps. The focusing plane is parallel to the array and located 0.88 m below (containing the edge step). In order to localize properly the aeroacoustic source, one has to take into account the flow effects on propagation; indeed the waves, propagating from the source to the array undergo some convection and refraction due to the mean flow and shear layer. The simplified model of Amiet (15, 16) was used in order to take into account properly those effects in the propagation times calculations. The background noise of the wind tunnel was also removed by subtracting the CSM of the background noise to the one obtained from the data with the step. The beamforming results are displayed for the frequency band [2950;3050] Hz in Figure 3. In Figure 3(a), the standard DSB technique is used and displays an elongated spot revealing that the source is located along the step edge. To improve the resolution of the analysis, the DAMAS technique (3) is used in Figure 3(b); the results confirm that the aeroacoustic source is located accurately along the step edge, confirming previous studies (11, 12). Conversely, the sound map does not reveal a dipolar behavior of the source, while theoretical (17) and numerical (11, 12) previous studies pointed out a dipolar radiation. By using DSB, a dipolar radiation would be evidenced by two energetic spots located around the edge (18).

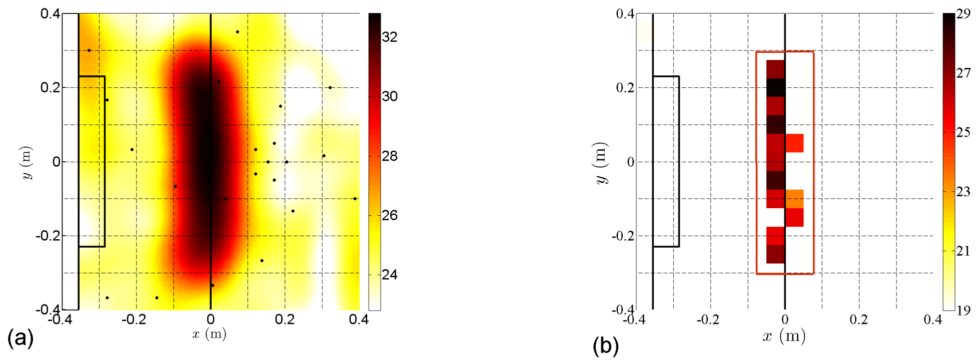

Figure 3 – Sound maps of the step noise at frequency 3 kHz (colorbar in dB). (a) DSB; (b) DAMAS deconvolution technique (the red rectangle displays the area of investigation for the intermittent events, see Section 5). The line at x=0 indicates the step, while the nozzle is represented on the left of the figures.

Results for frequencies in the range [2;6] kHz indicated a similar behavior to the one in Figure 3 with the following characteristics. For frequencies lower than 3 kHz, the source was found to be located slightly upstream the step, and could be due to the non stationary behavior of the vortex upstream of the obstacle. For higher frequencies the source was shifted slightly downstream the edge, located in the shedding region.

4. TIME-DOMAIN DSB FOR THE DETECTION OF INTERMITTENT EVENTS

In this section, the methodology for detecting and locating intermittent acoustic events is presented. Let us denote by $p'_a(\mathbf{r_m},t)$ the measurement of acoustic pressure at time t of a microphone located in $\mathbf{r_m}$. The array response by the time-domain DSB focused on a point $\mathbf{r_F}$ is then (2):

$$z(\mathbf{r_F},t) = \frac{1}{M}\sum_{m=1}^{M} w(\mathbf{r_m},\mathbf{r_F})p'_a(\mathbf{r_m},t+\tau_{m,F}). \qquad (1)$$

$w(\mathbf{r_m},\mathbf{r_F})$ and $\tau_{m,F}$ are respectively the amplitude and time corrections of the M microphone signals measured by the array. In particular, the terms $\tau_{m,F}$ are calculated using the Amiet model (15, 16) which takes into account the effects of the wind-tunnel flow on the propagation of acoustic waves.

