SOME NEAR-FIELD ACOUSTIC IMAGING TECHNIQUES IN NOISE RANGING

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ABSTRACT

Acoustical imaging of ship radiating noise sources requires the development of near field array processing. Performance analysis of a linear processing with static sources together with its adaptation to moving sources imaging are presented. Application of this processing to experimental measurements with static and moving electroacoustic sources is shown. Experimental results and theoretical analysis are in good agreement.

INTRODUCTION

Improvement of ship acoustic discretion requires the identification of radiating noise sources. An interesting way to achieve this purpose is to locate the radiating regions on the hull of the ship.

The acoustical facility could be a measurement station where the ship should follow, with fixed operating condition, a straight line parallel to a multihydrophones linear array.

Usually the aim of acoustic imaging is to identify the directions of a set of individual independent sources. Here, the situation is different. Sources are distributed on a ship of finite length, and they are to be separated spatially along the ship length in his own frame, rather than in angular direction in the observation frame. The relevant representation is therefore the amplitude of the noise source pressure as a function of frequency and axial position on the ship. The structure of the noise sources function may be complex, due to the number of independent sources, to their spatial dimensions (compact or distributed), and to their spectral or temporal content. In addition, this acoustic imaging must take into account the motion of the ship.

Although other techniques may be developed, the approach followed in this paper consists in adapting to imaging the classical beamforming technique.

1 THE NEED FOR NEAR FIELD IMAGING

Classical beamforming with sources in the far field of the array (plane wave appoximation) allows the spatial position of the sources to be determined if their radial distance D is known (see fig. 1 for definitions). The measurement of θ_0 yields $X_0 = D \, tg\, \theta_0$. The angular resolution of such an array being approximately $\Delta(\sin\theta) \sim \frac{\lambda}{L}$ (λ is the acoustic wavelength), its spatial resolution will be

$$(1) \qquad \Delta X \sim D/\cos^3\theta_0 \cdot \frac{\lambda}{L}$$

The best resolution seems to be obtained when D $\ll$ L but the plane wave approximation becomes irrelevant . The shortest distance D for this approximation is controlled by the limit of the Fresnel zone of the array $D_m \sim \frac{2\pi L^2 \cos\theta_0}{\lambda}$, so that the minimum value of ΔX is :

$$(2) \qquad \Delta X_m \sim 2\pi L/\cos^2\theta_0$$

To improve the angular resolution, the length of the array must be large with respect to the wavelength, so that $\Delta X_m \gg \lambda$. To obtain a better spatial resolution, the measurement has to be made in the near-field of the array, and the curvature of the wave fronts has to be taken into account.

Even in this case, the spatial resolution will never be very much smaller than the wavelength, If additional information on the sources is not known. Without such an information, the source function is not uniquely determined by the radiated pressure field, according to the Kirchhoff integral. One must then choose a particular representation for the noise source pressure description. Here, this representation will be the simplest one : an equivalent monopole source distribution along a straight line. The array processing presented here is the adaptation to this near-field imaging of the classical linear beamforming.

2 NEAR-FIELD ARRAY PROCESSING AND PERFORMANCE ANALYSIS IN THE STATIC CASE (ref.1)

In presence of a single plane wave and additive uncorrelated noise of same variance σ on each sensor, the optimal estimation for its amplitude and direction is obtained by classical beamforming. For a near-field array of N sensors, the equivalent of the plane wave is given by a single monopolar source of amplitude A and location $\vec{x}_0$ (fig.1). The pressure on the sensor i of location $\vec{y}_i$ is

$$(3) \qquad p(\vec{y}_i) = A\frac{e^{ik|\vec{y}_i - \vec{x}_0|}}{|\vec{y}_i - \vec{x}_0|} + b_i \quad , \text{with } \langle b_i b_j \rangle = \sigma^2 \delta_{ij} \text{ and } k = \frac{2\pi}{\lambda}$$

