PASSIVE AND ACTIVE SONAR APPLICATIONS FOR A NON-UNIFORM AND LOW COST LINEAR ARRAY

Enrico Armelloni[a], Fons Adriaensen[b], Angelo Farina[c]

[a] A.I.D.A. S.r.l. spin-off company of the University of Parma, Italy
[b] Audio Link S.r.l., Parma, Italy
[c] Industrial Engineering Dept, University of Parma, Italy

Contact author: dr. Enrico Armelloni, Advanced Industrial Design in Acoustic S.r.l., Via Sicuri 60/a, 43100 Parma, Italy – tel +39 0521 969036, fax +39 0521 256963, email address armelloni@aidasrl.it

Abstract: *one of the reasons to use a non-uniform linear array (NULA) is to reduce the cost and complexity of the array, since it can have fewer sensors than an ULA system.*

In this paper, authors describe the construction of a low-cost, ten-hydrophones, non-uniform linear array to be employed in passive and active sonar applications.

Many experiments were conducted, under controlled conditions (large pool), oriented to characterize both individual transducers as well as the complete array. Using the array in "passive" mode, employing an omnidirectional sound source and a non-impulsive signal, beamforming and inverse filtering techniques, the authors evaluated array directivity over a wide range of frequencies (1-23 kHz) and also its capability to estimate the direction of arrival (DOA).

Furthermore, this work also focuses on searching objects and identification. Different test were performed, in order to estimate system performances when used as the receiver of an active sonar. Using sine-sweep signals, and a specific real-time software developed by the authors, several measures were conducted in the shallow and very shallow water showing the ability of the system to detect objects in a 45° wide angle.

Keywords: *non-uniform linear array (NULA), sonar imaging, not-impulsive techniques, wide-band measurements.*

1. INTRODUCTION

The advantages of using arrays of transducers are well known and, probably, the “increase of directivity” is the most important. In fact the arrays are designed in order to maximize energy transmitted/received in a particular angle, simultaneously minimizing energy transmitted/received in other directions. This technique is known as array beamforming.

Considering an array of hydrophones, its performance will improve by increasing the number of transducers, which obviously also means raising the cost of the system.

In this work the authors describe the construction of a low-cost, ten-hydrophones, non-uniform linear array (NULA), suitable to be employed in passive and active sonar applications.

The study was divided into two parts: first the construction and acoustic characterization of the array, then its use in sonar applications. The array was assembled in the AIDA laboratory, while the tests for characterization and sonar application have been conducted in swimming pools. The authors have also conducted further tests, in addition to those already carried out previously [1], to validate the use of a sine sweep signal in active sonar.

Different projectors were employed during the tests, an ITC 1001 (for acoustic characterization) and an ITC 5264 (for active sonar). In both case sources are driven by a test signals generated by dedicated software running on a PC. Signals captured by the hydrophones were recorded and post processed in order to estimate inverse filters for each transducer. Furthermore, using Matlab™, it was possible to compare the directivity diagrams of the array for the theoretical case and the real one.

The second part of the study focused on using the system in passive and active sonar. In first case, the array was submerged in a large pool, then small iron objects were beaten to generate sounds other it. The post-processing of recorded signals, using beamforming techniques, allowed to estimate the direction of arrival of the sound. In the case of active sonar instead, the task was to test the capability of the system (NULA and software) to visualize a bottom profile and to discover submerged objects, placed at different angle under array. To do this, a dedicated real-time software was developed by the authors on the Linux platform.

2. ARRAY SET-UP AND CONSTRUCTION

The linear array is the simplest array geometry. In such an array all elements are aligned along a straight line and typically have an uniform inter-element spacing *d*. In practice the linear array represents the discretization of a continuous line at periodic locations in space. This discretization plays an important role in the “spatial aliasing” effect - the incident wavefront is sampled at specific locations and the polar patterns produced are affected by the Nyquist sampling criterion. The distance between elements, *d*, is related (inversely proportional) to maximum frequency detectable without “spatial aliasing”. Beam efficiency and beam directivity are affected negatively due to the introduction of secondary lobes at undesired angular locations.