The example of a numerical point source generated at a point of coordinates (-0,1;0) in the $(x;y)$ plane is proposed here. The source is a Gaussian pulse with a full-width at half maximum of 0.264 ms and emitted at time t_0. The array geometry is the one that is used in the experiments. We define a focusing plane for the array located at 0.75 m, parallel to the array plane and which dimensions are (1×1) m^2. Figure 4 represents the absolute value of the function defined in Eq. (1), calculated for a set of points $\mathbf{r_F}$ located in the focusing plane, for some instants surrounding the emission time of the pulse t_0. The center of the focusing plane, located at coordinates (0;0), is in front of the geometrical center of the array. The plot shows the convergence of an energetic wavefront to the source position located in (-0.1;0). This phenomenon can be explained by the fact that time-domain DSB is equivalent to a time-reversal technique applied to the wavefront portion measured by the array. A maximum of energy is then observed at time t_0 and at the pulse location. It is then possible, after the calculation of Eq. (1) function, to estimate the location and time emission of an intermittent acoustic source by seeking local spatio-temporal maxima.

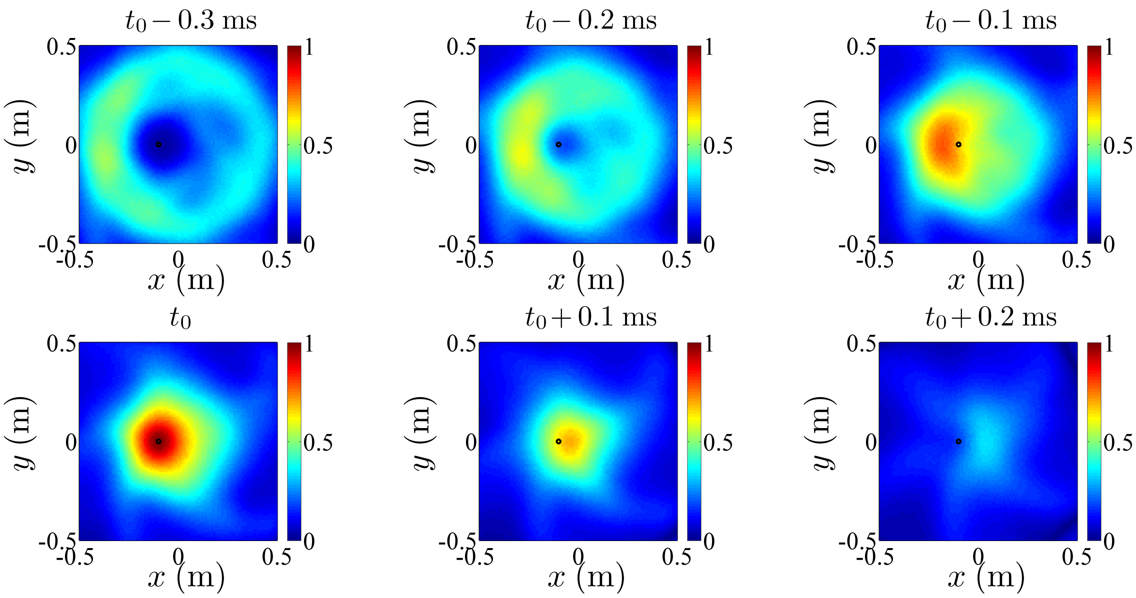

Figure 4 – Localization of a simulated source with time-domain DSB: the function of Eq. (1) is represented in the focusing plane at several instants bracketing the emission instant t_0. The source is at $(x;y)$ = (-0,1;0) m et at 0.75m from the array. The colorbar is non-dimensionalized with the absolute value of the maximum pressure.

