Proceedings of the 2nd EAA International
Symposium on Hydroacoustics
24-27 May 1999, Gdańsk-Jurata
POLAND

Ahead looking sonar with a cylindrical array

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Cylindrical arrays are widely used in omnidirectional or very wide sector sonars. These arrays utilise horizontal phasing for compensation of geometrical phase-delays, which form a narrow beam. The cylindrical symmetry of the array provides beam rotation around the array. The ahead looking sonar using the above method needs an array with a large number of staves and a larger number of receiver channels. This paper presents the design approach to ahead looking sonars with a cylindrical arc array using delay of the staves signals for equalising of the array and a beamforming processor for beam steering. This sonar performance is determined by array parameters and a processing method used to form the beams. There is no simple closed form of mathematical expression for a delayed signals and steered beam of such arrays so the array and method of beamforming have to be analysed by considering the elements spacing, weighting and directivity. The angular aperture and radius of array curvature are analysed. The results of a computer simulation of beam patterns for such sonars are presented. The indication for design of ahead looking sonars with cylindrical arc array using equalising and beam steering processing are presented.

1. Introduction

Cylindrical transducers are commonly used for the sonification of wide sectors [2]. Unlike transmitting scanning, they do not require a transmitting beamformer or a complicated design of the transmitter [1]. Cylindrical transducers are used mainly in round observation sonars where using transducer symmetry enables us to form a beam rotating around the transducer. When using a cylindrical transducer in an ahead looking sonar for the purpose of beamforming using the method applied to round observation, we need to design a transducer whose angular aperture will be much bigger than the width of the observed sector. The effect is an increased size of the transducer and the number of sections. For each section we need a separate channel of signal conditioning, and also a fast switch of beamfomer inputs. As a result, the size of the device (transducer) increases, so does the level of its complexity and the costs. This work intends to study the possibilities of designing an ahead looking sonar with a transmitting-receiving cylindrical transducer with angular aperture close to the width of the observed sector.

2. Forming of narrow beams for a cylindrical transducer

A multi-element cylindrical transducer is presented in Fig. 1.

The signals received by the particular elements of the transducer are delayed to equally distribute the location of all its elements. By doing that we obtain a linear transducer of unequal spacing of the elements with all the elements inclined in the direction of the tangent to the surface of the cylindrical transducer.

Let us assume, that a plane acoustic wave is incident to a multi-element cylindrical transducer from the zero direction which matches the symmetry axis of a transducer with an odd number of elements. This is presented in Fig. 2.

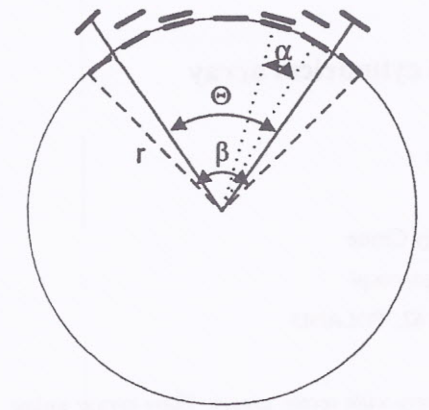

Fig. 1. Forming of a multi-element cylindrical transducer with angular aperture β into a linear one, with angular aperture θ.

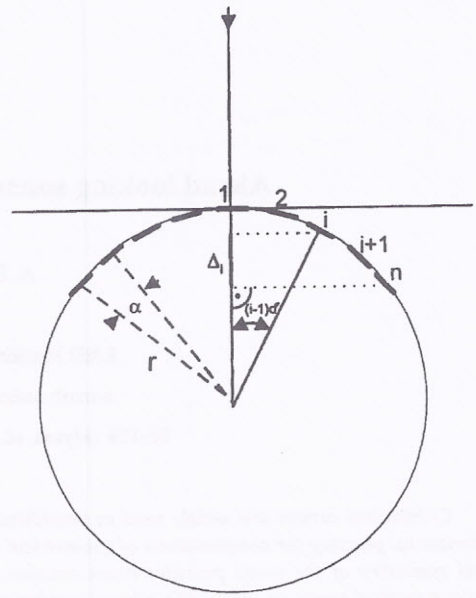

Fig. 2. Geometry of the cylindrical transducer for the zero direction matching the symmetry axis of the transducer.

