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Improving the localisation of sources based on shaped arrays with a reduced number of microphones

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The capacity of hardware today allows carrying out noise sources localisation without moving the microphone array at a limited financial and time cost. The single shot measurement processed with beamforming is comfortable for the user. But the quality of the results limits the interest of such systems: bad resolution, low dynamics and no quantitative levels.

This article proposes complementary methods to beamforming to improve the results based on the same single measurement. First a near field beamforming algorithm is developed improving the resolution, and then an inverse method is applied based on the transfer function between the sources and the acoustic pressure at microphone positions or on the hologram in order to "clean" the localisation map and to give quantitative results.

1 Introduction

The number of channel for acquisition hardware systems has increased in the last decade. In the field of noise source localization, this progress gives to the user the easiness to get noise maps from a single shot measurement. But the methods of noise source localization have to be adapted to give good results from a reduced number of microphones on the array.

The noise source localization methods are grouped in 3 families: beamforming, acoustic holography (NAH) and inverse frequency response function (IFRF). Acoustic holography needs a regular 2D microphone array, and the necessary high number of channels does not fit one shot measurement with a reasonable cost. This family is not studied in this paper.

Beamforming is convenient because it works from a shaped array. The basic algorithm is detailed in [1]. This article first deals with this localization method. Results are satisfying in middle frequency range, but the resolution is too poor in low frequency and levels are not quantitative.

The last family (IFRF) works from the transfer matrix between microphones and sources. It usually implies a larger number of microphones than sources. The method used in this article [2] works from under-determined system (fewer microphones than localization point on the map). It solves the system using the regularization of Tikhonov.

In a second time, this method is extended working with a transfer matrix including the beamforming map instead of directly the array. The results are improved in noisy measurement conditions because the localization map issued from the beamforming eliminates the extra noise.

Combining both methods: beamforming and IFRF, one shot measurement and a shaped array allow to get localization maps with a good resolution and quantitative results in noisy conditions.

The results are illustrated for each method with 2 artificial noise sources measured in different conditions.

2 Beamforming

2.1 Method

This technique is based on the different delays between microphones to receive the waves from the same source. For each point of the map which is supposed to be a source, the frequency components of each microphone are added with a shift of their phase corresponding to the delay between emission and reception (linked to the Rms microphone/source distance). Moreover a weighting is applied depending on the microphone, allowing placing the array in nearfiled:

$$s(f) = \sum_{m=1}^{M} w_{ms} P(f) e^{i2\pi f \frac{Rms}{c}} \quad (1)$$

Maxima of level on the map correspond to source positions.

2.2 Array and performance

The performance of the array is characterized by its dynamic (levels of secondary and imaginary lobes) and its resolution (ability to separate 2 close sources) inside an operating frequency range.

The geometry of the array imposes the performances. With a single shot measurement, microphones are not regularly spaced on the array to out perform regular grid with a limited frequency range. This range is increased with a loss of dynamic.

In farfield, the resolution of beamforming depends on the distance between the array and the source (L), the size of the array (D) and the wavelength (λ):

$$d_{-3dB} = \lambda \frac{L}{D} \text{ (2) for L >= D (2)}$$

In nearfield the resolution is improved with the expression:

$$d_{-3dB} = \alpha * \lambda \quad (3)$$

The α parameter asymptotically evolves from 1 to 0.3 with the distance L (from the size of the array D and to the microphone space sampling).

For an example, a 54 microphones array formed with 3 circular sub-arrays of diameter 16, 32 and 50 cm is used to localize 2 correlated sources 30 cm away from each other. The distance between the array and the sources (L) is 20 cm. Results are presented on figure 1 and 2 for the frequency range [900-1000] Hz and [1000-1100] Hz. 1000 Hz is the lower frequency range where they are separated (0.8 λ).