In order to avoid these problems and to increase the flexibility of the system, a non-uniform linear array (NULA) was considered. In this configuration elements are placed with different distances, so if the total number of elements is kept the same, it produces an array with different lengths respect to the ULA configuration. Changing the length of the array will affect the polar pattern beamwidth and sidelobe power, providing more flexibility in overcoming the limitations of uniform spaced arrays.

The array developed in this work consist of ten Aquarian Audio H2a-XLR omnidirectional hydrophones. This kind of transducer is designed to provide high quality audio performance in a low-cost device and it can be interfaced directly with professional audio microphone preamps. It offers very good sensitivity (-180dB re: 1V/mPa; +/- 4dB 20Hz-4.5KHz), low noise, and can be employed over the entire frequency range of our interest (500 Hz ÷ 40 kHz). Hydrophones are mounted on a 2 m long aluminum frame (*Fig. 1*) in different positions (- 0.875, -0.455, -0.250, -0.105, -0.035, +0.035, +0.105, +0.250, +0.455, +0.875 meter w.r.t. the center). Flexibility is provided by a mounting system that allows to change easily the transducers positions according to different design strategies.

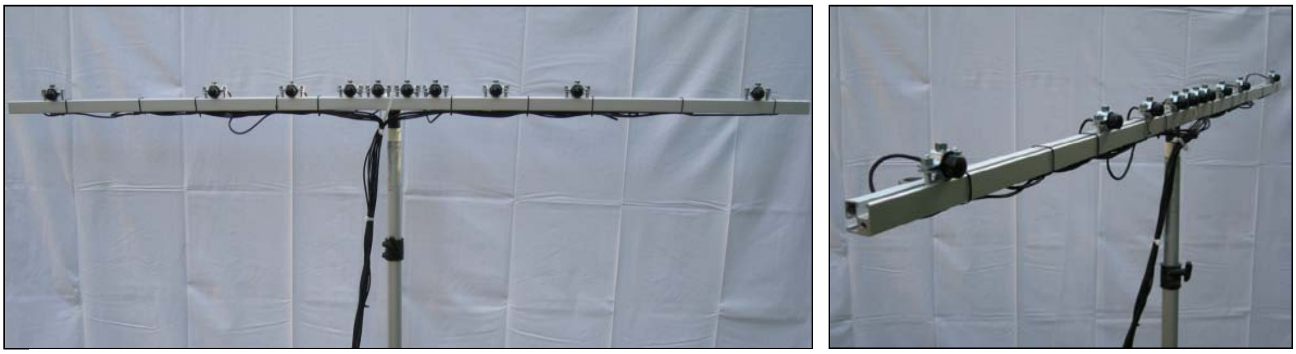


Fig. 1: Ten-hydrophone arranged in the Non-Uniform Linear Array.

The receiving system is completed by a high precision microphone preamplifier with ADAT outputs (APHEX 1788) and an ADAT to MADI converter (RME AD648), which is connected to the PC.

While the PC interface would allow expansion to 64 channels, using a single preamplifier limits this to 8 channels which means that only 8 of the 10 hydrophones can be used simultaneously.

3. TEST SIGNALS

The non-impulsive signals used in this research, as already mentioned, are sine sweeps, both logarithmic and linear. Sine sweeps (chirps) have been employed since some time for audio and acoustics measurements and characterization [2][3], but in recent years their use has increased thanks to the computational capabilities of modern computers. Recent research results allow for further refinements in sine sweep measurements, in particular when dealing with the problem of measuring impulse responses and distortion at the same time and when working with systems which are neither time-invariant, nor linear.

In underwater measurements (active sonar) also other not-impulsive signals as the MLS (Maximum Length Sequence) pseudo random signal can be considered. Various papers have studied the topic [4][5][6][7], comparing MLS to sine sweep [1] and demonstrating the latter's advantages.

The main advantage of the sine sweep method is its immunity to non-linear distortion. When using MLS signals this distortion can cause severe artefacts, appearing either as artificial background noise and, or worse, as spurious peaks which can be easily confused with reflections coming from non-existent objects (false echoes). With sine sweeps, instead, these artefacts can be separated in the time domain from the “clean” linear impulse response, provided that a linear deconvolution technique is employed (instead of the circular deconvolution, which causes the not-linear artefacts to “fold back” and contaminate the response).