At the output of the i element of the transducer, voltage $U_i(t)$ is formed and has the following form:

$$U_i(t) = G_i A_i(t + \tau_i)\sin[\omega(t + \tau_i) + \varphi] \qquad (1)$$

where:

- G_i – gain connected with the beam pattern of the transducer element,
- $A_i(t)$ – echo signal envelope,
- ω - pulsation,
- $\tau_i = \Delta_i / c$ – delay of the signal representing the difference between the path between the i and n extreme element of the transducer,
- φ - phase shift in relation to n element.

For an equal angle α of distribution of transducers, we will obtain signal delays defined with the following formulas:

For an odd number of transducer elements:

$$\Delta_{in} = (r / c)\{\cos[(i - 1)\alpha] - \cos[(n - 1)\alpha] \qquad (2)$$

and for an even number of transducer elements:

$$\Delta_{ip} = (r/c)\{\cos[(i - 1)\alpha + \alpha / 2] - \cos[(n - 1)\alpha + \alpha/2] \qquad (3)$$

where:

- r – radius of the cylindrical transducer,
- c – sound velocity in water,
- α – angle between the neighbouring elements,
- n - element – extreme element of the transducer.

Using formula (3) for an even number of elements, we calculate beam patterns for the zero direction for an electronically straightened cylindrical transducer with various transducer radii and the number of elements equal to 32. They are presented in Fig. 3.

The greating lobes of beam pattern of L/r=2 are too big to be applied in sonars.

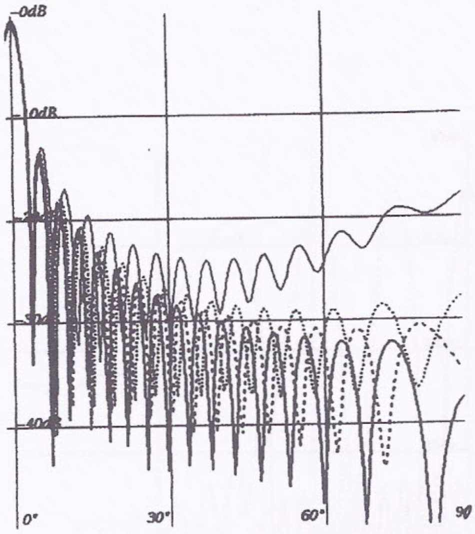

Fig. 3. Beam patterns for the zero direction of an electronically straightened transducer with 32 elements spaced at d=λ/2 for:

____ r=24λ; L/r=0.6(6)

_ _ _ r=16λ; L/r=1.06

. . . . . r=12λ; L/r=1.5

____ r=8λ; L/r=2.0

By applying identical principles like those for the zero direction beam, we can form beams for any direction by electronic straightening of the cylindrical transducer into a linear one.

Fig. 4 presents time delays for a central beam and a beam steered to the right.

By increasing the direction of the right steered beam, we obtain beam patterns as presented in Fig. 5 and undergoing a deformation caused by the increasing transducer asymmetry which is seen at an increasingly bigger angle.

Starting from a certain angle, it is deformed by a covering of the extreme elements placed on the opposite side.

The covering up of the extreme elements starts from angle γ which is determined with the following formula:

$$\gamma = 90^\circ (1 - L / \Pi r) \quad (4)$$

where:

γ - angle of incidence of an acoustic wave onto the transducer, for which the angle of incidence is

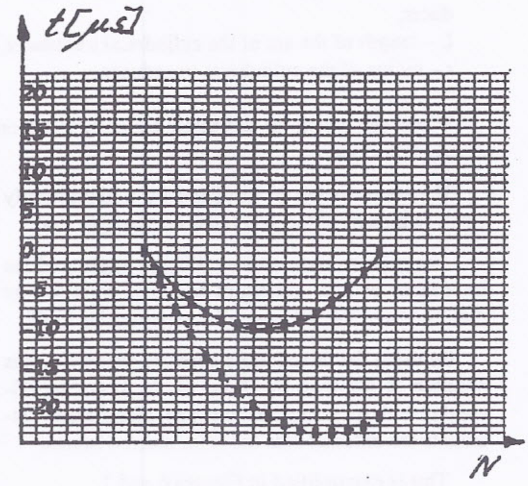

Fig. 4. Time delays for the central beam and right steered beam for a 16 element transducer.