It can be shown that the optimal estimate $\hat{\vec{x}}$ of $\vec{x}_0$ maximizes the function

$$(4) \quad B(\vec{x}) = \left(\sum_{i=1}^{N} 1/|\vec{y}_i - \vec{x}|^2 \right)^{-1} \left| \sum_{i=1}^{N} p(\vec{y}_i) \frac{e^{-ik|\vec{y}_i - \vec{x}|}}{|\vec{y}_i - \vec{x}|} \right|^2$$

and the optimal estimate $\hat{A}$ of A is :

$$(5) \quad \hat{A} = \left(\sum_{i=1}^{N} 1/|\vec{y}_i - \hat{\vec{x}}|^2 \right)^{-1} \sum_{i=1}^{N} p(\vec{y}_i) \frac{e^{-ik|\vec{y}_i - \hat{\vec{x}}|}}{|\vec{y}_i - \hat{\vec{x}}|}$$

As in classical beamforming, these estimates will be used, even with an unknown monopole source distribution. They are obtained by focusing the array and looking for the points giving the best contrast. The performance of this array processing is the following :

- the spatial resolution defined by the difference between the maximum of ($\vec{x}$) and the first zero-crossing of B ($\vec{x}$) around $\vec{x} = \hat{\vec{x}}$ is

$$(6) \qquad \Delta X = \frac{\lambda D}{L \cos^3 \theta_0} \qquad \text{if } L \lesssim D$$

if L $\gg$ D, B(X) is close to $J_0(k|X - X_0|)$, so that

$$(7) \qquad \Delta X = 0{,}38\ \lambda$$

For a fixed distance D, it is therefore not very useful to increase the length L when L $\gtrsim$ D.

Figure 2 shows simulated results for B (X) when the source is at location X = 0 for various values of the reduced wave-number K = kL, with D = L and N = 21

- the depth of field is approximatively :

$$(8) \quad \Delta \sim 3{,}3\ \lambda \left(\frac{D}{L}\right)^2 \qquad \text{when } L \lesssim D$$

Figure 3 shows simulated results for the same source and array parameters as in figure 2 and for some values of K.

- with N sensors equidistant of Δy $[(N-1)\Delta y = L]$, $B(X)$ shows spatial side-lobes like in classical beamforming. Also spatial aliasing appears, at angular positions $|\sin\theta - \sin\theta_0| \sim \lambda/\Delta y$, but with shape and amplitude different from far-field beamforming (fig.4).

3 EXPERIMENTAL RESULTS IN THE STATIC CASE

To evaluate the performance of a near-field array, an experiment has been carried out in the Castillon's facility of GERDSM. The array consists of 19 hydrophones spaced of 0,5 m and immersed horizontally at 20 m. Two electroacoustic transducers have been placed in front of the array at different positions ; they are driven at different frequencies (sine or third-octave bands). Some results of the array processing are shown in fig. 5 to 7. It appears that the experimental performance in spatial resolution and depth of field of the array are in good agreement with the prediction.

4 ADAPTATION TO MOVING SOURCES

The same near-field array processing can be adapted when the sources are in motion at a constant speed V. The principle is then to catch a set of single pictures of the sources in the frame of the array, each of them corresponding to a small displacement δX of the sources. The pictures are then averaged after shifting them in the sources frame with the help of additional information related to its trajectory.

Let T be the duration for a single picture ($T = \delta X/V$), and Δf the frequency resolution ($\Delta f = 1/T$). Due to the Doppler effect, the various array sensors do not receive the same frequency for a source at a frequency f. The maximum difference between two received frequencies must remain within Δf for a significative computation of B (X). Let φ_i be the angle giving the position of the source with respect to sensor i (fig.1). The Doppler shift on this sensor is : $f_d = f M \sin\varphi_i \; (M = \frac{V}{c} \ll 1)$,

and the maximum differential Doppler shift is $\delta f_d = f M \cos\theta_0 \Delta\varphi$ with $\Delta\varphi \# \cos^2\theta \frac{L}{D}$ ($D \gtrsim L$).

With the spatial resolution $\Delta X = \frac{\lambda D}{L\cos^3\theta_0}$,

$$\delta f_d = \frac{V}{\Delta X} \qquad (9)$$

Therefore $\delta f_d < \Delta f$ if

$$VT = \delta X < \Delta X \qquad (10)$$

In conclusion, the condition required to get each picture is that the displacement of the source must be smaller than the spatial resolution of the array.

