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SONAR TRANSDUCERS FOR A TEACHING LABORATORY

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ABSTRACT

In a teaching situation it is desirable to provide hardware which agrees as closely as possible with simple theoretical predictions of performance rather than the normal practical requirement of performing within prescribed limits. This paper outlines some of the practical problems encountered in achieving an acceptable directivity function from a multi-element array of sonar transducer elements operating at 500 kHz in a small water tank.

1. INTRODUCTION

1.1 Background.

The subject of Underwater Acoustics was introduced as a final year option of the Engineering Degree Course at the Royal Naval Engineering College, Manadon in 1980. Implementation of the course was to be undertaken within the Department of Signal Processing and Electronics, with emphasis on those aspects of signal processing common to all communication systems which could be readily demonstrated in the processing of a sonar signal. The requirement therefore existed for a suitable demonstration model to be created within existing laboratory space to show various aspects of spatial processing using transducer arrays.

1.2 The Model Sonar System

Constraints of space and convenience resulted in a water tank measuring approximately 1.5 m long, 1 m wide and 1 m deep. Glass construction was used to allow viewing of the underwater equipment by students, with no attempt at anechoic lining for the same reason. Thus a short pulse system with receiver range gating was essential to overcome the highly reverberant nature of the propagation volume.

Choice of operating frequency was primarily determined by consideration of the envisaged multi-element transducer configurations. The frequency should be high enough for the tank to represent as large a volume as possible and for highly directional transducers to be of a size compatible with far-field operation, but should not be so high as to make transducer construction inordinately difficult.

Parameters for the system were specified as:

Operating frequency	= 500 kHz	(λ = 3 mm)
Pulse duration	= 10 to 100 μs	(1.5 to 15 cm in water)
Pulse repetition interval	= 10 to 100 ms	

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2. ARRAY DESIGN

2.1 Requirements

It was required to demonstrate the basic principles of spatial processing, including:

a. the sin x/x directivity function of a simple element,

b. the sin Nx/N sin x directivity function of a multi-element array, including the existence of diffraction secondaries,

c. the reduction of side-lobe levels, with corresponding increase of beam-width as a result of the incorporation of a gain taper function across the array,

d. the ability to steer the main beam away from broadside by incorporation of a phase taper function.

In order to demonstrate these principles convincingly it was necessary that the practical performance should conform as closely as possible to the theoretical predictions in all respects. It was not sufficient to achieve the normal performance criteria of 'sidelobes at least x dB below the main beam, etc'.

A relaxation of practical requirements lay in the fact that the assembly would not be subjected to high hydrostatic pressures nor the typical harsh environment of practical sonar operations.

2.2 Theoretical Directivity Functions

The directivity function $[D_1(\theta)]$ of an array of N isotropic elements is the simple function

$$D_1(\theta) = \frac{\sin(Nkd \sin\theta)}{N \sin(kd \sin\theta)} \quad \text{.................. (2.1)}$$

where k = spatial frequency = $2\pi/\lambda$

and spacing between element centres = 2d

In view of the short wavelength (3 mm), at the operating frequency of 500 kHz, and the element thickness of 4 mm for a PZT plate operating in a $\lambda/2$ thickness resonant mode, it would not be practical to produce an element width sufficiently small compared with wavelength to create truly isotropic element sensitivity.

The directivity function for each finite width element is given by

$$D_2(\theta) = \frac{\sin(\frac{1}{2}ka \sin\theta)}{(\frac{1}{2}ka \sin\theta)} \quad \text{.................. (2.2)}$$

where a = element width

Therefore the directivity function for an array of finite width elements becomes [1].

$$D(\theta) = D_1(\theta).D_2(\theta)$$

$$= \frac{\sin(Nkd \sin \theta)}{N \sin(kd \sin \theta)} \cdot \frac{\sin(\frac{1}{2}ka \sin \theta)}{\frac{1}{2}ka \sin \theta} \quad \ldots\ldots\ldots\ldots\ldots (2.3)$$

Mounting of a practical array normally involves the introduction of a plane surface or baffle within which the array is incorporated. In bearing directions close to broadside the effect of this baffle may normally be neglected, however, in order to achieve realistic performance prediction from broadside to end-fire this factor must be taken into account. The modifying term[2], assuming an infinite baffle, involves the ratio of baffle acoustic impedance ($Z(\omega)$) to the acoustic impedance of the propagating medium (ρc), expressed as the specific admittance (β) of the baffle:

$$\beta = \frac{\rho c}{Z(\omega)}$$

Incorporation of the baffle effect results in the directivity function

$$D(\theta) = \frac{\sin(Nkd \sin \theta)}{N \sin(kd \sin \theta)} \cdot \frac{\sin(\frac{1}{2}ka \sin \theta)}{(\frac{1}{2}ka \sin \theta)} \cdot \frac{\cos \theta}{(\beta + \cos \theta)} \quad \ldots\ldots\ldots (2.4)$$

In the case of a rigid baffle ($\beta \ll 1$) the additional term is essentially unity until $\theta \to 90^{\circ}$ when the term rapidly reduces to zero. For a soft baffle ($\beta > 1$), however, the term approaches $\cos \theta$.