A technique for the detection of intermittent sound sources in a given region can then be developed, which enables to get the space and time information of intermittent acoustic sources (19). This procedure is composed of 4 steps which are briefly summarized here :

- step 1 : The mean position of the acoustic source is first estimated via frequency-domain DSB associated to the deconvolution algorithm DAMAS (3). That step settles the boundaries of the region (called investigation area in the following) where intermittent sources will be seeked;

- step 2 : the absolute value of the function defined in Eq. (1) is calculated for each time step of the measured signal in a focusing plane which boundaries have been previously estimated (the investigation area). We make the hypothesis that two sources are never emitted exactly at the same time (uniqueness of the source at a given time). A function denoted by $z_{\max}(t)$ is then calculated, which describes the temporal evolution of the instantaneous maximum pressure (in absolute value) on each acoustic map;

- step 3 : the detection of extrema's instants upon the $z_{\max}(t)$ function is then performed. In order to select the most energetic events, a classical method (5) is to set a threshold for the detection. Its choice is not explained here ; the threshold used here makes the best compromise between the energy of intermittent events and their duration. Emission instants t_i of the most energetic intermittent events generated by the source are estimated that way;

- step 4 : The $(x_i; y_i)$ position of each intermittent event is finally obtained by applying the time-domain DSB on each instants t_i that have been previously estimated.

In the next section, that methodology for the detection of intermittent events will be applied to the experimental forward-facing step noise.

5. DETECTION OF THE INTERMITTENT SOURCES RADIATED BY THE STEP

First, one has to set an area of investigation in which the intermittent events will be searched. Following Section 3, it was found that the source is an elongated source along the step spanwise; the area of investigation was then set to a rectangle surrounding the edge, x and y being contained in the intervals [-0.1,+0.1] and [-0.3;+0.3], respectively. In this way the algorithm performs quicker and discards any non-physical artifact in the results.

First, a statistical analysis was carried out in order to assess the random nature of the succession of intermittent events. The array signals were beamformed into the area of investigation by computing the time-domain DSB pressure of Eq. (1). The output signal $z(\mathbf{r_F},t)$ was then averaged at each time step for all focusing points $\mathbf{r_F}$ located in the area of investigation (the focusing points are separated by steps of 5 mm). In this way we obtain a signal $p_{foc}(t)$ estimating the acoustic contribution to the array data of the waves emanating from the area of investigation. A portion of the signal $p_{foc}(t)$ is represented in Figure 5. As explained in Section 4, the intermittent events correspond to local maxima of the the signal $z(\mathbf{r_F},t)$. A thresholding process was then applied in order to keep the most energetic events contained in the signal $p_{foc}(t)$ (5); the threshold value in this study was set to 1.4 time $\sigma_{p_{foc}}$, $\sigma_{p_{foc}}$ being the standard deviation of the signal $p_{foc}(t)$. This threshold was chosen after having assessed the value for which the best compromise was found between the total duration of the selected events and their contribution to the signal energy. In a study on the intermittency of jet noise (5), the threshold was set to a similar value, 1.5 time the standard deviation. The most energetic extrema were then selected (according to $|p_{foc}(t)| \geq 1.4\sigma_{p_{foc}}$), and the separation times between two successive events, noted down Δt_e, were calculated. A vector of values for Δ_{t_e} was obtained, which Probability Density Function (PDF) is displayed (in semi-logarithmic scale) in Figure 6. This linear law is typical of a Gamma law for the time lags separating uncorrelated events (5). The exponential decrease of this Gamma law indicates that the selected events appear in a random manner as a function of time, and are not governed by any deterministic mechanism. In the present case, the mean value for Δ_{t_e} is $\bar{\Delta}_{t_e}$ =0.830 ms, which correspond to a mean frequency rate of about 1.2 kHz.

Now the method for the detection of intermittent acoustic events presented in Section 4 is applied to the step noise. The function $z_{max}(t)$ is calculated and thresholded for values of less than 1.4 time the standard deviation (as explained above), in order to keep the most energetic events. A typical example of a selected event is represented in Figure 7; snapshots are displayed at instants bracketing the estimated emission instant of the event, noted down t_1, by steps of 0.1 ms. The red rectangle indicates the area of investigation for the sources. At the instant t_1, the pressure level is maximum at the point of coordinates (0;-0.2), located on one side of the step, meaning that the intermittent source radiating at t_1 is located at this position, interpreted as the emission point. Similarly to Figure 4, a wavefront convergence appears until it collapses at the emission point. This result, typical of the detected events, confirms the intermittent nature of the radiated noise; this event is due to a local fluid dynamics event occurring in the flow, producing a pressure variation radiating sound efficiently.

