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Towed array plane and non-plane wave beamforming under ship's maneuvering*

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Abstract. Towed hydrophone arrays are commonly used for determining the spatial characteristics of the underwater acoustic field. The assumption that the hydrophones lie in a straight and horizontal line is often made when beamforming the hydrophone outputs. However, due to tow vessel motion, ocean swells and currents the array adopts a nonlinear shape and the beamformer output is degraded. In order to estimate the positions of the hydrophones, an array was instrumented with a set of positioning sensors: compasses, tiltmeters, accelerometers and pressure gauges. This paper presents the array deformations recorded at sea when the tow vessel is turning and along straight line tracks. The influence of the observed deformations on the performance of the conventional beamformer output is discussed and illustrated with simulated and real acoustic data. In particular it is shown that the sensor positioning information allows for introducing the appropriate corrections on the plane-wave beamformer and obtain an unambiguous localization of sound sources in the 0-360° plane under heavy ship's maneuvering. Non-plane wave beamforming using a normal mode model shows that towed array deformations are also extremely important for source localization. In this case, the influence of towed arrays deformation in the vertical plane is studied in particular, since this deformation is significant even when the array is being towed along a straight line track.

1. INTRODUCTION

Different underwater acoustic techniques, like beamforming, use data sampled by towed arrays. When processing those data, very often the array is assumed straight and horizontal, what gives rise to the design of efficient computing algorithms, specially if the hydrophones are uniformly placed. In a real environment, due to underwater currents, swell, and other effects, some disturbance of the array shape is expected, even thought the tow ship lies in a straight track and the speed and course fluctuations are small. Larger deformations are observed when the tow ship is maneuvering. Some beamforming algorithms are robust to small array shape disturbances, however with larger deformations the performance of those algorithms decreases and in those conditions their outputs are meaningless. To avoid this problem, the hydrophone positions must be estimated and this information introduced in the beamforming algorithms. The present work addresses the problem of determining the

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influence of the array deformation on the beamforming output. The study starts from a set of array shapes recorded at sea from a towed array instrumented with passive positioning sensors (compasses, tiltmeters, accelerometers, pressure gauges). An interpolation scheme was used to estimate hydrophone's positions. Array shapes were recorded both when the tow vessel was turning and along a straight line track. The plane-wave and the full-field beamformer outputs are illustrated with simulated and real acoustic data. In the plane-wave case the conventional beamformer output is presented and it is shown that the right-left ambiguity problem can be solved if the array is deformed and if that deformation is considered when processing the acoustic data. In the full-field case, the influence of the array deformation in source localization (range-depth-bearing) is discussed. Here, a minimum variance beamformer is considered.

2. BEAMFORMING

Considering the conventional (Bartlett) processor and a narrow frequency band *f*, the beamformer is defined by

$$b_{CV}(\xi) = \mathbf{E}\left[\left|\mathbf{y}^H(\xi_T)\mathbf{p}(\xi)\right|^2\right] = \mathbf{p}^H(\xi)\mathbf{R}_y(\xi_T)\mathbf{p}(\xi), \qquad \xi \in \Gamma \tag{1}$$

where $b_{CV}(\xi)$ is the beamformer output for a search parameter ξ in the search space Γ, ξ_T is the true value of the search parameter ξ, $\mathbf{y}$ is the vector which elements are the complex spectral components of the hydrophones at frequency *f*, $\mathbf{y} = col([y_1, y_2, \ldots, y_M])$, M is the number of hydrophones, $\mathbf{p}$ is the replica of the acoustic field and $\mathbf{R_y}$ is the cross-power spectral matrix. The beamformer output should exhibit a maximum for the search parameter ξ that matches the true value ξ_T. In this work the minimum variance (Capon's) processor is also considered. The beamformer output obtained with this high-resolution processor is given by [1]

$$b_{MV}(\xi) = \left[\mathbf{p}^H(\xi)\mathbf{R}_y^{-1}(\xi_T)\mathbf{p}(\xi)\right]^{-1} \tag{2}$$

where the symbols have the same significance as in (1).