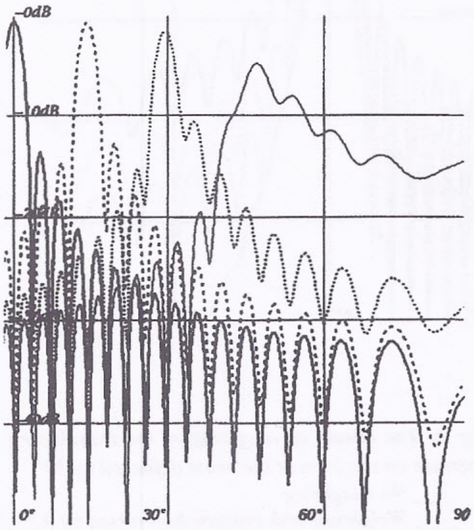

Fig. 5. Deformation of beam pattern of a 32 element transducer with L/r=0.6(6), with an increased beam steered angle towards the zero direction.

90° onto the opposite extreme element of the transducer,

L – length of the arc of the cylindrical transducer,

r – radius of the cylindrical transducer.

When the beam is deflected by 30°, it becomes clearly deformed.

The deformation is exhibited by a significantly small reduction of the side lobes on the right side.

For a beam deflected by 47°, an angle γ of the transducer of 33°, the beam becomes significantly deformed and the greating lobe increases by 15 dB.

By using the transducer's aperture weighting, it is possible to improve the form of the beam significantly, and in particular we can significantly attenuate the external side lobes for steered beams.

This is exemplified in Figures 6 and 7.

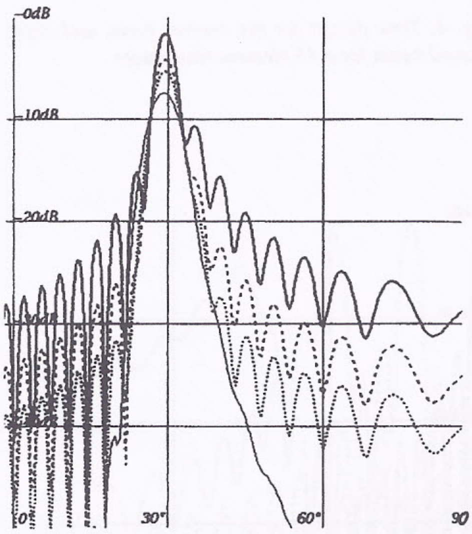

Fig. 6. The effects of weighting of the transducer's aperture on the form of the beam deflected by 30°.

____ No weighting

_ _ _ Weighting with cos function raised by 0.5

. . . . Weighting with cos function raised by 0.3

____ Weighting with cos function

Weighting of the transducer's aperture cannot compensate for the deformation of its symmetry, and in particular for the covering up of the extreme elements for angle above γ.

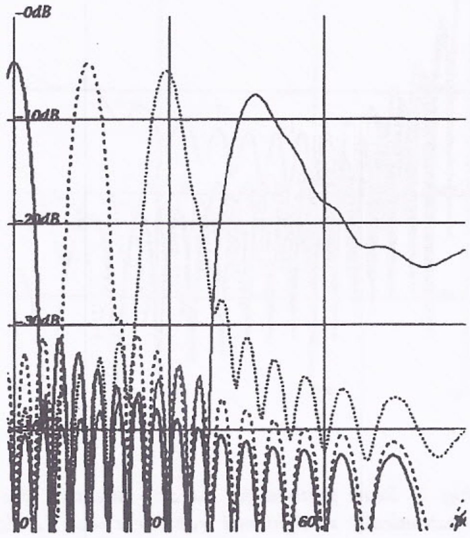

Fig. 7. The effects of weighting of the transducer's aperture on the form of beams steered at various angles.

Because of that, it does not help to significantly change the form of the steered beam by 47° (see Fig. 7.).

Fig. 8 presents beam patterns of a 32 element cylindrical transducer weighted with cos function, raised by 0.3 for various L/r and their matching angles γ.

The level of the right side lobe for L/r≤1.5 is below 20 dB.