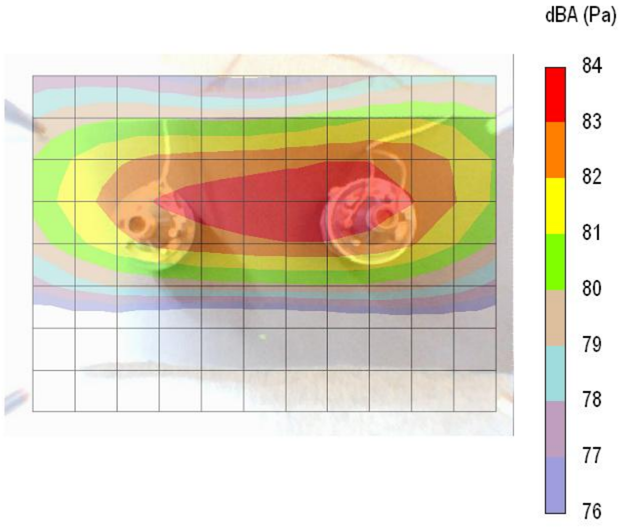

Fig 1. Beamforming: [900-1000] Hz

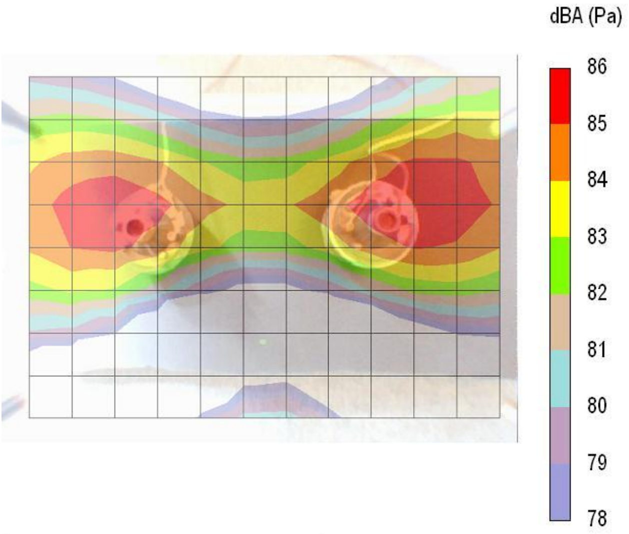

Fig. 2 Beamforming: [1000-1100] Hz

This resolution is reasonable down to 1000 Hz (10 cm) with small noisy object (engine, car door) but in low frequency the resolution is too pour and another method of localization has to be applied.

3 IFRF from under-determined system

3.1 IFRF from microphone array method

This localization method is based on the inversion of a transfer function matrix between the receivers (microphones of the array) and the sources (calculation points of the map). The expression of one element of the matrix is:

$$H(f) = \frac{1}{4\pi Rms} j\rho 2\pi \frac{f}{c} e^{-j2\pi f Rms / c} \quad (4)$$

The difficulty in this case is the under-determined system (more points on the map than microphones on the array). A technique is developed in [2] to solve such a problem using the "right pseudo inverse" [3] with the Tikhonov regularization based on the L-curve analysis [4].

The algorithm has to retain a solution with the help of the L curve. This curve links the "mue", a normalized least squares residue (difference between measured and calculated microphone pressure level) and the normalized "eta" norm of the solution (for the normalization of eta, the correction introduced in [5] has to be applied). First one is increasing while second one is decreasing with the regularization amount (refer to figure 8). The number of sources that is retained corresponds to the first compromise "mue+eta" which over passes this value for one source (the values after the angle of the L curve).

Such a method is applied with the preceding example of 2 correlated sources. The figure 3 now separates the sources for the same frequency range than figure 1. The resolution is improved by a factor of 2 because the sources start to be separated from the low frequency 400 Hz.