2.1 Plane-wave beamformer

Assuming that the acoustic pressure field can be modeled as a sum of plane-waves and that the array has shape can be parametrized in the coordinate system illustrated in figure 1, the replica field **p** is given by

$$\mathbf{p} = col(\left[1, \exp(jk\{(x_2 \sin\varphi - y_2 \cos\varphi)\}), \ldots, \exp(jk\{(x_M \sin\varphi - y_M \cos\varphi)\})\right]), \tag{3}$$

where (x_i, y_i) is *i*-th hydrophone coordinates and *k* is the wavenumber, $k=2\pi/\lambda$, λ being the wavelength of the plane wave. In this case the search parameter, ξ in (1), is the source field direction noted here as φ.

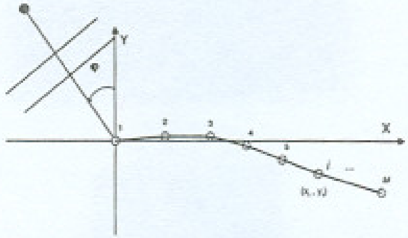

Figure 1: array axis system orientation

2.2 Full-field beamformer

When a full-field beamformer is considered in source localization, frequently a normal-mode model is considered. In this case the i-th element of the replica vector **p** in a cylindrical coordinate system is given by [2]

$$\mathrm{p}(r_i, z_i) = \sum_{m=1}^{N} \frac{\Phi_m(z_s)\Phi_m(z_i)}{\sqrt{\mathrm{k}_r(m) r_i}} \exp(-\alpha_r(m) r_i) \exp(jk_r(m) r_i) \quad (4)$$

where p is the acoustic pressure, r_i is the horizontal range of the i-th sensor and z_i is its depth (i=1,...,M), z_s is the source depth , N is the number of modes , Φ_m is the m-th modal function , $\mathrm{k}_r(m)$ is the horizontal wavenumber for the m-th mode and $\alpha_r(m)$ is a loss factor in the r direction for mode m.

3. RESULTS

The results presented in this section were obtained from towed array positioning sensors and respective acoustic data acquired during a sea trial that took place in the Strait of Sicily. We concentrate on the data acquired in a 20 minutes interval during a 180° port turn of the tow ship, since in those conditions we expect significant disturbances in the array shape. Before and after the turn the tow ship was keeping a constant heading.

3.1 Estimated array shapes and associated beam power patterns

The array used in the experiment has 40 uniformly spaced hydrophones at 4m and was instrumented with 6 sets of compasses, tiltmeters and acclerometers. Also pressure gauges were installed in the array head and tail. The array shapes were estimated by interpolation from positioning data[3]. Figure 2 illustrates a set of representative array shapes measured before the turn (doted line), during the turn (dashdot line) and after the turn (dashed line). We observe that the array shape is disturbed even when the tow ship steams in a straight line track. This deformation increases significantly during the turn, specially in the XY plane. The spatial filtering characteristics of an array are sometimes illustrated by the beam power pattern. In figure 3, it is plotted the normalized beam power patterns according to the array deformations of figure 2 for the maximum work frequency of the array (187.5Hz) without steering.

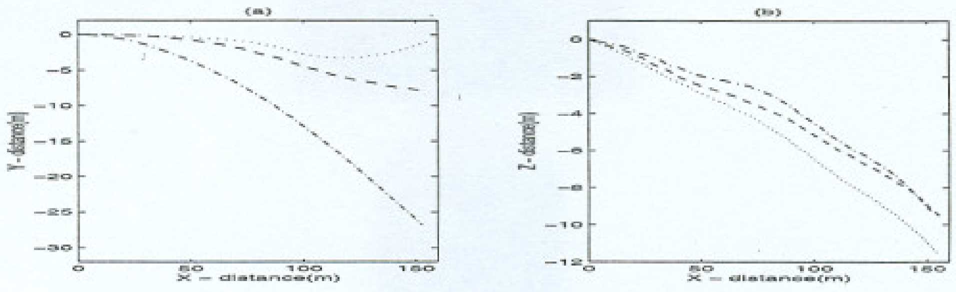

Figure 2: measured array deformations-before the ship turn (...), during the turn (-.-) and after the turn (- - -) in the horizontal XY plane in(a) and in the vertical XZ plane in (b).