After having presented the case of an isolated event, a greater number of events can be investigated. The average duration of the events is about 0.3 ms. The spatial distribution for the emission locations was also

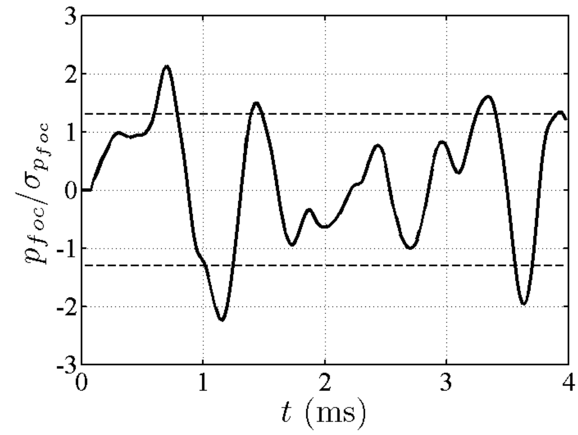

Figure 5 – Sample example of the signal $p_{foc}(t)$ (normalized by $\sigma_{p_{foc}}$) as a function of time (in ms). The dashed line indicates the threshold for selecting the events.

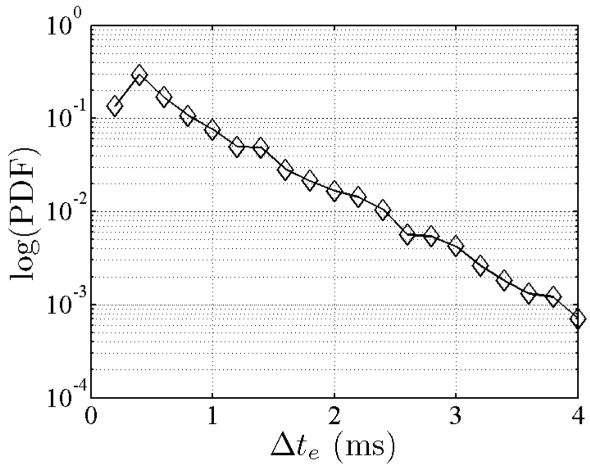

Figure 6 – Histogram (in semi-logarithmic scale) of the values found for the time steps Δt_e between the intermittent events.

investigated. Figure 8 displays the distribution of these positions for a set of 200 events. Those events are seen to be scattered on an area approximately centered on the step. The majority of the sources is however located slightly upstream the step, in the area corresponding to the unsteady vortex upstream the step. Those results are in good agreement with the results given by the frequency-domain beamforming (Figure 3). It can then be concluded that by using a time-domain imaging method based on DSB, it is possible to assess the intermittent nature of the aeroacoustic noise radiated by the step: this noise is the result of a great number of intermittent sources located randomly in the vicinity of the step, and emitted at uncorrelated times. The results provided by the frequency-domain DSB are obtained by a time-averaging process, and can be seen as representing an average estimate of the positions of the intermittent sources.

6. CONCLUSION

This study has shown that a time-domain imaging method can be used to investigate the intermittent nature of aeroacoustic noise, in particular the noise radiated by a forward-facing step in a flow. A methodology for the detection of intermittent acoustic events in a flow has been developed by using the standard time-domain DSB technique for processing the array data. The aim is to compute the temporal evolution of the pressure distribution projected onto a focusing plane parallel to the array. By using an algorithm for detecting the space-time maxima of this pressure distribution, a tracking in space and time of the intermittent acoustic events occurring in the flow can be achieved.