An experimentation was done at the Lake Castillon facility with a vertical array of 19 hydrophones and an electrodynamic transducer mounted in a guided streamlined body (fig.8). The source location information was given by a revolution counter. The speed of the source was about 3 m/s. Figures 9-10 give typical results of this test that show the ability of the technique.

5 CONCLUSION

The experimental results show that the imaging technique based on near-field array processing is valuable for static or moving sources.

The applications of this linear processing are limited by the spatial resolution and the monopole source model.The spatial resolution limited to the wavelength becomes very poor at low frequencies and this technique becomes irrelevant when the wavelength is not small with respect to the length of the ship.

The acoustic image of the sources may be difficult to read if the real source structure is far from being of a monopolar type. To overcome such problems, particular signal processing techniques already developed for far-field location could be adapted to the near-field situation. It should be necessary to take into account the Doppler effect and have relevant information on the sources to model them.

REFERENCE

1. ELIAS, G. & MALARMEY, C. Utilisation d'antenne focalisées pour la localisation des sources acoustiques. 11th ICA Paris 19-27/7/83 Vol 6 pp 165-166.

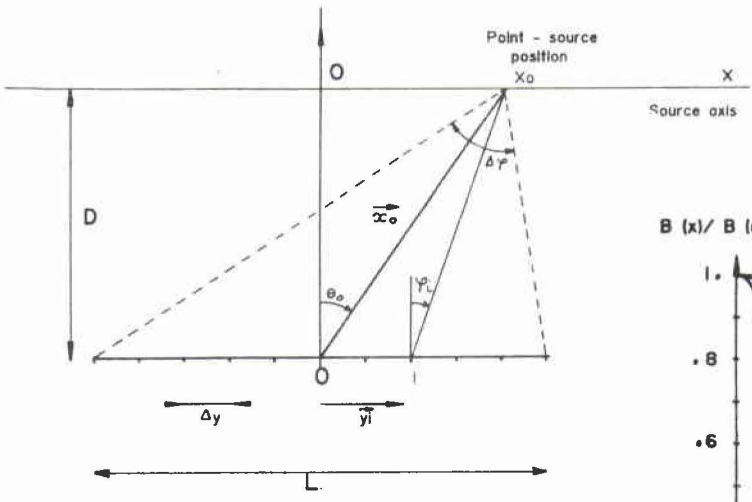

Fig I - Near field array geometry

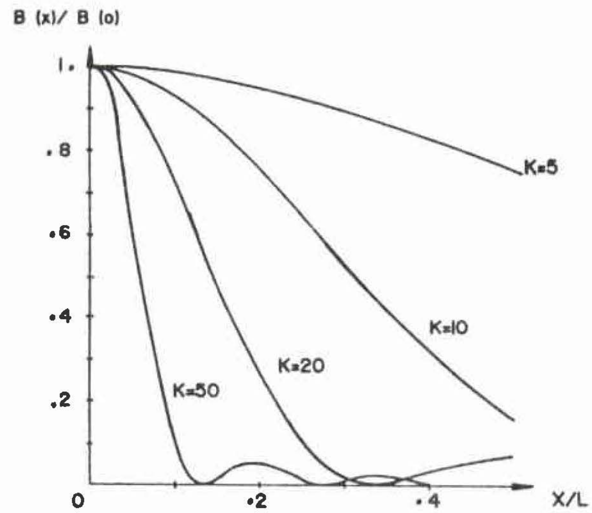

Fig 2 - Spatial resolution N=21 - D/L=I
Position of the source X=O

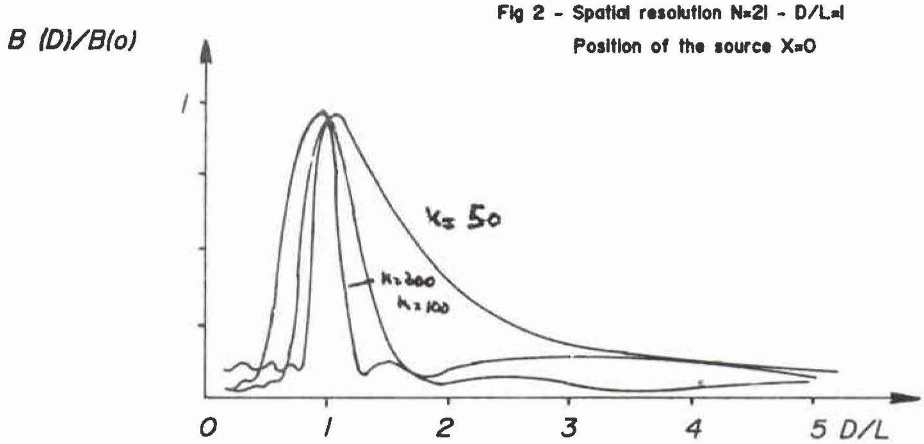

Fig 3 - Depth of field - N=21
Position of the source : D/L=I - X=O

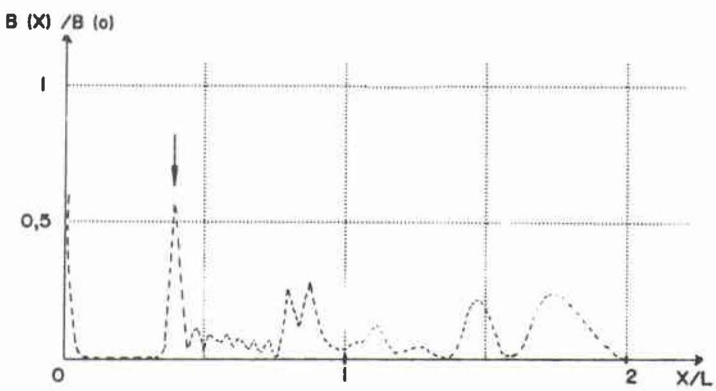

Fig 4 - Aliasing effect - N=I3 - D/L=I-K=200
Source position X=O - ↓ : $\sin\theta = \frac{\lambda}{\Delta y}$

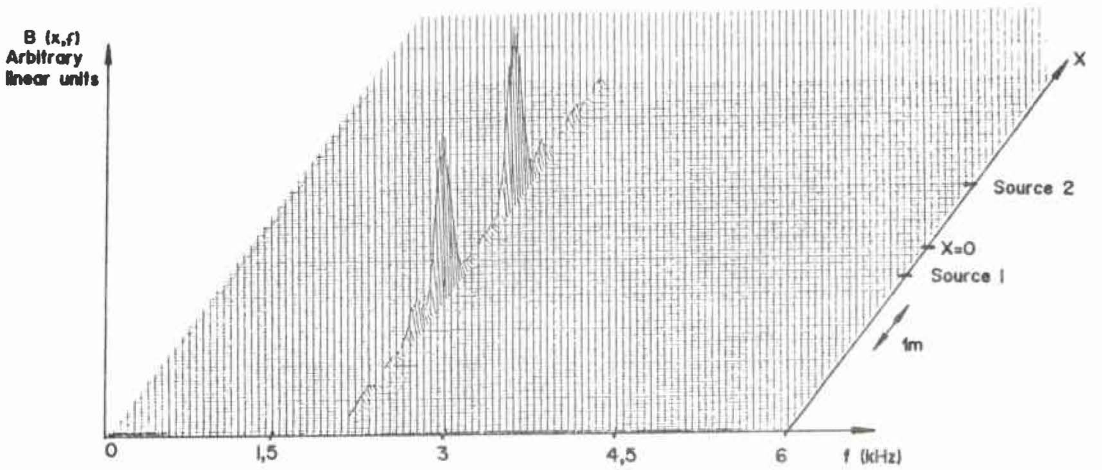

Fig 5 - Acoustic image B (x,y) of two electroacoustic sources excited with a sine wave at 2 kHz
N=19 - L=8m - D=7,2m