The above analysis shows that it is possible to form beams by equalising the cylindrical transducer for specific directions.

Only beams formed in the sector 2γ for a cylindrical transducer of L/r≤1.5 have a practical implementation.

Fig. 9 presents 15 beams formed for various directions from the sector ±26 for transducer L/r=0.6 with 32 elements with d/γ=0.5 and weighting with cos function raised by 0.3.

The beams are well formed with side lobes below –25dB, and widths of the beams change from 3.8° for the central beam to 4.3° for extreme beams.

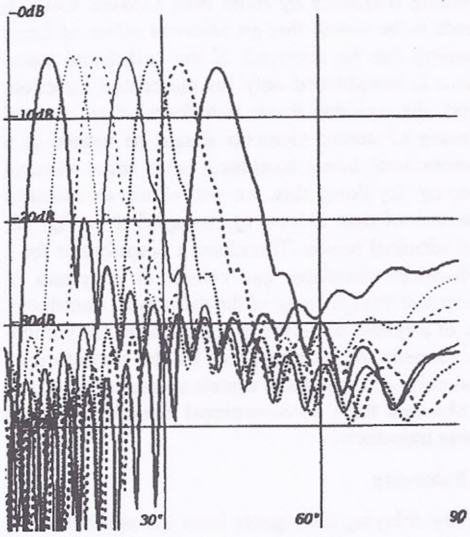

Fig. 8. Beam patterns for a 32 element cylindrical transducer electronically straightened with aperture weighting with cos function raised by 0.3 for:
____ L/r=0.5 γ ≈ 42°; _ _ _ _ L/r= 0.6(6) γ ≈ 33;
. . . .. . L/r=0.8 γ ≈28°; ______ L/r=1.0 γ ≈22°;
_ _ _ L/r=1.3(3) γ ≈16°; . . . . L/r=1.6 γ ≈12°;
____ L/r=2.0 γ ≈8.;

Fig. 10 presents 15 beams identically distributed, but in this case for a transducer of L/r=1.3(3).You can observe a degradation of the extreme beams caused by the raising of side lobes. For angles slightly less than 2γ, it is possible to obtain well formed beams. This is presented in Fig. 11.

3. Beamformer realisation for a cylindrical transducer

A beamformer which forms the particular beams should perform delays of the signals or shifts of phase for each element of the transducer and the direction of the beam being formed, following formulas (2) and (3) generalised for all directions. It should realise complicated delay functions exemplified in Figures 4 and 12.
Since it is necessary to precisely shift the phase or change delays following complicated functions, it seems that a beamformer like that will require a very high frequency of sampling exceeding the device's

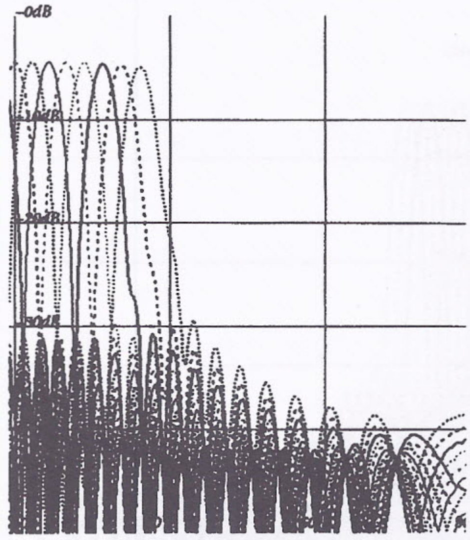

Fig. 9. Beam patterns of 15 beams in the sector <2γ for a transducer of L/r=0.6(6), d/λ=0.5 and weighting with cos function by 0.3.

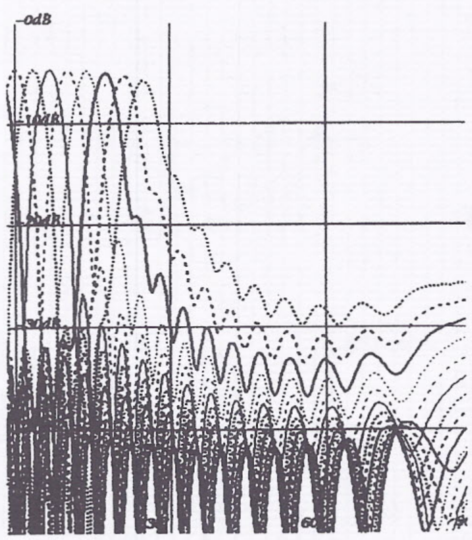

Fig. 10. Beam patterns of 15 beams for a cylindrical transducer electronically straightened of L/r=1.3(3), d/λ=0.5 and weighting with cos function raised by 0.3.

