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THE DESIGN OF A HIGH POWER BROADBAND NOISE SOURCE

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1 INTRODUCTION

The design principles of piston stack transducers are now well established, and a high degree of fine tuning is often possible to meet specific individual requirements. However, one aspect remains particularly elusive, namely the ability to produce a high power piston transducer with a wide frequency bandwidth.

A great deal of effort has been expended on this problem and the usual result has been a trade-off between useful power into the water and frequency bandwidth. Increasing the bandwidth of the transducer has invariably led to a decrease in efficiency and a reduction of acoustic power output. Conversely increasing the power output decreases the effective bandwidth.

A number of possible approaches to this problem are re-examined in the first part of this report. Attention is confined to variants on piston stack transducer designs; other approaches such as the use of flextensional transducers fall outside the scope of this paper. It is shown that a category of transducer termed "double head mass" or "Rodrigo" transducer (after the pioneer of such designs) offers a promising basis for further study.

2 STAGGER TUNED ARRAYS

The obvious method of achieving a broadband source would be to build an array with groups of transducers mechanically designed and tuned to resonate at different frequencies within the required bandwidth. This obviates the need for a single transducer to operate over the whole bandwidth. However, an array built with some of the elements tuned to one frequency and some to another frequency will obviously be less sensitive than an array with all the elements tuned to a common frequency. Reference 1 discusses such an array.

If there is a need for a single transducer to operate over the entire bandwidth then it is necessary to consider other methods.

3 ELECTRONIC MATCHING

Electronic matching of sonar transducers is a complex subject and only a brief overview is necessary here. Figure 1 represents a typical sonar transducer of the piston stack type which consists of a radiating head mass, a relatively heavy tail mass, sandwiching a stack of active material which is usually piezoelectic or magnetostrictive.. Figure 2 shows a typical output from such a transducer where f_r is the resonant frequency and f_1 and f_2 are the half power frequencies.

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If we assume a resonant frequency of 5 kHz for this device, then a typical bandwidth for the single element would be about 600 Hz. ie a Q Factor of about 8 or 9.

The main problem in driving a transducer from a generator is that the impedance seen by the generator becomes reactive very quickly either side of the resonant frequency. By placing some form of electrical matching network between the transducer input terminals and the generator the transducer can be driven over a broader range of frequencies. The choice of the various electrical components is critical and is fully discussed in References 2 to 7.

Dearlove (reference 4) suggests that the effect of electrical matching is greatest when the transducer itself is a broadband device. The broadening of the frequency band is accompanied by a decrease in the sensitivity of the device as whole. It is therefore suggested that electrical matching is used in conjunction with other methods, and not as the sole means of achieving a broadband source.

4 ACOUSTIC MATCHING LAYERS

Pursuing the theme of impedance matching, Reference 8 considers the effect of applying acoustic impedance matching layers to the radiating head masses of transducers.

The acoustic matching layers are approximately one quarter wavelength long at the operating frequency of the transducer and the method is obviously more suited to the the higher frequency transducer since at lower frequencies the lengths of the matching layers become disproportionate compared to the rest of the transducer. Bandwidths in excess of one octave are possible but there are limitations in available materials and this would reduce performance at certain frequencies.

5 DOUBLE HEAD MASS PROJECTORS

Figures 3 and 4 show a typical double head mass projector and illustrate the characteristic performance expected from such a transducer. Transducers of this type were pioneered at ARE by Rodrigo (reference 9).

The equivalent circuit for this type of transducer can be described as a three pole Butterworth bandpass circuit. In this case an extra capacitance represents the compliant section, and an extra inductor represents the second head mass, and there are extra electrical tuning components.

Transducers of this type are relatively difficult to design because not all electrical circuit components are mechanically realisable. A very rigorous analysis of the design is therefore required, before attempting to build a transducer.

Although difficult to design and manufacture, the double head mass transducer offers the possibility of achieving bandwidths in the region of one octave.

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6 CAMEL TONPILZ AND VARIABLE DRIVE STACK TRANSDUCERS

The approach discussed in this section is based on concepts developed at GERDSM, Le Brusc, France. This involves exciting a transducer both at the longitudinal resonant frequency, and at the frequency which would cause the head mass to flap. The head flapping frequency is typically about three times the base resonant frequency of the device. Since the head flapping mode is a very inefficient method of transferring power into the water, transducer heads are normally shaped to avoid this mode being excited. For the purposes of producing a broadband device however, some potential advantage is claimed by use of the transducer head flap mode.

Transducers have been designed and built which can be driven at different amplitudes and phases at different points along the ceramic stack. Mechanical null points occur at different positions along the stack where adjacent rings reverse mechanical phase.

Both of these methods of achieving broader band transducers are well suited to analysis by Finite Element Analysis Techniques, although such techniques must be applied with care, and are not well validated with fluid loading.

Steel, Gazey and Smith (Reference 10), describe a transducer whose resonant frequency is tunable from 250 kHz to 700 kHz. The transducer consists of two ceramic blocks with matching and backing layers. One of the ceramic blocks is known as the "drive" ceramic, and the other ceramic is known as the "control" ceramic. The control ceramic is either loaded with passive electronic components, or is driven with a known voltage. The characteristics of the signal supplied to the control ceramic, affects the output of the drive ceramic.

This is basically a variation of the technique described above, where part of the ceramic stack can be described as the "control section", and the other part can be described as the "drive section".

7 MECHANICALLY VARIABLE HEAD AND TAIL MASSES

The head and tail masses and compliance of the ceramic stack are the dominant factors in the design of a piston stack transducer. If a means is provided to change either or both of the masses, then a change in resonant frequency is possible. Imagine concentric masses (either head or tail or both) which can be locked together by an electromagnet or magnetic clutch system. A lower frequency is possible when the masses are locked together than when the masses are completely isolated.