In practice, this is obtained very simply by linear convolution of the recorded signal with a suitable inverse filter. As demonstrated in [2], and confirmed independently in [3], this inverse filter is simply the time-reversal of the sweep signal itself (with a frequency-dependent gain factor in case of logarithmic sweeps).

In this work sine the sweep signal is used to obtain an acoustic characterization of both each hydrophone, and the entire array. It also used as source signal in active sonar application.

4. ACOUSTIC CHARACTERIZATION

To perform the acoustic characterization the array was placed at a depth (3 m) equal to half the depth of the pool (6 m) (*Fig. 2 – left*). This made it possible to minimize the effects of reflections on both the bottom and the surface. The source (ITC 1001) was positioned 3 m distant in front of the array. Feeding the projectors with a long linear sine sweep from 1 to 23 kHz, the frequency response for each receiver was measured. The following *Fig. 2*, on the right, shows the results of this measurement. The frequency responses of the ten hydrophones are very similar except for one transducer (shown in red) that has a higher attenuation at frequencies over 15 kHz.

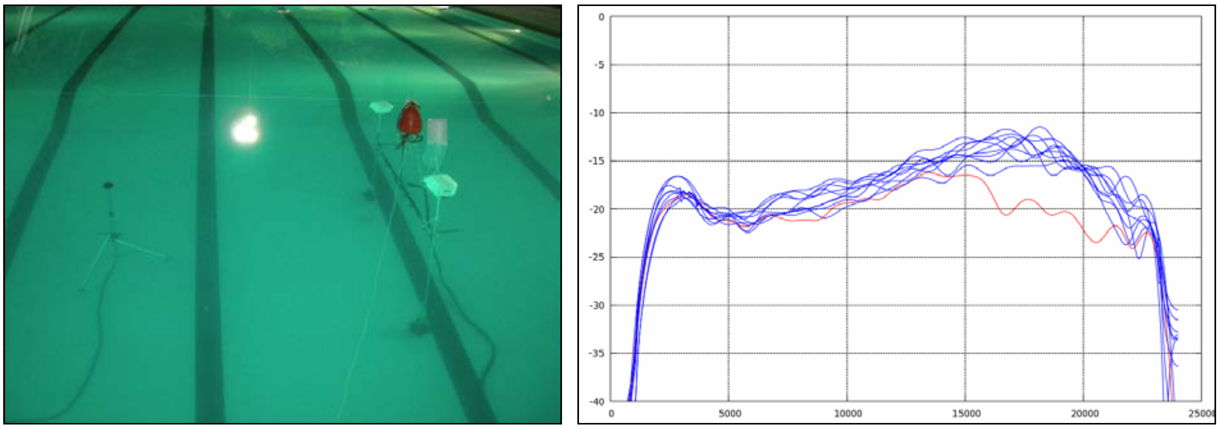


Fig. 2: Acoustic characterization: measurements set-up (left), frequency response for every hydrophone (right).

The second part of this experiment was to verify the real directivity of the array. Maintaining always the same distance between source and array (3 m), the source was placed in seven well defined positions (named m4...m10) in front, on left and on right of the array centre. Recorded signals were processed applying beamforming and inverse filtering techniques. Using processing in Matlab™ it was possible to compare the directivity diagrams of the array for the theoretical case and the estimated one at different angles of beamforming. The next figure on the left shows the result with source placed in position m6 (0.5 m to the right of array centre) at a frequency of 9 kHz. On the right is represented the directivity vs. frequency.