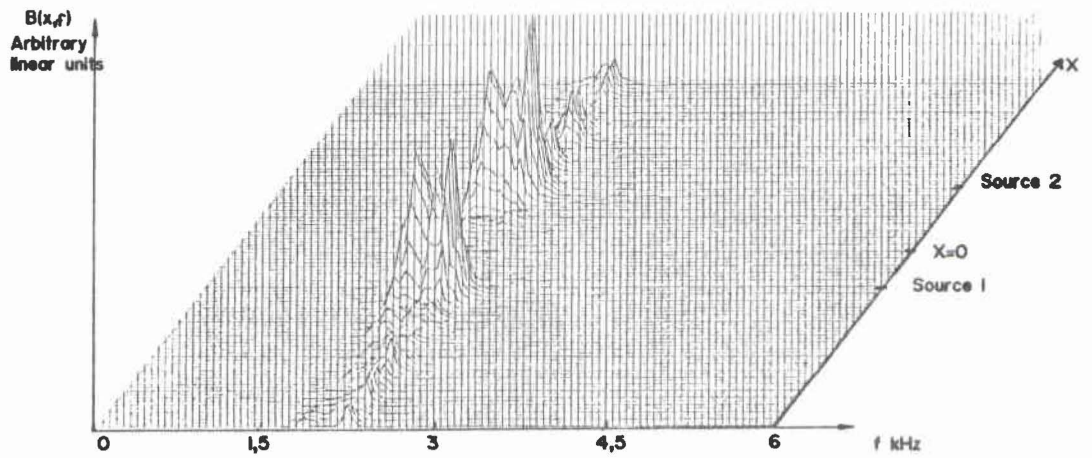

Fig 6 - Acoustic image B (x,y) of two electroacoustic sources excited with
a third octave band at 2kHz N=19 , L=8m , D=7,2m

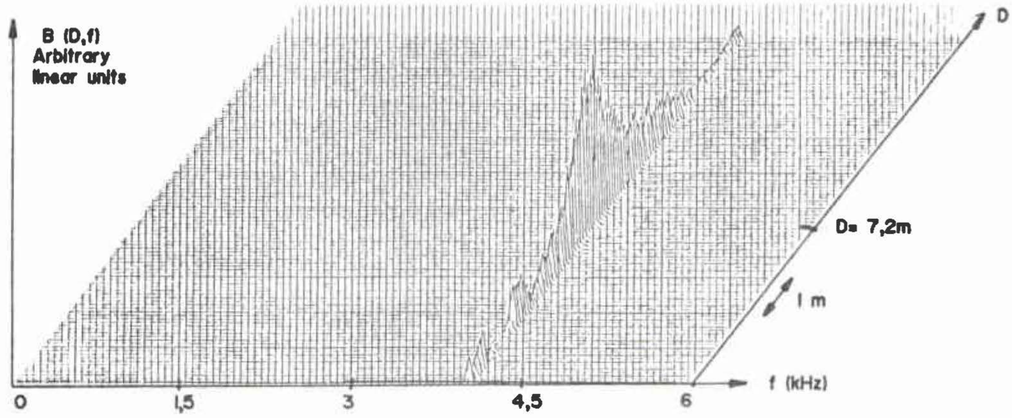

Fig 7 - Depth of field : Acoustic image of an electroacoutic source excited by
a sine wave at f= 4 kHz - N= 19 - L= 8m
Source position X= 1,5m - D= 7,2 m

