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DESIGN AND MEASUREMENT PROBLEMS RELATING TO AN UNDERWATER ACOUSTIC PINGER TRANSDUCER

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INTRODUCTION

During the design and development of an underwater acoustic pinger transducer, several problems arose associated with the realisation of certain design aims. These problems stemmed mainly from the limited space envelope available for this transducer and the need for an economical and very rugged form of construction. Although difficulties have now largely been overcome, it was considered that for the purposes of this Transducer Workshop, it would be of mutual benefit to highlight some of the more interesting aspects of this work. Also, we have yet to find a detailed and satisfactory explanation of discrepancies which occurred in the results obtained using different measurement techniques.

It is not our intention to discuss the detailed performance data of this transducer and references to its specification are in general terms. The work was carried out as part of an M.O.D. contract in collaboration with the Royal Aircraft Establishment, Farnborough, and the Admiralty Underwater Weapons Establishment, Portland.

DESIGN AIMS

The transducer was required to act as a 'pinger' in the audio frequency range and at moderate power levels with an electroacoustic efficiency of greater than 80%. It was to be omnidirectional in the horizontal plane and have a specified beamwidth in the vertical plane with minimum possible sidelobes and end fire.

Unfortunately, as is often the case when designing transducers, there were considerable limitations in the size of space envelope available. The overall length could not be greater than about $1{\cdot}8\,\lambda$ and the diameter not greater than $0{\cdot}75\,\lambda$. Also, the space within the transducer had to be large enough to allow for a drive unit and power supply. There were also rigorous shock and vibration requirements.

INITIAL DESIGN CALCULATIONS

It appeared that a stack of lead zirconate titanate piezoelectric rings of the 'hard' type operating as circumferential expanders would be the best solution. Calculations showed that a ceramic ring conforming to the above size limitations and with air backing would resonate in water at about 10% below the operating frequency required.

In the case where such a transducer is a continuous stack of rings, its length should theoretically be about $2\,\lambda$ rather than the $1{\cdot}8\,\lambda$ allowed in order to achieve the vertical beam angle required. It was considered that to have ceramic rings along the entire length of the transducer would be prohibitively expensive, and only about 20% of the length needed to be active ceramic in order to fulfil the power requirements. It was therefore decided to consider the transducer as a multielement line array.

ELECTROACOUSTICAL EFFICIENCY

It can be shown that the electromechanical efficiency (η_{ea}) may be calculated from the equation:-

$$\eta_{ea} = \frac{R_w}{R_m + R_w} \quad \frac{1}{1 + \dfrac{\tan\delta}{\dfrac{k_c^2}{1 - k_c^2}\,Q_m}} \times 100\%$$

Where R_w = water load resistance
R_m = mechanical loss resistance
$\tan\delta$ = dielectric loss factor
k_c = circumferential coupling factor
Q_m = mechanical quality factor

A range of values for η_{em} were calculated for various 'hard' lead zirconate titanate materials and after allowing for operation 10% 'off resonance' it was found that for the likely voltage drive levels needed, η_{em} ranged from 96·4% to 99·4%. Therefore the variations in ceramic parameters were not likely to be a serious problem and it was not essential to use the best possible type of these materials. Providing that the transducer could be constructed so that the mechanical losses were less than about 15% of the water load, an electroacoustical efficiency of greater than 80% should be realisable.

There are two basic methods used to determine the efficiency of an underwater transducer. There is a simple and approximate method when it is calculated from the conductances G_w (in water) and G_a (in air) using $\frac{G_a - G_w}{G_a} \times 100\%$.

However this assumes that the resistive air loading is negligible on the parts of the transducer which would normally be in contact with water. It also ignores heating losses due to the dielectric loss factor of the ceramic material. The efficiency in this case is really only an approximate form of the mechanoacoustical rather than the true electroacoustical efficiency.

The other more exact method is obtained by comparing the real part of the electrical input power to the transducer and the associated far field acoustic power radiated into the water. The acoustic power is calculated from the source level (S.L.) and directivity index (D.I.). The electroacoustical efficiency can then be obtained from

$$\eta_{ea} = \text{antilog}\left(\frac{S.L. - D.I. - 170{\cdot}52}{10}\right)\%$$

where S.L. is in dB re 1μPa at 1 metre for 1 watt input, D.I. is in dB and the value of 170·52(dB) is the sound pressure re 1μPa produced by 1 acoustic watt at 1 metre in fresh water.

DERIVATION OF DIRECTIVITY INDEX FROM THE ARRAY POLAR RESPONSE

This work is limited to arrays with omnidirectional horizontal polar diagrams since the arrays under discussion are of this type.

Directivity Index (D.I.) can be defined as the output of a directional transducer or transducer array used in a receiving mode compared with that of a non-directional hydrophone of the same response when both are placed in the same isotropic noise field.

From this one can obtain:-

$$D.I. = 10 \log \frac{4\pi}{\int_{4\pi} b(\theta, \phi) d\Omega} \quad \ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where b (θ, ϕ) is the polar response of the array and dΩ is an elemental solid angle.