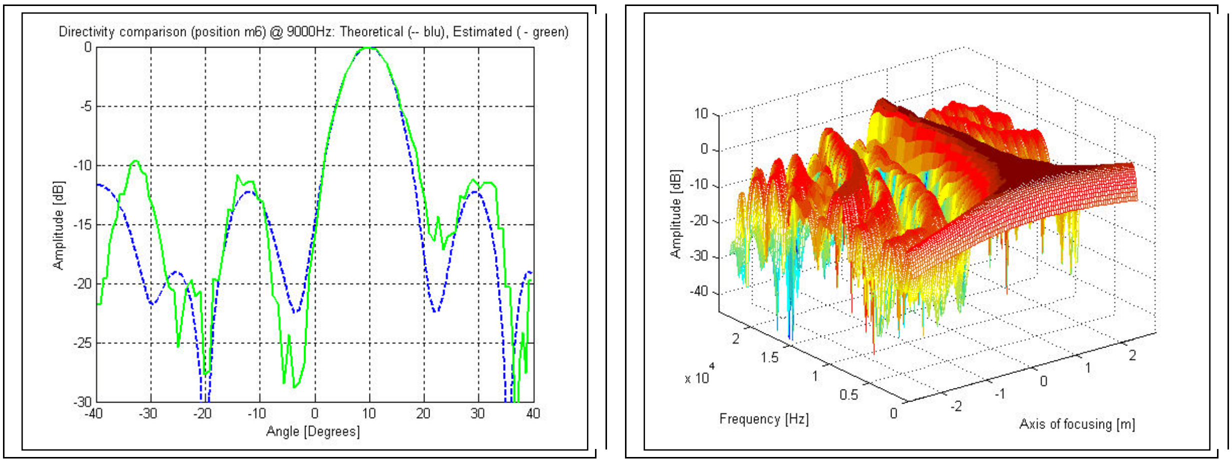


Fig. 3: Array directivity (source position m6): comparison between theoretical and estimated @ freq. 9 kHz (left), directivity Vs frequency (right).

5. “PASSIVE MODE”

Using the same array setup some experiments were carried out to estimate the capability of the system to find the direction of arrival of the sound. At various positions noises were produced beating two iron objects. The eight tracks were recorded and processed by beamforming techniques, also applying inverse filtering for each transducer. In *Fig. 4* are shown the direction of arrival for two different positions “A” (13° on the right) and “B” (35° on the left) of the source. The analysis was performed in five octave bands 1, 2, 4, 8 and 16 kHz, but the most significant results were obtained in the last three. Obviously, working in a confined environment such as a swimming pool means there will be reflections on the walls. These effects are noticeable in the figure related to position “A”, where, at low frequencies (1 kHz band), a broad lobe is present at around -40°, caused by reflections on the lateral wall. This “false images” disappear at increasing frequency because of the increase in directivity of the array.