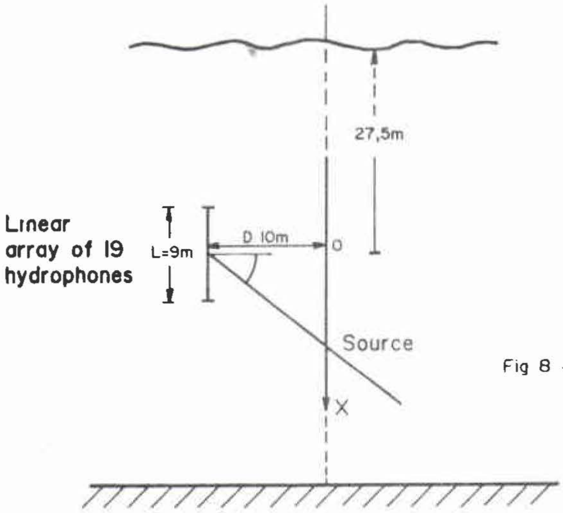

Fig 8 - Experimental set-up for moving source imaging

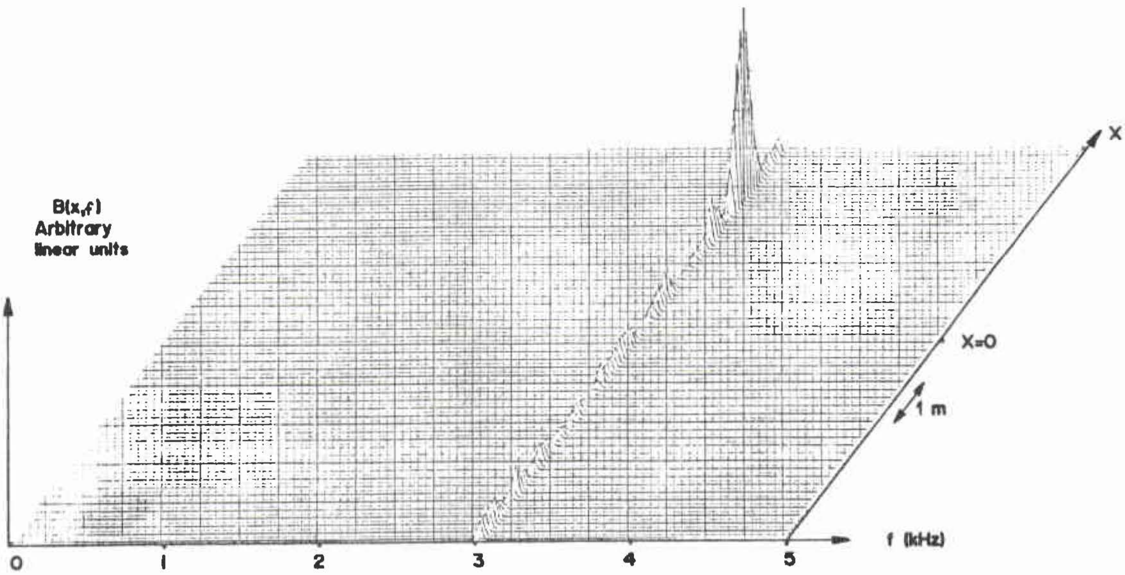

Fig 9 - Single image of the moving source excited at y=3kHz in the array frame
V= 3m/s

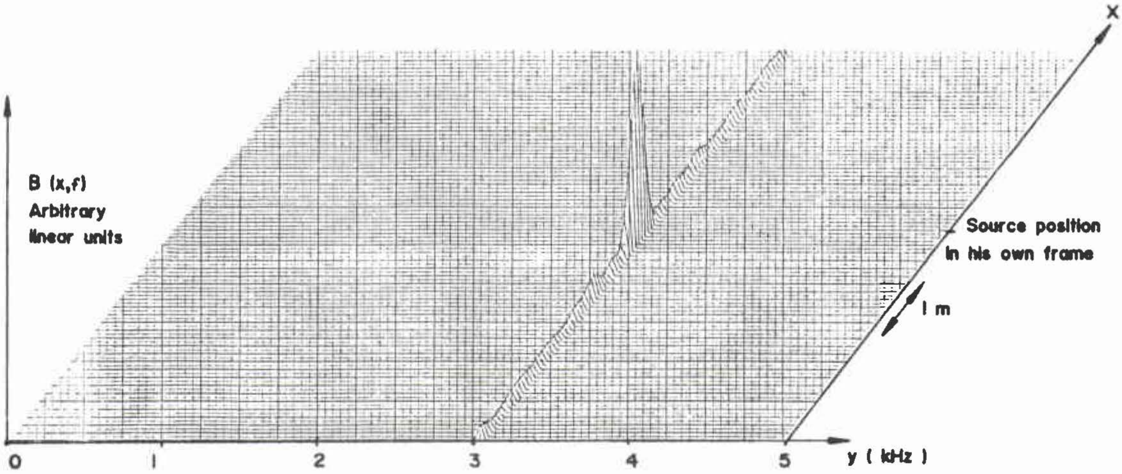

Fig 10- Averaged image of the moving source (V=3m/s) in his own frame
over 40 single images (the source has covered 8m)