A piston stack transducer with a low tail to head mass ratio will be an inefficient device with a low sensitivity. If the masses were optimized to the ceramic stack for maximum power and efficiency in the first place, then increasing either mass individually will result in degraded performance. Increasing both at the same time results in an overworked stack, and thus a poorer transducer. Ideally the compliance of the stack needs to vary at the same time as the masses change. The problem is not only to produce a change in resonant frequency but to maintain a high acoustic power output at the new resonance.

At present it seems unlikely that this technique would produce a significant useable increase in bandwidth, and in view of the increased mechanical complexity of such a device this approach has not been pursued.

8 VARIABLE COMPLIANCE STACK

Here the concept is to vary the compliance of the active section by some independent means. One possible method might involve doping the ceramic with iron filings and wrapping an electric coil around the stack. Passing electric current through the coil would induce a magnetic field within the ceramic stack, which would change the orientation of the iron filings within the ceramic, thereby inducing a change in the compliance of the ceramic stack.

In order to change the resonant frequency by even a small amount however the compliance of the stack has to change considerably, and in practice the iron doping method turns out to be insufficiently sensitive. Furthermore, doping lead zirconate titananate with iron filings would destroy the crystal lattice structure which makes the piezoelectric effect possible.

An alternative approach might use the rare earth magnetostrictive material TERFENOL which exhibits a variation in Young's Modulus as the applied magnetic field changes. The possibility of a "composite transducer" has been considered in double head mass designs, where (Figure 9) the active stack is made up of conventional piezoelectric ceramic rings, and the compliant section consists of TERFENOL rods. In practice the variation of the Young's Modulus of the TERFENOL is too small to provide sufficient variation of compliance to effect a significant broadening of the transducer bandwidth.

9 MULTIPLE PISTONS ON A COMMON HEAD OR TAIL

This is a development of the concept of Stagger Tuning which was discussed previously. If the geometry of the transducer will allow, the easiest solution may be to use several projectors combined in some way within a larger transducer body. Consider, for example, the case of a large low frequency projector surrounded by four high frequency devices, and all assembled within a common body. All five transducers use the same head mass which is itself inert. Each transducer has its own ceramic stack and tail mass. Alternatively they may share a common tail mass.

10 CONCENTRIC STACKS

This discussion leads to the possibility of designing a transducer with two or more concentric stacks. The stacks may or may not share common head and tail masses. If only one stack is used as the driving force at any particular time then the other stack(s) must be synchronised to the motion of the head and tail masses so as to impose no loads on them or cause fracture of the joints.

The multiple projector on a common tail type of device and the concentric stack type of device

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have been analyzed extensively by Lipscombe and Morris of DBE Technology. The conclusion is that neither device can be realized in practice because the undriven stacks present a destructive impedance which cannot be removed.

The multiple projectors within a common head device is believed to work but the weight of the low frequency head must be considerable leading to a very high Q Factor for the low frequency resonance.

11 ORGAN PIPES

This method relies upon the fact that a resonance occurs in a tube or pipe when the length of the tube is an odd multiple of quarter wavelengths. A vibrating piston at the bottom of a cylindrical cavity has been examined in detail by Nomura and Inawashiro (Reference 12 and 13). The acoustic power radiated from the tube depends upon the acoustic resistance, and this can be shown to vary with length and radius of the cavity.

The most pronounced effect occurs in a cavity of length corresponding to 0.25 and 0.75 wavelengths. This is obviously a fixed frequency effect, but a means of varying the depth of the transducer within the cavity would alter the resonant frequencies. The idea of using hydraulic rams or some other means of pushing transducers up and down pipes has been discarded as impractical. However the idea of using an organ pipe to add an extra resonance to the transducer remains a viable proposition as is shown later.

12 EXPERIMENTAL STUDIES

It was decided to concentrate upon the design of a "double head mass" transducer which would yield a device with a bandwidth of about one octave. Further improvement in performance can then be achieved by the addition of electrical matching networks.

This part of the paper describes results of measurements on a variety of double head mass and conventional transducer designs. Transducers designed and built by three different UK Defence Contractors, DBE Technology, Universal Sonar and Marconi Underwater Systems are included in this study.

The transducers supplied by DBE and Universal Sonar were developed under contract to the MOD.

The equivalent circuit of these transducers often requires electrical components in the form of a coil and resistor in series with the transducer.

The transducer supplied by DBE Technology (designated DBE_1) is a double head mass device with a compliant section made up of a circular block of nylon. No electrical components were supplied for testing with the transducer.

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The transducers supplied by Universal Sonar (designated USL_1, USL_2) are double head mass devices with the compliant section made up of three titanium rods. The transducers were tested with and without organ pipes. As for the DBE device no external electrical components were supplied.

The transducers supplied by Marconi also incorporate a double head mass and were tested with and without external electrical components.

The ARE Rodrigo transducer is a double head mass device with compliant section made up of three beryllium copper rods, and did not incorporate the electrical components. This transducer was smaller than the devices supplied by the Contractors and utilized barium titanate rings in the stack rather than lead zirconate titanate.

In addition measurements were carried out on a conventional single head mass design in order to provide a useful reference. This transducer also utilized barium titanate rings as the active material.

Figure 5 compares the performance of a conventional single head mass design with the ARE Rodrigo transducer and DBE_1. The characteristic double hump of the double head mass device is readily apparent. The DBE device is much more powerful due to its increased size and the use of lead zirconate titanate for the active material.

Figure 6 compares the performance of the Marconi transducers with and without extra electrical components and the conventional single head mass device. Notice the characteristic double hump of the double head mass device by itself and also that the addition of the electrical components improves the sensitivity between the two peaks

Figure 7 compares the performance of the USL transducers with and without organ pipes and the conventional single head mass device. USL_1 operated without an organ pipe displays the characteristic double hump of such transducers. The addition of the organ pipe shifts these two resonances and introduces a third resonance. The lack of sensitivity at 7 kHz is probably due to the mounting arrangement of the transducer within its case.

13 CONCLUSION

This paper presents a review of methods of achieving high power piston transducers with wide frequency bandwidth. If limitations are placed upon the overall physical size of transducer, then the double head mass design currently offers the most promising solution.