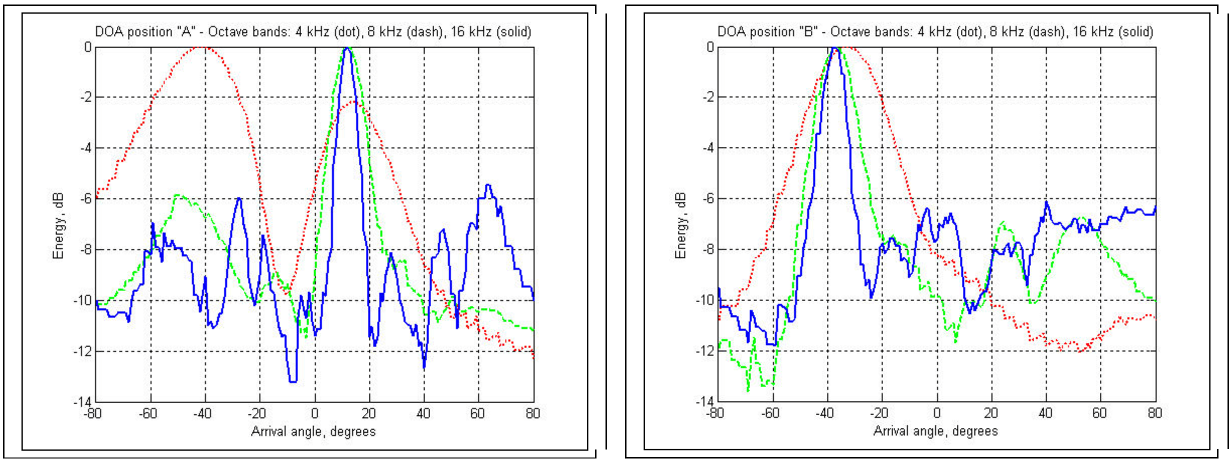
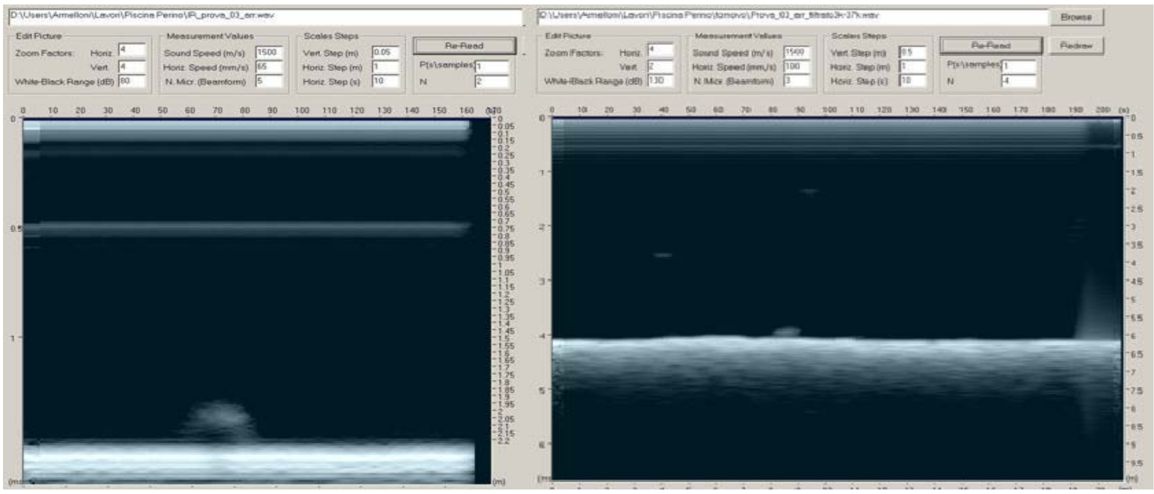


Fig. 4: DOA estimated: position “A” (left), position “B” (right)

6. “ACTIVE MODE”

A series of tests were also performed in order to verify the performance of a linear sine sweep signal and to analyse the array behaviour when used as the receiver of an active sonar.

A first measurement campaign was focused on validating the use of a sine sweep signal in active sonar. The authors conducted several tests, working first in a pool and then in a lake, at different depths of 2.2 m and 6.0 m respectively. Two hydrophones ITC 5264 equipped with parabolic reflectors were employed as transmitter and receiver respectively. The aim of the experiment was to identify a submerged target, a 0.35 m height iron box, using a 1 second long linear sine sweep signal, with a frequency increasing from 2.0 kHz to 42.0 kHz. The following *Fig. 5* show the detected shape of the object placed on the bottom (pool on the left and lake on the right).



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Edit Picture: Zoom Factors: Horiz. 4; Vert. 4; White-Black Range (dB) 80

Measurement Values: Sound Speed (m/s) 1500; Horiz. Speed (mm/s) 65; N. Micr. (Beamform) 5

Scales Steps: Vert. Step (m) 0.05; Horiz. Step (m) 1; Horiz. Step (s) 10

P(s\samples) 1; N 2

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Measurement Values: Sound Speed (m/s) 1500; Horiz. Speed (mm/s) 100; N. Micr. (Beamform) 3

Scales Steps: Vert. Step (m) 0.5; Horiz. Step (m) 1; Horiz. Step (s) 10

P(s\samples) 1; N 4

Fig. 5: Shape of object placed on the pool bottom (left) and lake bottom (right).

It is important to note that the image taken in the lake is well defined, even in presence of high background noise (boat engine noise). This confirms that the sine sweep technique yields a high Signal-to-Noise ratio. So as already explained by the authors in previous paper [1], high immunity to external noise, coupled with the very fast and easy processing required for the deconvolution of the impulse responses, make linear the sine sweep signal a very appealing choice for underwater measurements.

The purpose of the second measurement campaign, conducted only in the pool, was to test both the array system and the real-time software, properly developed for this application. In this experiment the receiver was the non-uniform linear array.

Transmitter and receivers were placed on a specially constructed raft, and targets were pulled, with uniform speed, at various angles underneath the system (*Fig. 6*).