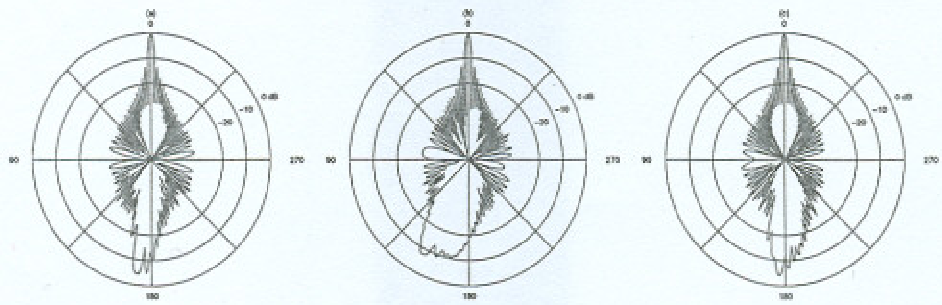

Figure 3: Normalized beam power patterns without steering for real array deformations according to figure 2 before ship turn (a), during the turn (b) and after the turn (c).

We remark that depending on the level of array deformation the beam power pattern for the steering angles complementary to the source bearing has a lower main lobe but a larger beam width - like a shade. This is the starting point to solve the right-left ambiguity problem.

3.2 Plane-wave beamforming of real data

In this section, real acoustic data has been processed by a conventional plane-wave beamforming algorithm where the array shape was introduced. The plane-wave beamformer outputs plotted in figure 4 were obtained from field data recorded at one minute interval, between 11:05 and 11:07 am. The sampling frequency was 750Hz and a 1024 FFT block size was used. Since we are interested in the azimuthal direction of the acoustic field, only the deformations in the XY plane are considered. In the beamformer outputs the frequency increase from the center to the border covering the range 0-187.5Hz. Along the sequence (fig. 4a) the array deformation was increasing up to 25m deviation at the tail. The acoustic field is composed by echoes from nearby merchant ships. In figure 4(b), with an almost straight array, a strong echo can be clearly seen at 10° and 170°. At this moment the left-right ambiguity can not be solved . In figures 4(c) and 4(d), with a progressive array deformation the left-right ambiguity can be solved and the plot gives a precise information regards the exact starboard position of the strong ship echo at 0° in (c) and -10° in (d).