14 ACKNOWLEDGEMENT

The Marconi transducers are a proprietary design known as the MUSL Type 152, and Marconi's co-operation and the loan of their transducers for evaluation by ARE is gratefully acknowledged.

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Fig 1

Piston / Stack (Tonpilz) Type Transducer

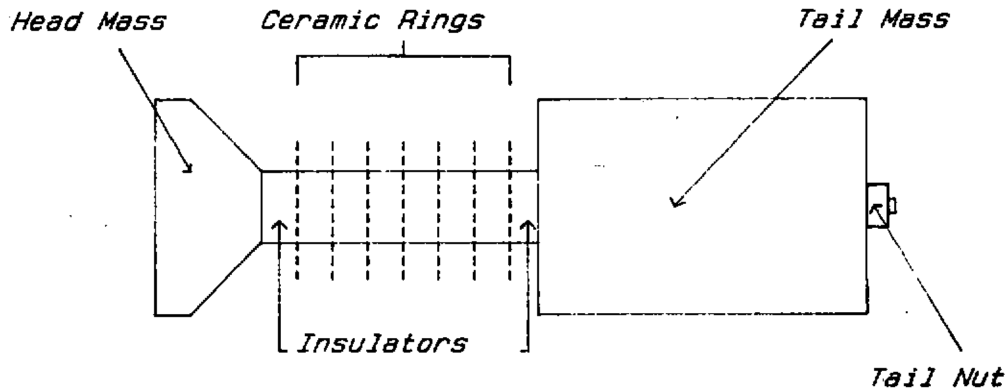
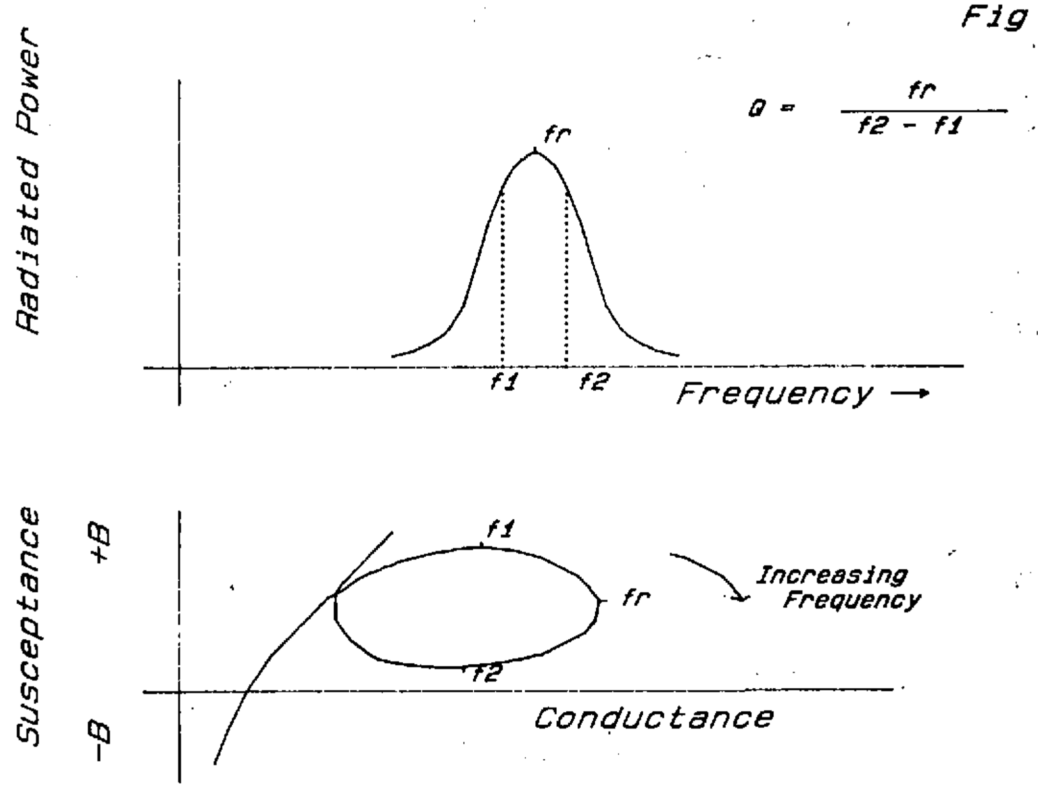


Fig 2



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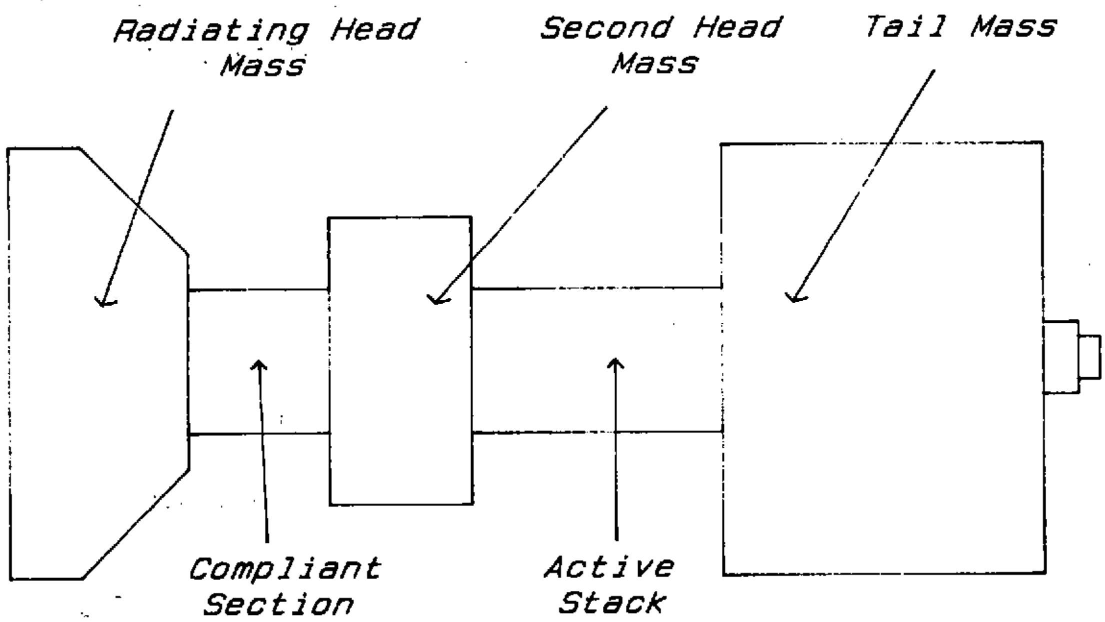
Double Head Mass Transducer   *Fig 3*