The targets used were a small iron box and a human diver. Different frequency ranges were used with the upper frequency limited to 16 kHz, and using sweep durations of 0.5 or 1.0 second. The following figures show the real-time software output in two different experiments (the box and the diver), for each are depicted both the shape of the object (left) and energy reflected (right) at three different angles of beamfoming, 0° (vertical beam), 15° left and 15° right.

Fig. 6: Active sonar - source and array of receivers set-up(left) and test in the pool (right).

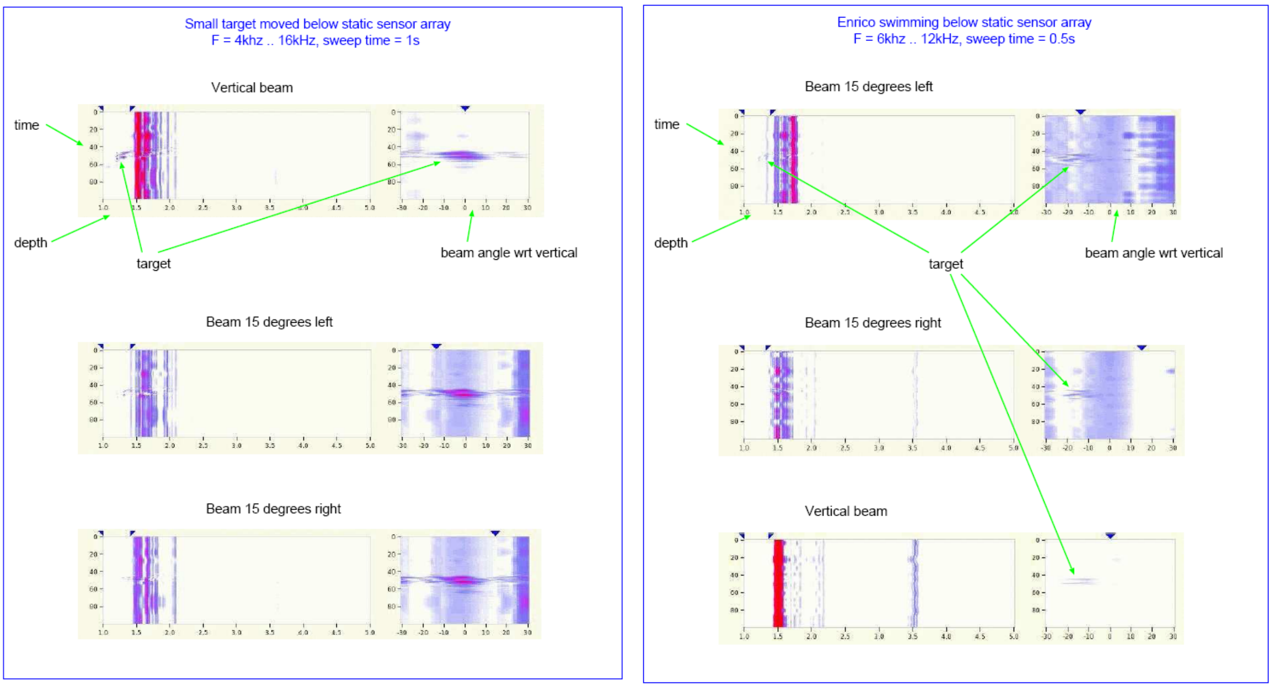

Fig. 7: Real-time software output: small iron box (left) and diver (right).

7. CONCLUSIONS

In this work the authors described the construction of a low-cost, ten-hydrophones, non-uniform linear array (NULA). Different test to investigate directivity of the array were conducted and results confirmed a good agreement between the estimated values and theoretical ones. Furthermore others experiments shown the capability of the system to detect real angle of incoming sound (DOA), especially at medium-high frequencies, where array directivity is greater. Also in this case there is perfect agreement between real and estimated arrival angle, and efficiency and accuracy increase using the inverse filtering technique. With respect to active sonar applications, tests based on sine sweep signals have shown that the use of such a system allows the identification of submerged objects, also placed in a wide angle under the array.

8. ACKNOWLEDGEMENTS

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