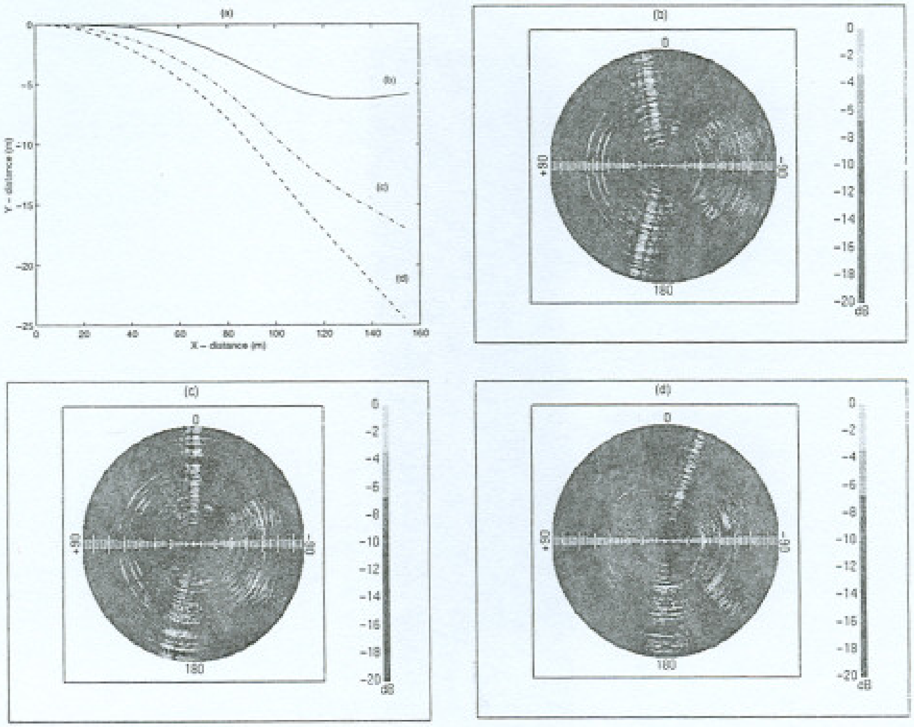

Figure 4: real data processing: sequence of estimated array shapes (—), (-.-) and (--) (a). beamformer outputs using array shapes of (a) in (b) to (d).

3.3 Full-field beamformer

The array shape data of figure 2, before the turn and during the turn, was used to compare, based on simulations, the straight line array case and two real array shape deformations. Figure 5 shows the source localization performance of the minimum variance processor for a broadside source at 187.5 Hz, located at 60m depth and 10 km range and 10dB, with a straight line array (a), a small array deformation (b) and a heavy deformed array during ship's maneuvering (c). It can be remarked that the large depth ambiguity of the horizontal array (a) has been resolved when the real deformations were used (b) and larger (but known) deformations gave a less ambiguous localization (c). In fact, the source was correctly located in cases (b) and (c) with only one sidelobe within 5dB of the main peak in (c). When a sensor localization mismatch was introduced the localization was always lost.

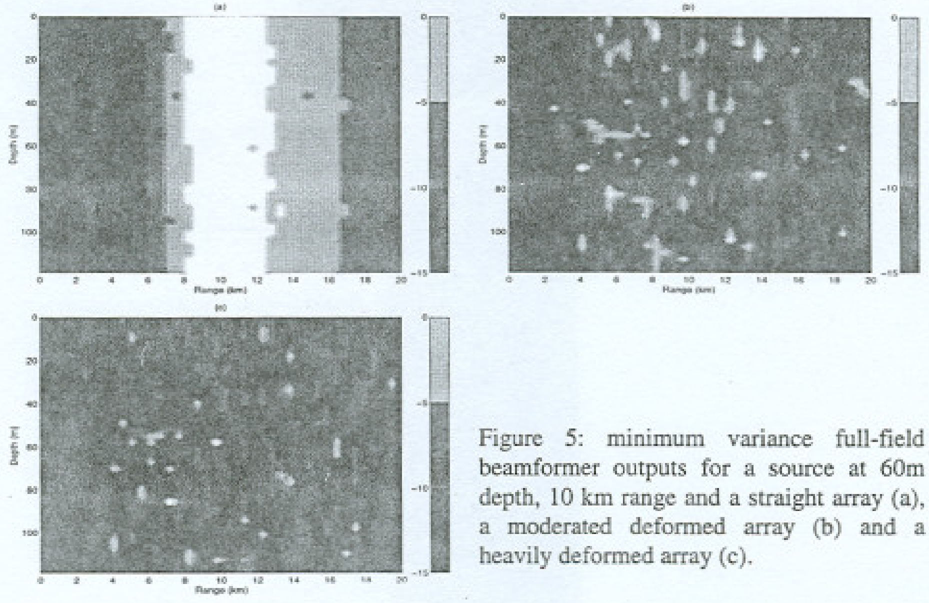

Figure 5: minimum variance full-field beamformer outputs for a source at 60m depth, 10 km range and a straight array (a), a moderated deformed array (b) and a heavily deformed array (c).

4. CONCLUSION

The at sea shape of an horizontal towed array was estimated based on passive instrumentation: tiltmeters, accelerometers, compasses and pressure gauges. From the measurements, it can be concluded that a moderate aperture towed array is never horizontal nor straight. The deduced sensor positions were used to improve plane-wave beamforming of real acoustic data during ship's maneuvering and resolve the inherent left-right ambiguity. These results served as to validate the estimated array shape. Range-depth source localization with the at-sea measured array shapes showed that a moderate aperture with a small, but known, vertical aperture has an improved performance in source depth resolution when compared with the horizontal array. In the other hand a sensor mismatch completely destroys the localization.

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