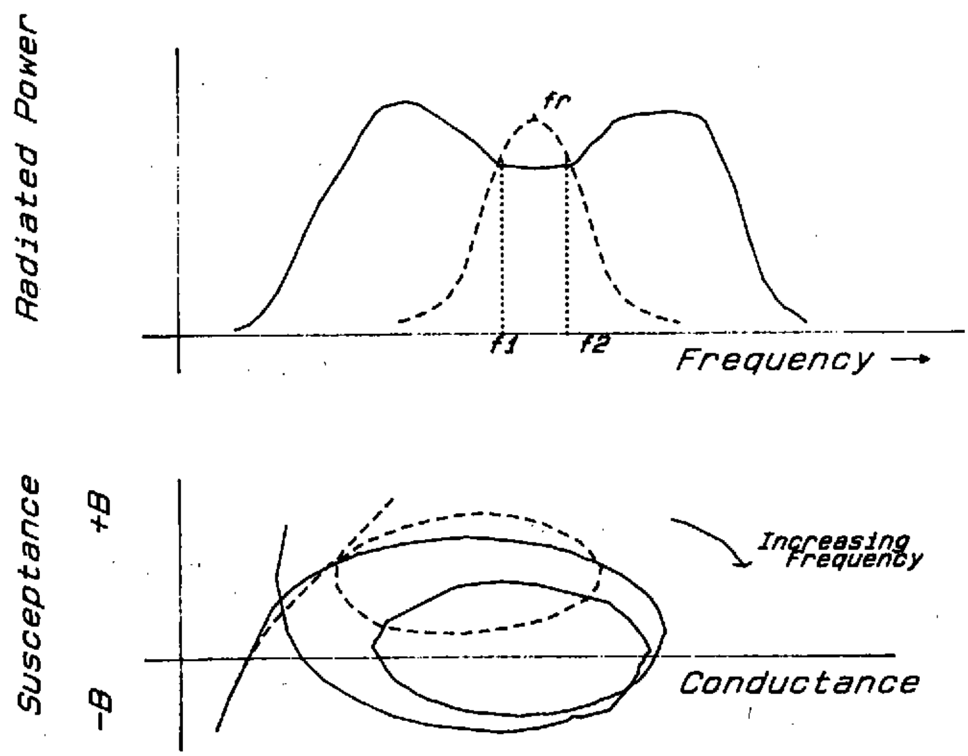


Fig 4

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Fig 5

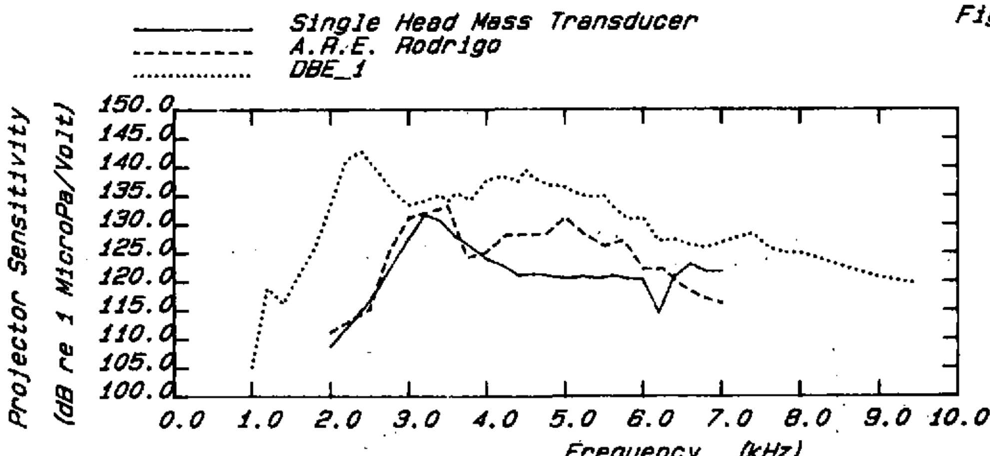


Fig 6

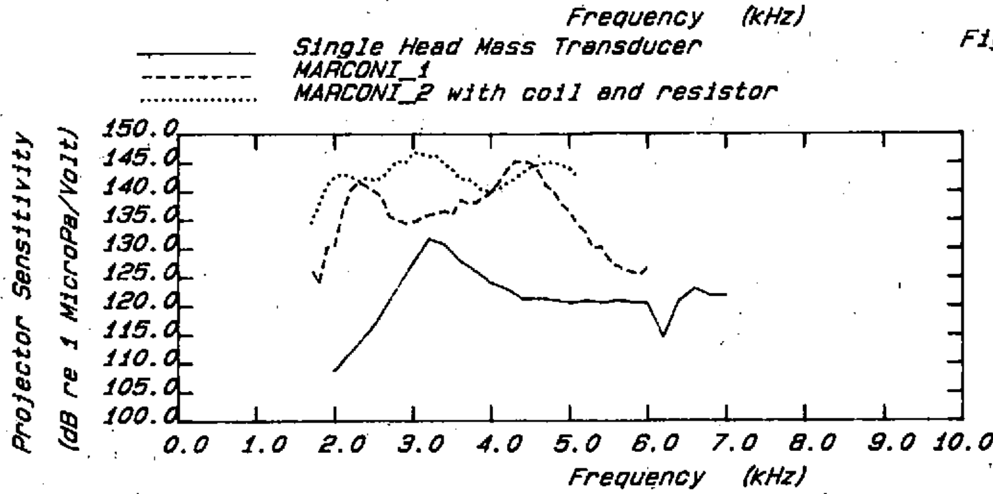
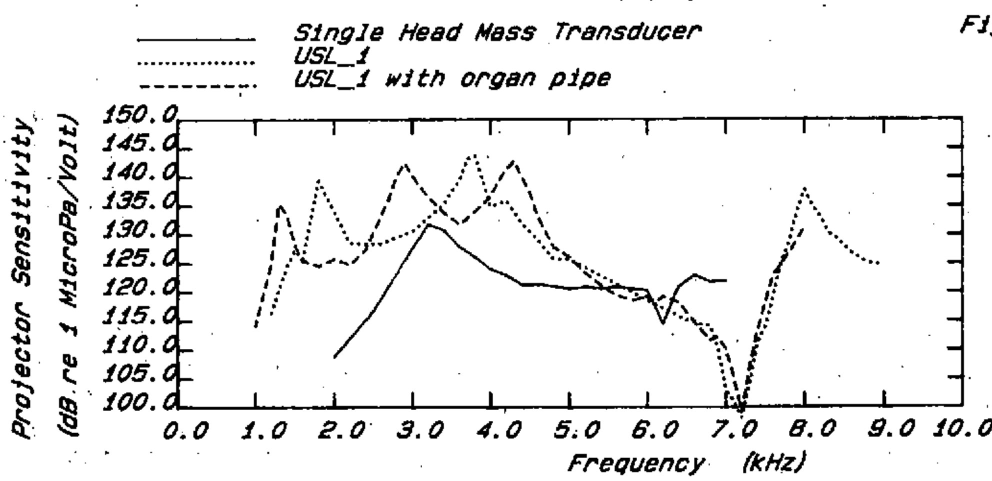


Fig 7



HIGH FREQUENCY RECEIVER ARRAY FOR SONAR APPLICATIONS

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INTRODUCTION

This paper describes the development of a sonar receiver array to form part of a large acoustic system. Initial specifications for the array were as follows:

Sensitivity	-185dB re 1V/μPa
Frequency	120kHz to 140kHz
Bandwidth	±10kHz @ 130kHz (-3dB)
Beamwidth	23° in both major planes
Maximum depth	100 metres (survival)
Maximum steer	±45°

The relatively high sensitivity indicated a requirement for operation around resonance. This is usually avoided in receive arrays because small mismatches in transducers cause large relative phase errors near the resonant frequency.

Conventional piston transducers are suitable for resonance up to about 80kHz, while simple ceramic plates are rarely used below 200kHz. Hence, current technology does not offer a standard solution for accurate resonance in the 130kHz region.

A trial array was first produced using stacked PZT 4 (lead zirconate titanate) ceramics with intermediate bonds to achieve the required resonant thickness. Acoustic measurements on this array confirmed the high sensitivity, but showed significant phase errors.

Close examination of the system requirements revealed that beamforming and steering (and therefore phase matching) were more important than absolute sensitivity. It was decided that a reduction to -200dB re 1V/μPa could be tolerated. This allowed an array of simple non-resonant transducers to be constructed using bars of lead titanate, a relatively new ceramic material.

The Trial Array

Early on in the project, it was decided to build an experimental array to investigate the likelihood of producing a satisfactory resonant structure. The physics of beamshape and sensitivity were fixed by the adoption of standard design principles, so the trial array was built as a partial structure to investigate the basic sensitivity and electrical characteristics only.