The predicted directivity function based on equation (2.4) is shown in Figure 2.1.

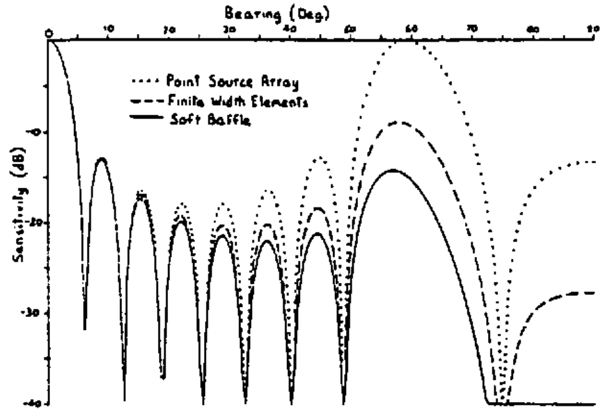

Fig 2.1

2.4 Computer Assistance

In Support of student investigations into the properties of arrays, computer generated theoretical predictions are available to the user for any parameter values.

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3. ARRAY CONSTRUCTION

3.1 Transducer Element

The basic element for the arrays was based upon a resonant plate of PZT material operating in a symmetrically loaded thickness resonance mode which, at a frequency of 500 kHz, required 4 mm thick plate.

It was anticipated that the use of elements of the order of 2 mm width may cause problems due to other mechanical resonances but in practice such problems were not encountered.

3.2 Manufacturing Problems

The two greatest problems in element production were the fundamental ones of cutting accurately dimensioned elements and of achieving reliable, low profile electrical connections to the silvered faces of the ceramic plates.

Satisfactory machining accuracy was eventually achieved using TCT and diamond dental cutters in a high speed miniature pillar drill, operating as a vertical milling machine, with fine control in two dimensions of the horizontally mounted ceramic plate.

Production of good soldered contacts proved more difficult but was very effectively resolved by the arrangement in Figure 3.1.

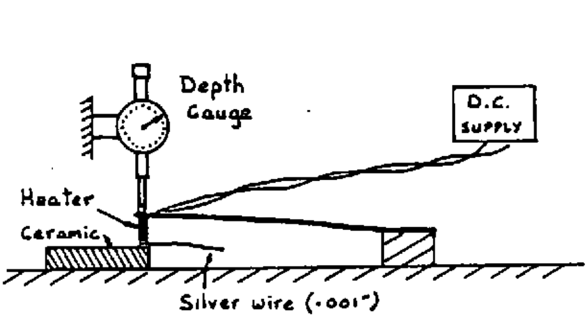

Fig 3.1

The pretinned joint was carefully located and retained in position by light pressure through the heating element. On application of heating current the depth gauge indicated first the expansion of the joint, followed by a sudden fall as the solder flowed. Interruption of the heater supply could therefore be precisely timed and a reliable joint formed at each attempt.

4. PRACTICAL TRANSDUCERS

4.1 Encapsulated narrow elements

With a view to simplicity of manufacture initial assemblies comprised arrays of separate elements in anepoxy encapsulation, with screened multicore cabling of 1 m length between transducer and receiver.

Figure 4.1 compares the measured and predicted performance of a typical array.

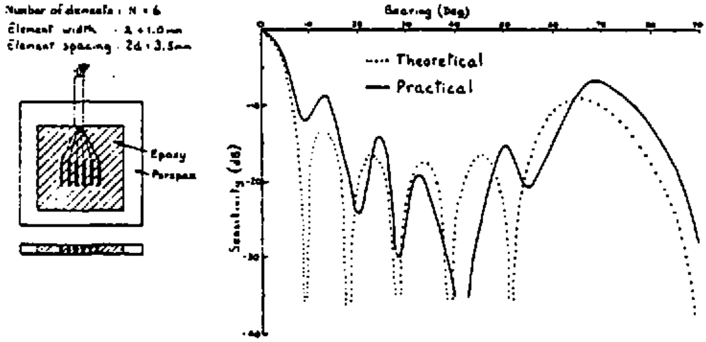

Fig 4.1

Whilst the major features of the practical measurements were in general agreement with predicted performance there were significant shortcomings, in particular the poor nulls and rather erratic side lobe structure.