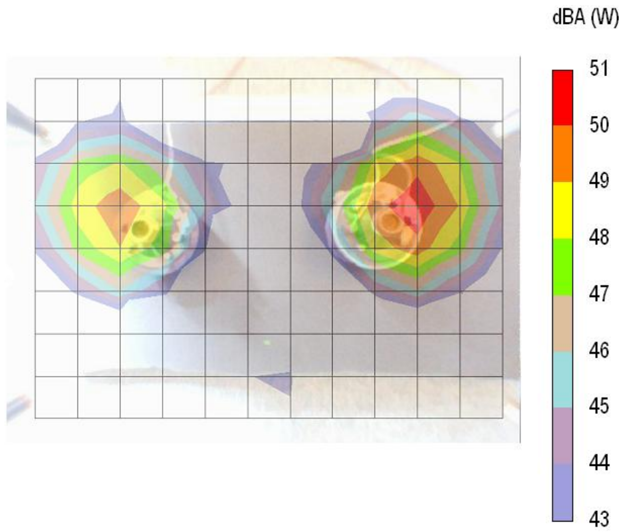

Fig. 3 IFRF array: [900-1000] Hz

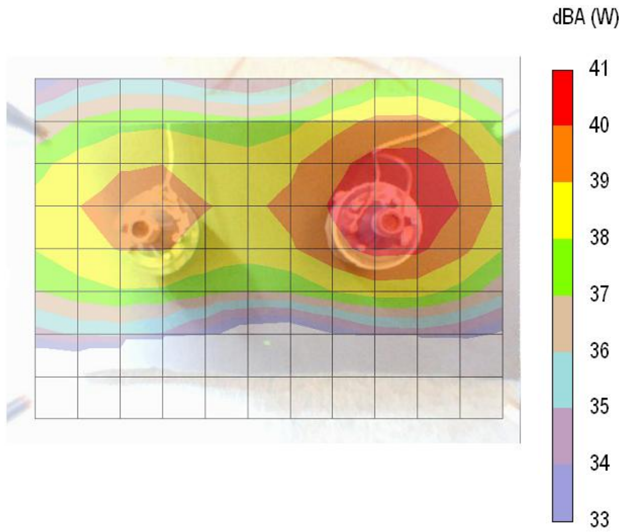

Fig. 4 IFRF array: [400-500] Hz

This method has also the advantage to give quantitative results. The integration of the level for the calculated points that rounds the sources gives its power spectrum.

Calculations are fast: the FRF matrix has a limited number of element (number of microphone multiplied by the number of point on the grid) and the SVD to solve the system is not time consuming.

3.2 Results in noisy measurement conditions

Microphones on the array sometimes record some extra noise coming from sources out of the map (for example with an engine noise coming from another face than the measured one or when reflections are important). In this case, the algorithm is disturbed by the extra sources measured by the microphone array but outside the map and the results are difficult to interpret.
The same type of example with 2 sources is processed with both methods: beamforming and IFRF. The maps presented on the figure 5 and the figure 6 now cover one of the source to get noisy conditions from the second one. The Beamforming method only gives a good localization on the Figure 5. Results presented on figures 6 show the first source and other maxima in the direction of the other source. The IFRF method from the transfer function between microphones and sources is improved with the consideration of the beamforming results in next paragraph.