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Calculations showed that a theoretical length of 14mm would provide a length resonance of 130kHz. However, the difficulty in predicting the thickness of the inter element bonds naturally led to uncontrolled compliance and a resultant lowering of the resonant frequency. The results obtained from the trial array proved that the bonds were having a significant effect and it was from that evidence that the resonance at operation design was discarded.

Final Array Design

The initial transducer requirement introduced a number of unnecessary restrictions to the designer. Firstly, a minimum sensitivity of -185dB re 1V/µPa was specified, but only available in a resonant design. Secondly, seven individual staves of four transducers per stave was specified but only seven single transducers were required. Finally, the inter-element spacing had to meet a minimum spacing of 0.5 lambda to avoid the incursion of diffraction secondaries at the extremes of steer.

The revised specification of -200dB re 1V/µPa led to the construction of the relatively simple array shown in figure 1. It comprised seven rectangular ceramics of area 27mm * 3mm and thickness 7mm. The spacing between elements was 1mm giving a total width of 27mm to satisfy the beamwidth requirement in both directions.

A major problem in arrays of this kind is acoustic coupling between adjacent elements. With long ceramic bars and close spacing, the problem using conventional ceramics was potentially very serious. The advent of lead titanate provided a solution. It has a very low g_{31} coefficient and is hence very insensitive to lateral pressure. It is therefore a highly suitable material for any array where inter-element coupling through the structure must be avoided.

Lead titanate has a relatively high g_{33} coefficient of $34 * 10^{-3}$ Vm/N. When used with a high impedance backing, the sensitivity would be g_{33} * thickness giving -192dB re 1 V/µPa. However, in this case the backing impedance was close to that of water so the predicted sensitivity was 6dB lower at -198db re 1V/µPa. Using the frequency constant N_1 = 2130 Hz.m the predicted resonant frequency was 304kHz which was sufficiently high to achieve a flat response in the frequency range of interest.

A disadvantage of lead titanate is its low capacitance. The dielectric constant K_{33}^{T} = 250 gave a predicted value of C_{LF} = 25pF for each element. In addition an estimated cable capacitance of 6pF caused a further 2dB loss in sensitivity.

The array is shown in schematic form in Figure 1.