It was considered that the main factors contributing to these faults were likely to be:

a. poor alignment of the individual elements,

b. coupling between leads in the multicore cable,

c. coupling between elements via the encapsulating material.

4.2 Slotted Plates

Alignment of individual elements in the array could be ensured by using a single plate of ceramic with elements separated by slots rather than complete separation [3].

Figure 4.2 shows the result of using this approach in a similar assembly to that of para 4.1.

Side lobe structure was much closer to the theoretical response as regards the spatial distribution of peaks and nulls. The major differences now were in the side lobes being smaller than predicted, by about 5 dB, and a slight broadening of the main beam. These effects could be anticipated due to the inevitable inter-element coupling through the continuous part of the ceramic plate, the multi-core cable and the epoxy encapsulant.

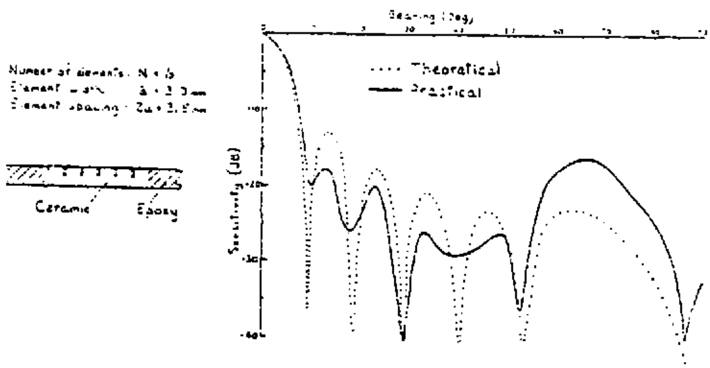

Fig 4.2

4.3 Un-encapsulated Array

Reduction of these inter-element coupling mechanisms was attempted using the construction shown below. Coupling to the water was via a very thin plastic film, with a backing material comprising high density rigid polystyrene.

Slot depths in the ceramic plate were increased to 90% of the full thickness and the multicore cable replaced by separate screened co-axial cables.

The results in Figure 4.3 showed very good agreement between theoretical and practical results between broadside and 45° but increasing discrepancies beyond that point.

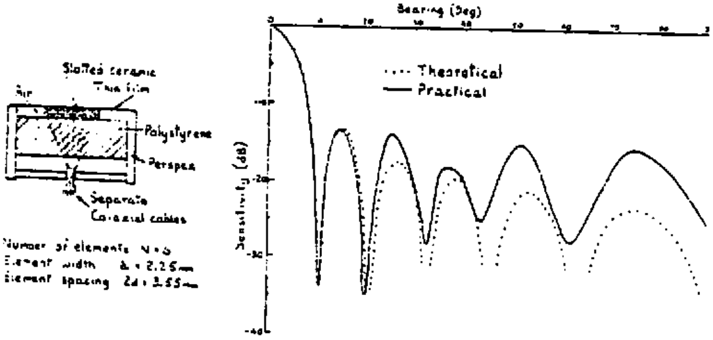

Fig 4.3

4.4 Separate Elements

In order to assess the effect of the slotted plate in the configuration of Figure 4.3 a further array was constructed using the same method of construction but with completely separate elements, very accurately aligned.

Figure 4.4 shows that good agreement between practical performance and theory was now maintained over a greater bearing range and depths of nulls were generally 5 dB greater than in Figure 4.3.

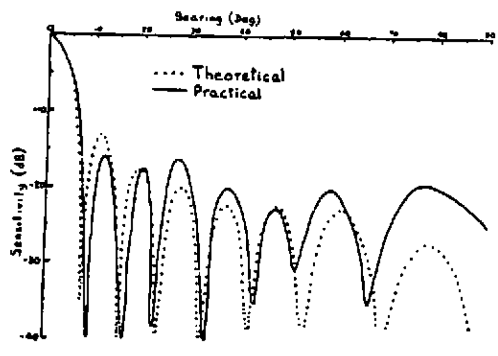

Fig 4.4

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5. CONCLUSIONS

A practical sonar transducer has been produced, using separate elements, with a directivity function in close agreement with theoretical predictions and therefore suitable for use in a teaching laboratory.

Manufacture of the array could be significantly simplified by using a slotted plate but at the expense of an increased discrepancy between theoretical and practical performance at high bearing angles.

6. REFERENCES

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2. MORSE, P M and INGARD, K U Theoretical Acoustics McGraw-Hill, 1968.

3. BRUNEEL, C et al Electrical coupling effects in an ultrasonic transducer array, Ultrasonics, Nov 1979.