If the array is omnidirectional in the ϕ- plane then equation (1) reduces to

$$D.I. = 10 \log \frac{2}{\int_0^{\pi} b(\theta) \sin\theta \, d\theta} \quad \ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Now the integral $\int_0^{\pi} b(\theta) \sin\theta \, d\theta$ is a measure of the area under the $V^2(\theta) \sin\theta$ curve, where V (θ) is the polar response of the array. Therefore, the directivity index can be calculated from the measured polar response of the array.

Let the area = A. Then from equation (2)

$$D.I. = 10 \log_{10} \frac{2}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots(3)$$

In order to reduce the tedium of this calculation a desk calculator programme was written.

D.I. PROGRAMME

The polar response of the array is entered into the machine at set angular intervals and then from these figures the D.I. is calculated by the method described above. The area under the curve of $V^2 \sin\theta$ is calculated by dividing it into strips and summing the area of all the strips. This area is converted from degrees to radians and then the D.I. is calculated using equation (3).

The programme was checked by entering a known D.I. and it was found that less than 0·03dB error resulted using angular intervals of up to 20°. The effect of sidelobes on the D.I. was obtained by considering an array with a fixed main beam and changing the height of the sidelobes. This showed that sidelobes less than 20dB down on the main beam cause less than 0·1dB change in the D.I.

ARRAY DESIGN BASED ON THEORETICAL POLAR DIAGRAMS

Using general array theory the response of various types of line arrays has been predicted. For the purpose of this analysis the array elements have been considered as omnidirectional point sources.

During the initial stages of the design it became obvious that there were two conflicting requirements, the maximum array length and the specified beamwidth. It was decided to design the array to meet the beam pattern requirement and to keep it as short as possible even if were over the maximum length.

The array parameters which we investigated were; the number of active elements, the spacing between elements and amplitude weighting of the elements. Of the types of arrays considered all, except for equally spaced 4 and 5 element arrays, were within the beam pattern requirement. Although a 4 element unequally spaced array would have a beam pattern just within the requirements, this is unlikely to be realised in practice due to difficulties in constructing such an array which is acoustically transparent. Analysis showed that the types that are likely to be of practical use are weighted 4 or 5 element arrays and unequally spaced 5 element arrays. Since the total array length depends on the length of the outside pair of elements this was calculated for two element lengths, $1/6\,\lambda$ and $1/12\,\lambda$.

The only arrays which are likely to meet the requirements and be under the overall length are ones having $1/12\,\lambda$ long elements. However, other considerations show that $1/6\,\lambda$ elements have definite advantages.

Therefore some compromise is necessary such as may be achieved by having a combination of 1/6 λ and 1/12 λ elements.

PRACTICAL RESULTS

Several experimental transducers with various ring sizes, mounting configuration and numbers of rings were made and evaluated. In general, there was good agreement between the predicted and measured beam patterns, but rather surprising results were obtained from efficiency measurements. The efficiencies of these transducers when measured by the simple method ranged from between 75% and 96%. The higher values being clearly related to transducers which had lower mechanical losses. However, when these same transducers were evaluated using the S.L./D.I. method, efficiencies ranged between 18% and 67%. There appeared to be some other factor which gave rise to a much greater variation between types of transducers.

The following Table shows values of three transducer types measured:-

Transducer Number	Number of Ceramic Rings	Length of Rings	Proportion of Transducer Length with Ceramic	Efficiency	
				Simple Method	S.L./D.I. Method
1	4	λ/12	19%	76%	18%
2	4	λ/6	40%	88%	44%
3	8	λ/6	80%	80%	67%

These figures indicate that the higher efficiencies (S.L./D.I. method) are obtained for transducers with the higher ceramic content. Various checks were made on the test methods and calculations used but there did not seem to be any obvious errors large enough to cause such variations. When the efficiencies of simple one-ring transducers were measured there was good agreement between the two test methods.

It seems that there was some interaction between the individual rings within the transducer, or between the rings and the array structure, which did not affect the measured water load or the mechanical losses (as measured in air). This resulted in cancellation of acoustic power before it reached the far field. To improve efficiency by having a design similar to transducer number 3 which consisted of a continuous stack of ceramic rings would have been prohibitively expensive and would not have the required beam pattern due to the length restriction.

With the aid of the array theory outlined above and some optimisation of ring mounting and element spacing, several transducers of a compromise design with five $\lambda/6$ rings were made and evaluated. These transducers gave efficiencies in the range 88% to 96% (simple method) and 55% to 75% (S.L./D.I. method). They also had the correct vertical beam angle and acceptable side and end fire lobes. Further transducers of modified design gave efficiencies 68% to 84%. (S.L./D.I. method).

CONCLUSION

A transducer has been designed which is an acceptable engineering compromise. This has been achieved at the expense of rather more ceramic than would strictly seem to be necessary, and with an average transducer efficiency slightly lower than originally intended.

We have shown how electroacoustic efficiency may be determined from measured values of source level and directivity index. Although there was good agreement between efficiencies calculated from this method and the simple method for small single ring transducers there were considerable differences for large multielement types. Comparisons between source levels measured for single and multielement transducers indicated that the lower efficiencies obtained with the larger transducers are correct within normal measurement error. Therefore there are two basic questions raised by the results of this work for which we have not yet found convincing answers:-

1. Why do the transducers with less ceramic give lower electroacoustic efficiencies?

2. Why does the loss mechanism or mechanisms associated with this lower efficiency not show up when using the simple method of measurement?

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