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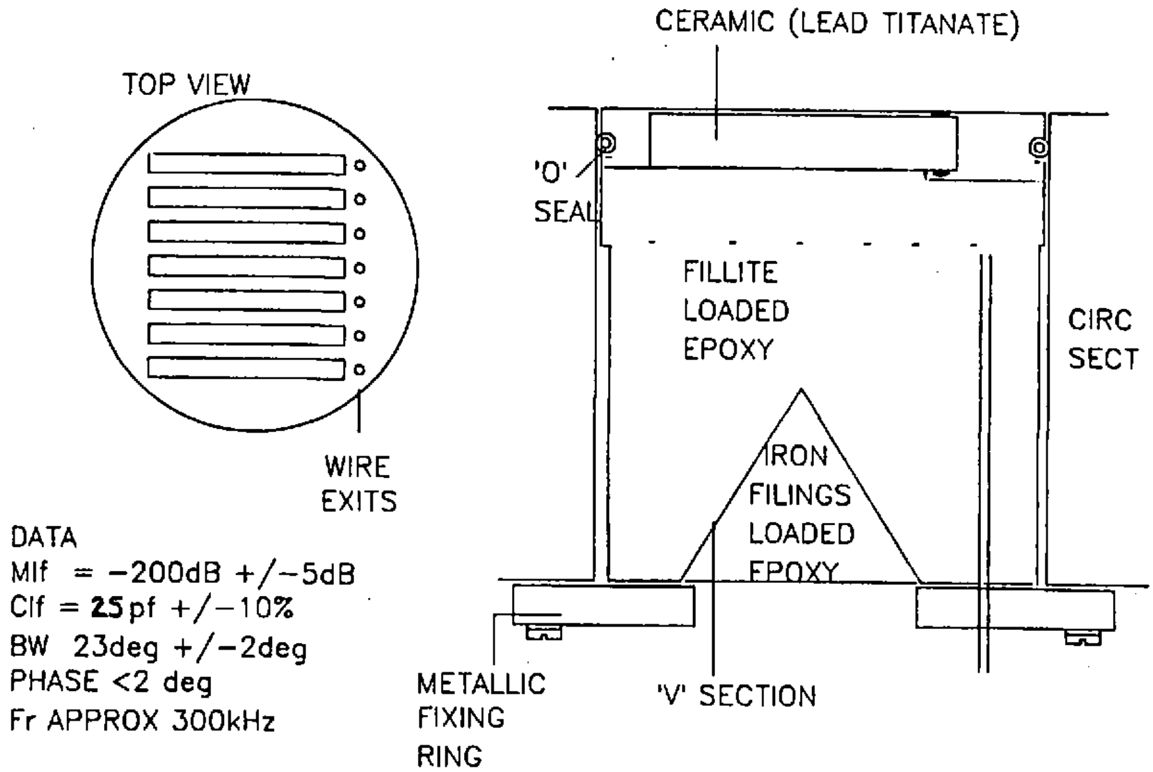

FIGURE 1 : SCHEMATIC OF THE ARRAY

The body of the array was formed using a variety of jigs and moulds and used loaded epoxies to introduce a high level of acoustic dispersion within the structure. The main body was formed from standard Versamid epoxy, loaded with Fillite. This material provided a high level of scatter within the structure thus discouraging the build up of standing waves. An eccentric cone was then machined into the back of the block and this was re-filled with iron filings-loaded epoxy, to provide further scattering and support against hydrostatic pressure.

A depression was then machined across the front face of the block, the boundary of which formed a chord line of some 20mm length. Measuring only 3mm deep, the resultant depression served as the accommodation cavity for the wire joints to the underside of the ceramic. Also, the side of the main block was machined to allow the wire array to run down the side of the main body and exit on the rear plane.

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Once the main block machining operations were complete, the ceramics were bonded to the face of the main body using a dedicated location jig and a set of separation pins. This assembly was effected while the ceramic bonding material was still 'wet' in order to ensure a high degree of locational accuracy of the ceramic active faces with respect to the array body.

With the ceramics safely bonded to the main body, a further epoxy potting was made over the ceramics, to slightly increase the diameter around its periphery to provide an 'O' ring groove to effect water tight integrity of the unit. The final potting requirement was to seal the cable array into its cut-out.

The assembled array is shown in Figure 2.

Electro-acoustic Tests

Throughout the various stages of assembly, measurements were taken of the low frequency capacitance to ensure that the assembly processes did not introduce any ceramic failures. Once the array had been built, these tests were extended to include in - air admittance, in-water admittance, receiver sensitivity and polar performance. The in-water tests used a 20dB pre-amplifier and line driver to minimise the losses due to cable capacitance.

Measurements made of the in-air admittance showed that the predicted capacitance parameter was easily met. There is little further useful information from these plots apart from the indication that the sensitivity at the intended frequency of operation was likely to be flat. Equivalent circuit information was derived from these plots and assisted in the design of suitable pre-amplifiers for this project.

Measurements of the element receive sensitivity were of significant importance from a systems point of view in that a virtually flat response was required. It was for this reason that the array design contained so much consideration of the likely interference problems. Figure 3 shows that the sensitivity of a single bar over the 120kHz - 140kHz band is flat to within ±1dB. Moreover, the predicted sensitivity of -200dB re 1V/µPa was achieved to an accuracy of better than ±2dB.

Figure 4 shows the beamwidth performance of the array and clearly, the specified 23° beamwidth has been achieved. This characteristic was specified at the outset of the project and could not be compromised. Sidelobe levels have also exceeded the requirement and meet the theoretical limit of -13dB.