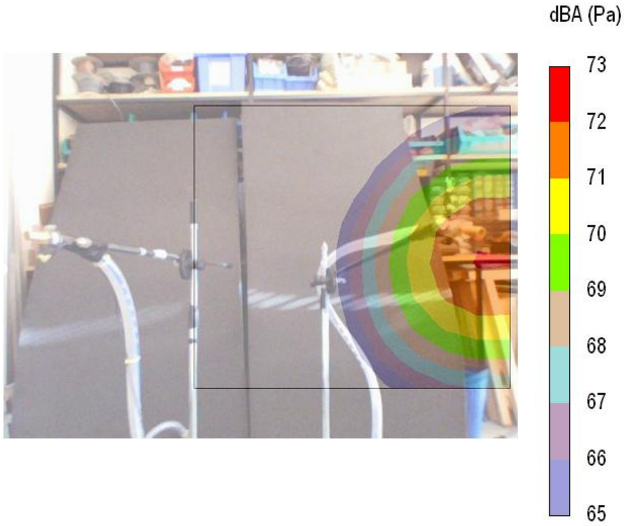

Fig. 5 Beamforming in noisy conditions: [1100-1200] Hz

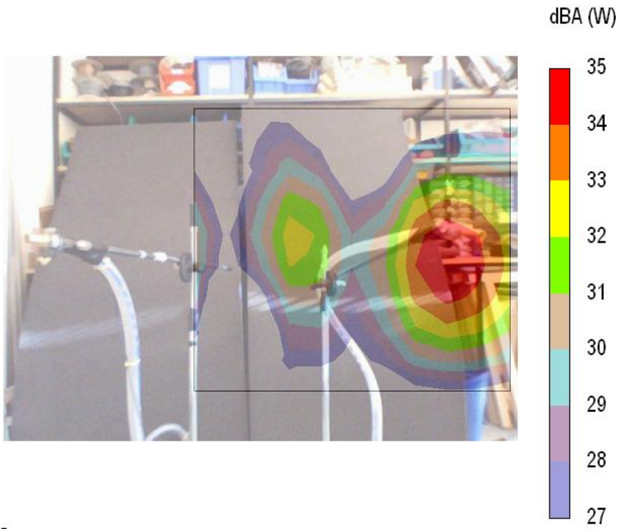

Fig. 6 IFRF from the array in noisy conditions: [1100-1200] Hz

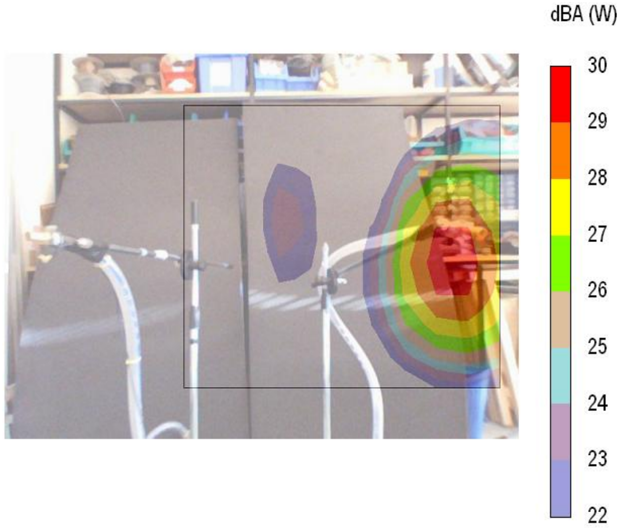

Fig. 7 IFRF from the beamforming map in noisy conditions: [1100-1200] Hz

3.3 IFRF from beamforming map method

This method uses the same algorithm to solve the inverse problem than the preceding one but the transfer functions change. They are established between the beamforming localization point x of the map and another point s of the same map for the sources. There is one more stage after the propagation from sources to microphones: the beamforming map. The new element of the transfer function matrix is derived from equations (1) and (4):

$$H(f,x,s) = \frac{-i\rho f}{2}\sum_{m=1}^{M} w_m \frac{1}{R_m(s)} e^{i\frac{2\pi f}{c}[R_m(s)-R_m(x)]} \quad (5)$$

This new method is applied with the preceding examples: two correlated sources and one source measured in noisy conditions. The L curves for IFRF methods from the array (ARRAY) and beamforming map (HOLO) are compared on figures 8 and 9. The results are similar for 2 correlated sources, because the L curves have the same evolution and present a real L shape. In noisy conditions, the compromise immediately increases with the array method while there is a small stability with the beamforming map improving the L curve shape. It is easiest for the algorithm in those conditions to define the sources.
The map presented on figure 7 computed from the beamforming map with the IFRF method shows that the ghost sources are quite lower than the first method from the microphones array.
The drawback of this method is the size of FRF and their complexity that implies long computations.

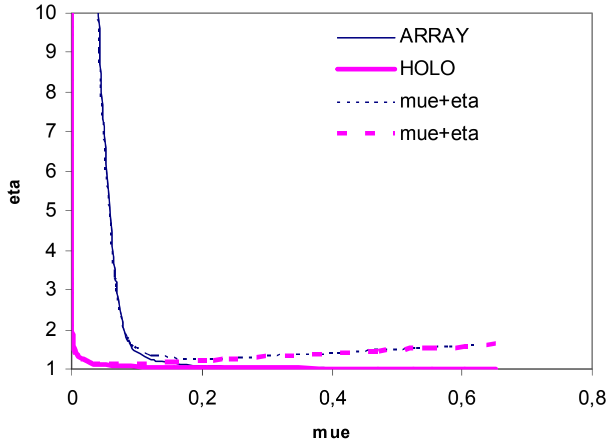

Fig. 8 L curve for 2 correlated sources (1150 Hz)

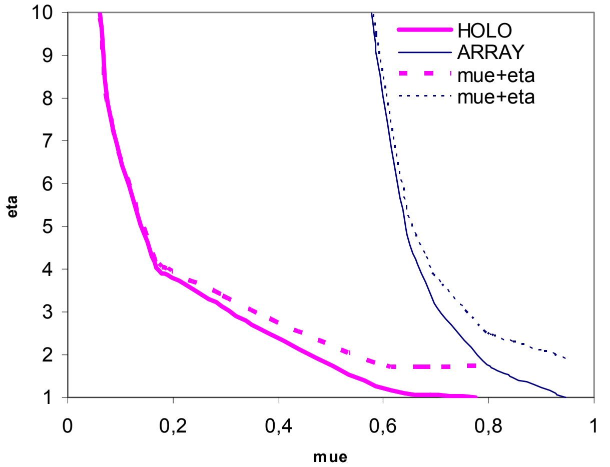

Fig. 9 L curve for 1 source measured in noisy conditions (1150 Hz)

4 Conclusion

The three methods presented in this article are complementary to carry out localization and quantification maps with limited financial and time cost. They have the advantage to work from shaped array. The beamforming method gives good results of localization in middle and high frequency. The IFRF method from the microphone array is interesting to improve the resolution in low frequency and to quantify the sources on the entire frequency range. In both cases, calculations are quick and allow the user to visualize the results in real time in post processing.
In noisy measurement conditions, the IFRF method from the beamforming map should only be preferred. It has the advantage to eliminate external noise sources to the map area. But calculations are long because they are proportional to the number of element in the transfer matrix (the square of the calculation points on the map!).

References

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