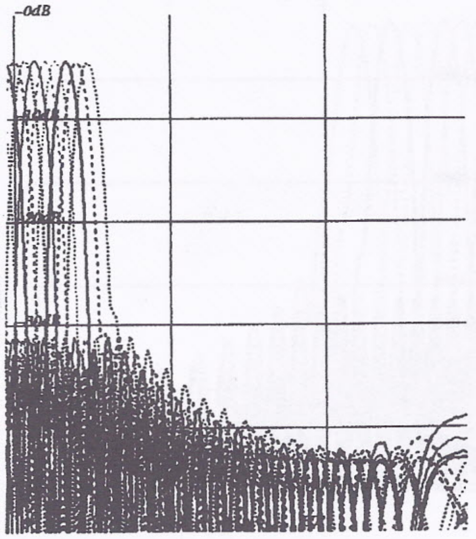

Fig. 11. Beam patterns of 15 beams for a cylindrical transducer electronically straightened of L/r=0.6(6), d/λ=0.6 and weighting with cos function raised by 0.3.

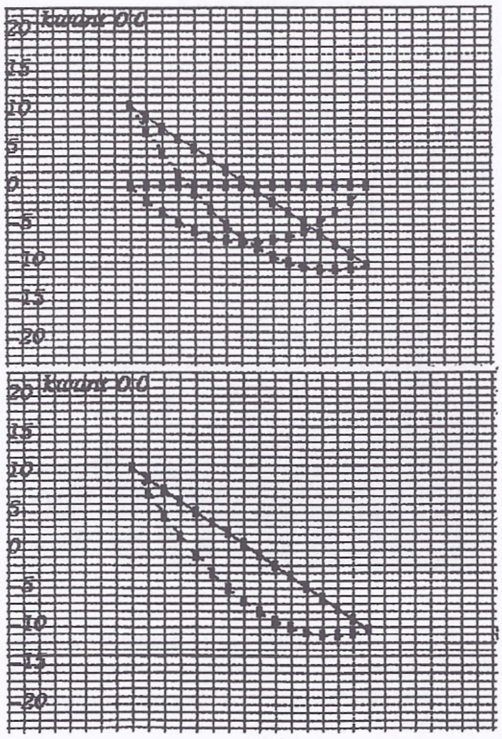

Fig. 12. Functions of time delays in the forming of beams from various directions for a cylindrical transducer.

working frequency by more than a dozen times. It needs to be noted, that an identical effect of beam forming can be achieved, if the cylindrical transducer is straightened only for the central direction. Next, the resulting linear transducer of an unequal spacing of steered elements should be treated as a conventional linear transducer with equal element spacing. By doing this, we will obtain an identical function of time delays, as exemplified in Fig. 12, and identical beams. Therefore, a beamformer for a cylindrical transducer can consist of a system of electronic straightening of the cylindrical transducer, i.e. of a system of delays of signals from the particular elements of the transducer for the central direction only, and then these signals should be treated as if obtained from a conventional beamformer for a linear transducer.

4. Summary

By delaying the signals from the particular elements of the transducer according to formulas (2) and (3) and by generalising them for all directions, it is possible to form well formed narrow beams in a sector which does not exceed angle 2γ described with formula (4). Since big greating lobes are quite likely to appear, the transducers used should be with L/r≤1.5. Weighting of the transducer's aperture reduces the level of side lobes, and especially, external lobes. It is possible to design a sonar with one cylindrical transmitting-receiving transducer of a high angular resolution, side lobes below –25dB, operating in the sector up to 60°, however, all elements of the transducer must be active in the forming of receiving and transmitting beams.

A beamformer for a cylindrical transducer can be designed by equalising delays of signals for the particular elements for the central direction only. They should then be treated as signals obtained from a linear transducer for which we can apply one of the known beam forming for linear transducers.

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