HIGH FREQUENCY RECEIVER ARRAY

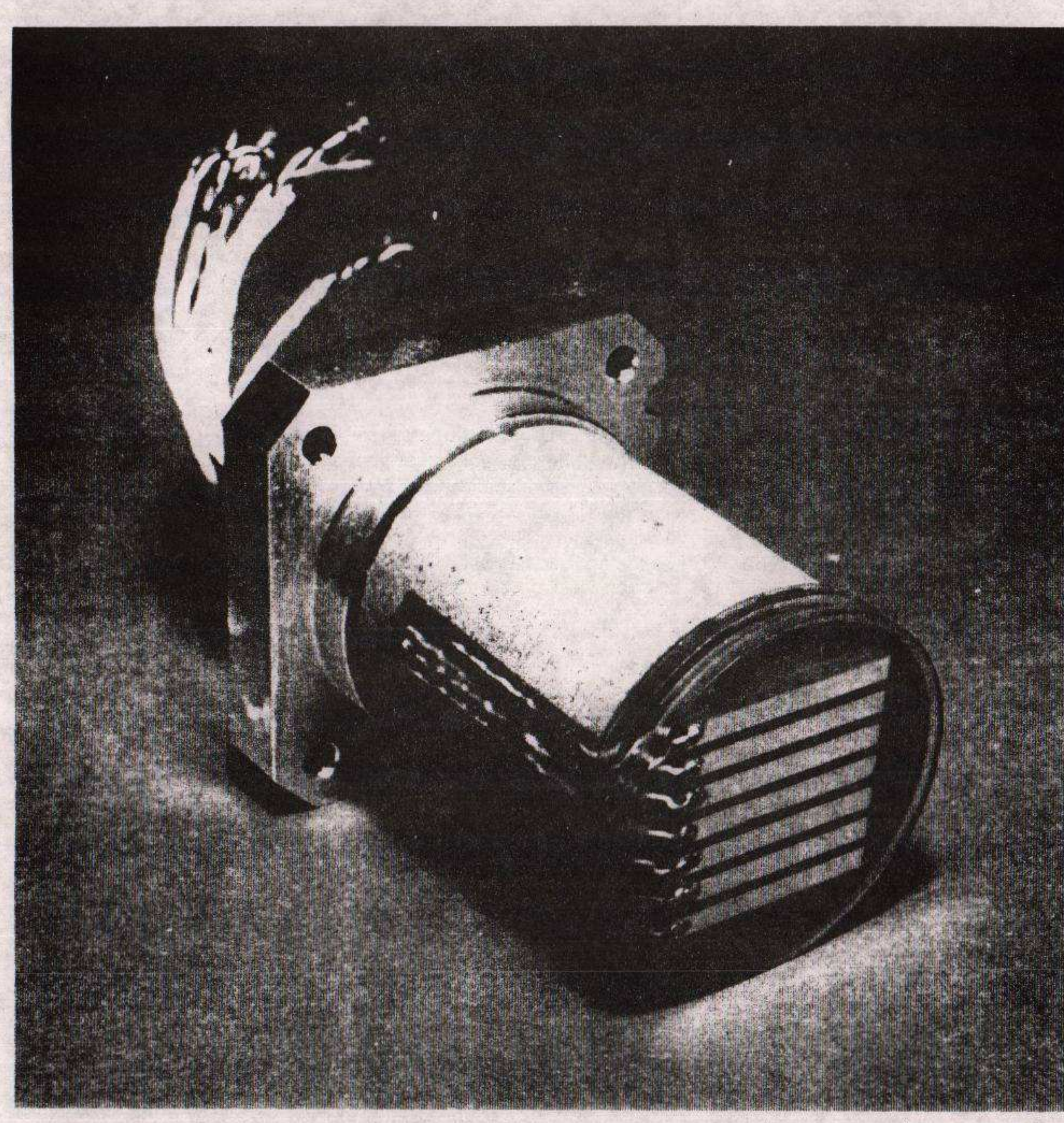

FIGURE 2 : THE ASSEMBLED ARRAY

HIGH FREQUENCY RECEIVER ARRAY

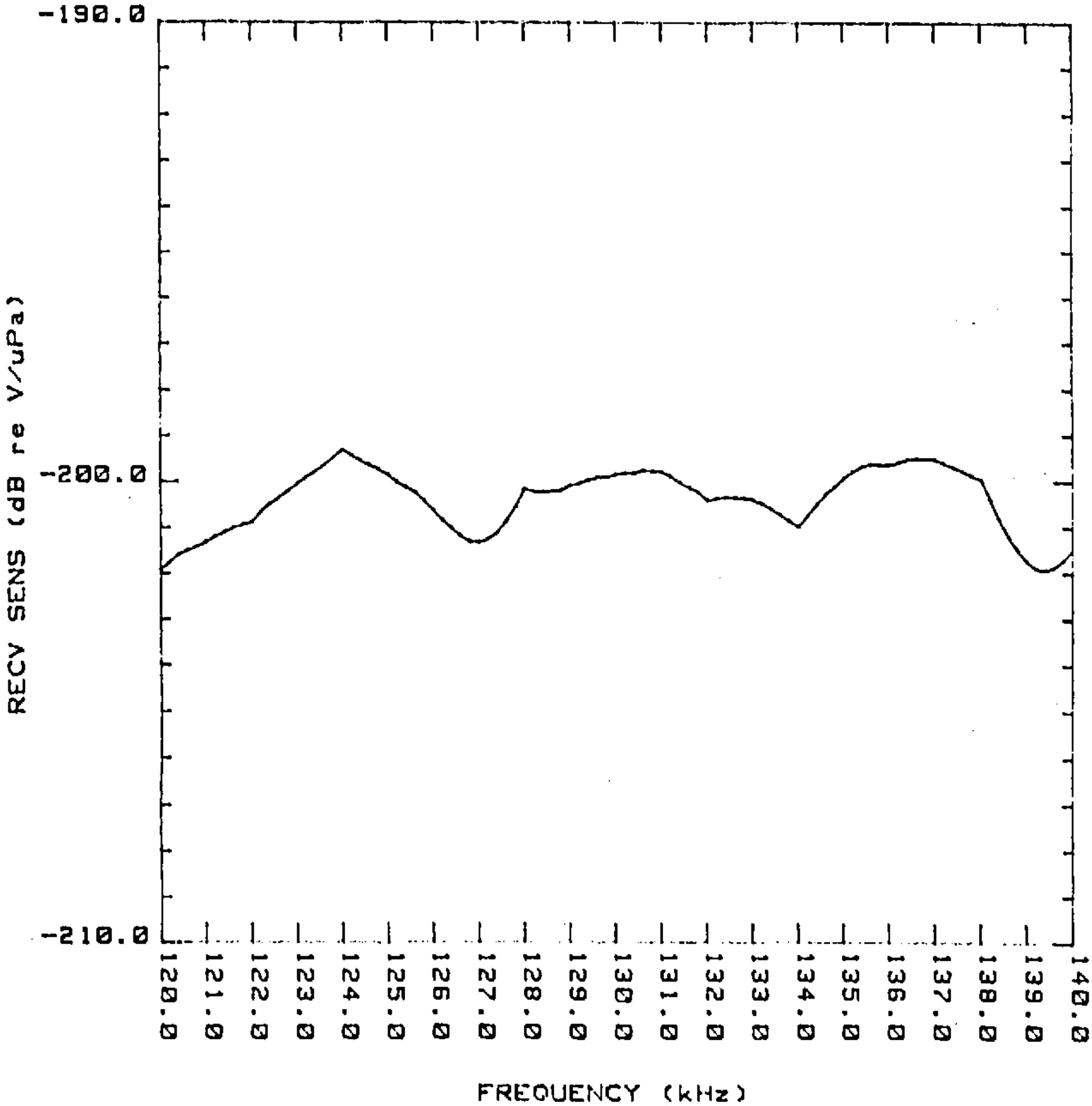

FIGURE 3 : FREQUENCY RESPONSE 120-140kHz

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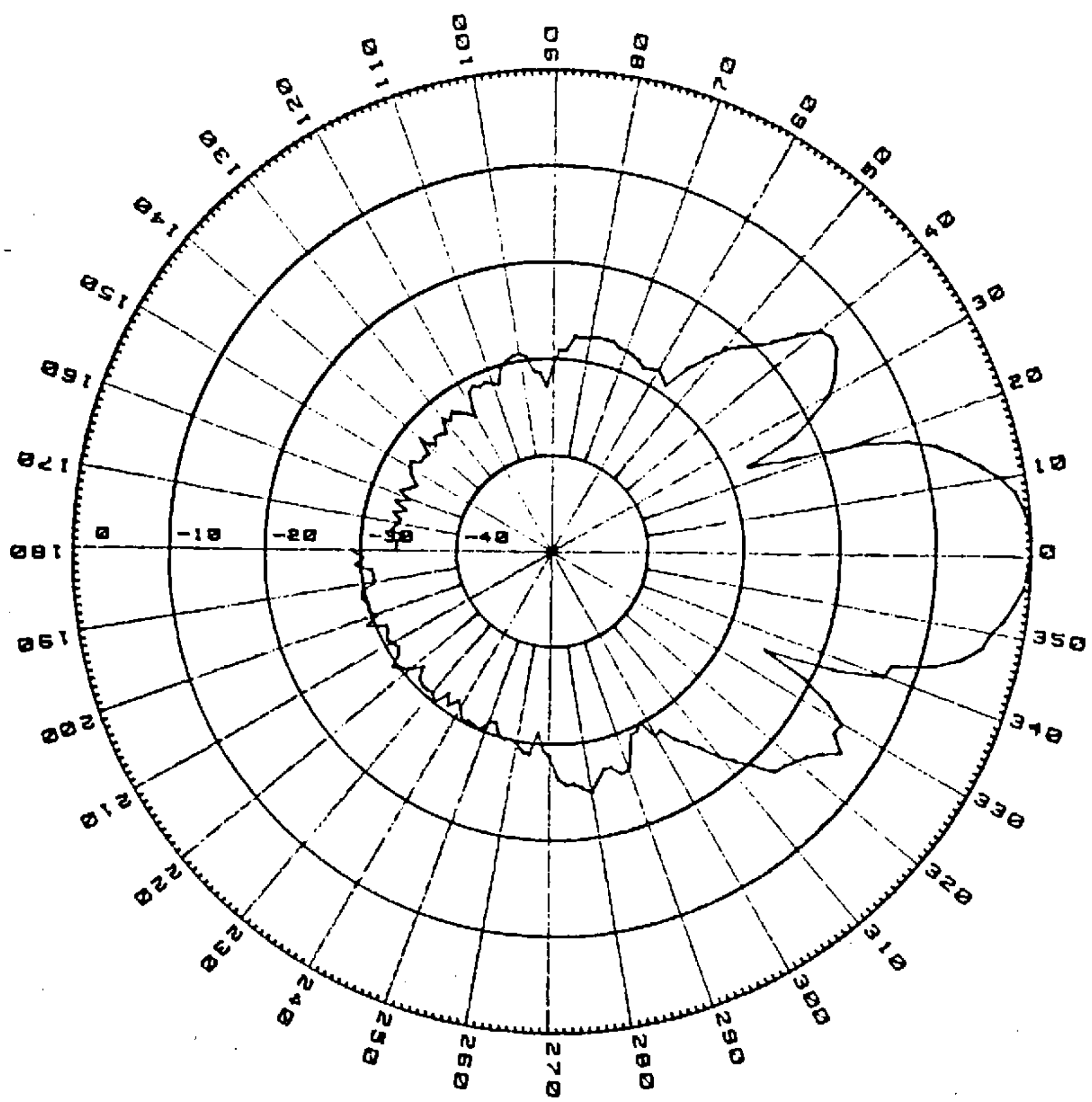

FIGURE 4 : POLAR PERFORMANCE AT 122.5kHz

HIGH FREQUENCY RECEIVER ARRAY

CONCLUSION

The development of this array highlights the importance of ensuring that the limitations of transducer technology are reflected back into the system specification at an early stage. The trial array was built as a demonstration that achieving accurate resonance characteristics in the 100kHz region is risky. The adoption of a device which is operated well below its resonance eliminates virtually all risk and is simply dependant on good design. Further guarantees of performance were provided by the use of lead titanate, the use of which could be considered as an alternative to Lead Zirconate Titanate material.

Ostensibly, the structure is simple yet it guarantees a creditable performance from a system point of view. Its construction as a one piece solid unit means that it is durable, reliable and may easily be produced in resonable quantities in short time scales. Furthermore, it's life span is extended by the use of epoxy materials for all the exposed parts in preference to metallic options.

ACKNOWLEDGEMENTS

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