By applying this method to the aerodynamic noise generated by the step, a set of intermittent sources

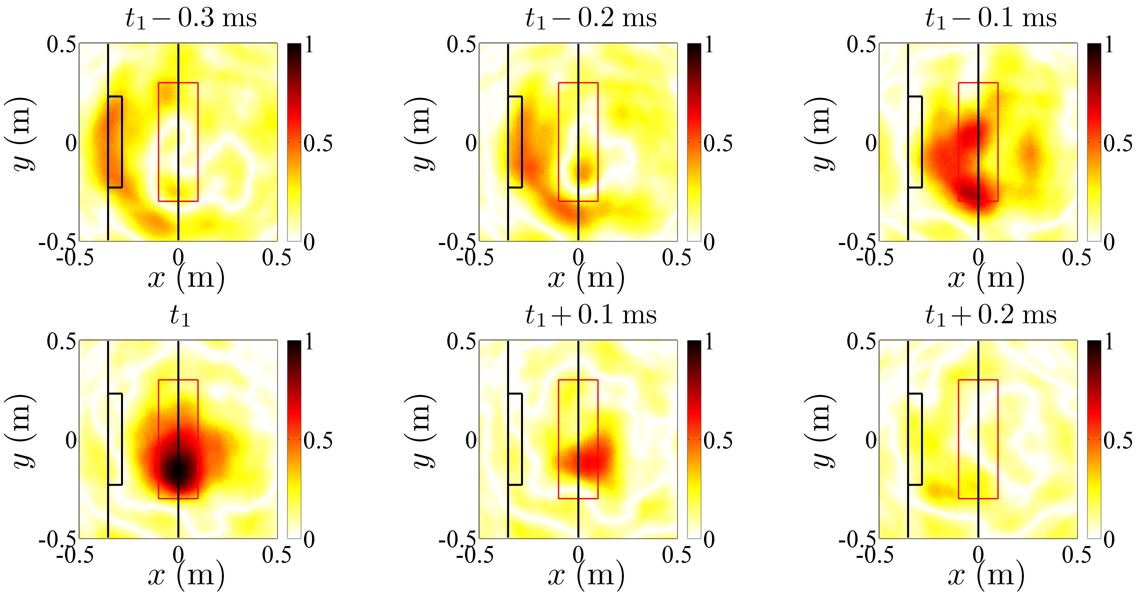

Figure 7 – Results for the time-domain DSB applied to the step noise at 50 m/s for an event emitted from the point (0,-0.2) at an emission time t_1. Each sub-figure indicates the field reconstructed in the focusing plane at several instants bracketing t_1. The red rectangle represents the investigation area for the intermittent sources. The colorbar is non-dimensionalized with the absolute value of the maximum pressure.

was computed. The spatial distribution of the sources has been shown to be in agreement with the source imaging computed by using the frequency-domain DSB technique. The noise source identified by the latter are the result of acoustic events of short duration (about 0.3 ms on average for the investigated case) emitted at positions distributed around the step. The frequency-domain DSB technique can be seen as an average estimate (in space and time) of the positions of the short events. These result will be completed in the future by the investigation of the flow events responsible for the emission of such events, to get a better understanding of the aerodynamic noise produced by objects in flows.

ACKNOWLEDGEMENTS

The authors warmly thank Pascal Biais, Janick Laumonier, Laurent Philippon, Philippe Szeger and Jean-Christophe Vergez for their technical support to the experimental work.

REFERENCES

1. Mueller TJ. Aeroacoustic measurements. Springer; 2002.
2. Koop L. Beamforming methods in microphone array measurements. Theory, practice and limitations. Von Karman Institute; 2007.
3. Brooks TF, Humphreys WM. A deconvolution approach for the mapping of acoustic sources (DAMAS) determined from phased microphone arrays. Journal of Sound and Vibration. 2006;294, p. 856-879.
4. Juvé D, M S, G GCB. Intermittency of the noise emission in subsonic cold jets. Journal of Sound and Vibration. 1980;71 (3), p. 319-332.
5. Kearney-Fischer M, Sinha A, Samimy M. Intermittent nature of subsonic jet noise. AIAA Journal. 2013;51 (5), p. 1142-1155.
6. Koenig M, Cavalieri AVG, Jordan P, Delville J, Gervais Y. Farfield filtering of subsonic jet noise : Mach and Temperature effects. 17th AIAA/CEAS Aeroacoustics Conference. 2011;Portland, Oregon.
7. Deneuve A, Druault P, Marchiano R, Sagaut P. A coupled time-reversal/complex differentiation method for aeroacoustic sensivity analysis: towards a source detection procedure. J Fluids Mech. 2009;642:181–212.
8. Padois T, Prax, C, Valeau, V, Marx D. Experimental localization of an acoustic sound source in a wind-tunnel flow by using a numerical time-reversal technique. Journal of the Acoustical Society of America. 2012;132:2397–2407.

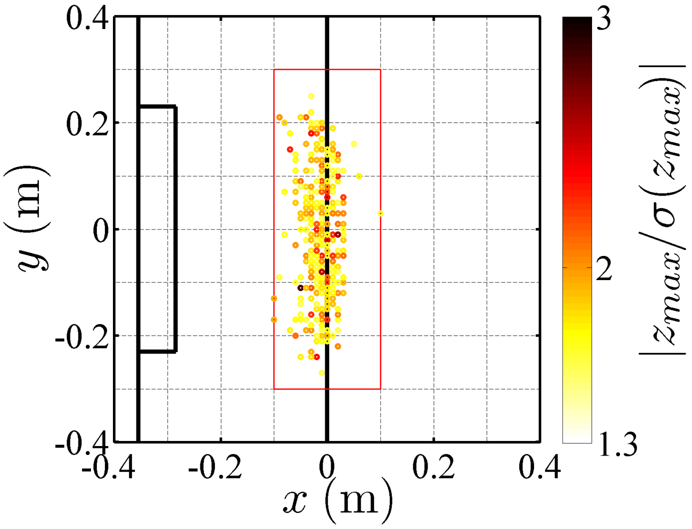

Figure 8 – Spatial distribution of 200 intermittent acoustic events detected by time-domain DSB at 50 m/s. The red rectangle represents the investigation area for the intermittent sources. The colorbar is non-dimensionalized with the standard deviation of the fonction z_{max}.

9. Mimani A, Doolan CJ, Medwell R P. Multiple line arrays for the characterization of aeroacoustic sources using a time-reversal method. JASA Express Letters. 2013;134:327–333.

10. Fink M. Time-reversal acoustics. Journal de Physique: Conference series. 2008;118:1–28.

11. Sabanca M. Noise generated by turbulent flow over forward facing steps. Computers & Fluids. 2009;38, p. 1467-1479.

12. Ji M, Wang M. Sound generation by turbulent boundary-layer flow over small steps. Journal of Fluid Mechanics. 2010;654, p. 161-193.

13. Martinuzzi RJ, Tropea CD. The flow around surface-mounted obstacles placed in a fully developed channel flow. Journal of Fluids Engineering. 1993;115, p. 85-92.

14. Underbrink JR. Circularly symmetric, zero redundancy, planar array having broad frequency range applications. US Patent No 6,205,224. 2001;.

15. Amiet R. Refraction of sound by a shear layer. Journal of Sound and Vibration. 1978;58 (4), p. 467-482.

16. Bahr C, Zawodny NS, Yardibi T, Liu F, Wetzel D, Bertolucci B, et al. Shear layer time-delay correction using a non-intrusive acoustic point source. International Journal of Aeroacoustics. 2011;10 (5-6), p. 597-530.

17. Howe MS. Influence of separation on sound generated by vortex-step interaction. Journal of Fluids and Structures. 1997;p. 11, p. 857–872.

18. Liu Y, Quayle AR, Dowling AP, Sijtsma P. Beamforming correction for dipole measurement using two-dimensional microphone arrays. Journal of the Acoustical Society of America. 2008;124 (1), p. 182-191.

19. Fischer J. Identification de sources au voisinage de corps non profilés par formation de voies fréquentielle et temporelle. PhD., University of Poitiers; 2014.