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CASE HISTORY - A HIGH POWER WIDE BAND TRANSDUCER OPERATING AT 75KHz

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Introduction

This transducer design resulted from the need to develop a deep sea narrow beam echo-sounder, which would achieve the required narrow beam at a low enough frequency to propagate to full ocean depths by exploiting the non-linearity inherent in acoustic propagation. The project was a joint IOS-UOB effort financed by NERC. The division of work required IOS to produce the transducer to an agreed specification, as follows:

Centre frequency	-	80KHz (subsequently amended to 75KHz)
Peak envelope power (acoustic)	-	6Kwatts
Operating bandwidth	-	Greater than 10KHz
Efficiency	-	Better than 60% (to limit demand on the amplifier to 10Kw peak)
Dimensions	-	Active face to be 40 x 40cm square
Operating depth	-	30 metres (this is dictated by the cavitation threshold)

The basic acoustic design was the work of Dr. Rusby at IOS. The final details and the construction, testing and sea trials were overseen by Somers.

The Acoustic Design

The designer of transducers for underwater use has a number of compromises to make and the choices get more critical as the frequency is removed above or below the optimum. The first essential in designing for low mechanical Q is to ensure that the various elements of the array have as high a ratio of self radiation resistance to mutual radiation reactance as possible (see Ref.1). This ensures that minimum phase differences occur in diaphragm velocity between elements as a function of frequency and geometry in the array, so that a common high resistive radiation loading is developed by all the array elements within the desired band. (This is also a necessary requirement for high power, high efficiency, radiation from pre-stressed ceramic stacks which are usually amplitude limited). In order to achieve this one aims to make both the element diaphragm diameter and the centre to centre distance between elements an appreciable fraction of a wavelength. If λ is the acoustic wavelength in water, a the radius of the element face and d the centre to centre spacing of the elements, calculations show that if $\frac{2\pi a}{\lambda}$ approaches the value 2 (and hence $\frac{2\pi d}{\lambda}$ approaches at least 4) the elements will have very little mutual impedance. The need to keep power density at the radiating face as low as possible suggests that the elements should be as closely packed as possible, so it is doubly important to maximise the element face diameter.

The second requirement for low Q is that an acoustic impedance match should exist between the radiation impedance of the element face working into water and the acoustic impedance of the driving resonator, which is usually a ceramic stack in modern designs. A perfectly matched air-backed half wave resonator would have a $Q = \frac{\pi}{2}$ (Ref.1), which can be regarded as the ideal. By contrast for PZT-4 working into water the impedance mismatch leads to a Q of 24. Usually the designer overcomes this by increasing the area of the radiating face relative to that of the cross-section of the ceramic stack, by making the radiating head conical in form. This matching process is limited in practice by the production of flexural modes in the radiating head as the ratio of diameter/thickness of the cone is increased. The frequency of the gravest flexural mode in the head should be > 4 x the longitudinal driving frequency if the cone is to act as an effective piston. There is also a physical/acoustic limit to attainable Q. The transducer parameter we are interested in maximising is the bandwidth of the electro-acoustic transfer function, and in the case of a ceramic material with imperfect electro-mechanical coupling there is an optimum mechanical Q which maximises the overall bandwidth so that a mechanical Q lower than optimum makes the electrical circuit more selective.

There is in principle another route to reduction of Q in transducers without loss of efficiency, and this is to interpose a quarter-wave matching stub between the stack and the load. The stub material should have an acoustic impedance geometrically midway between the stack and the load. This approach has been tried (Ref.2) but at present it is hampered by shortage of suitable matching materials.

The design evolved by Dr. Rusby at IOS was originally worked out at 6.5KHz but has been scaled up in frequency to the 75KHz of this transducer, and is usable at any intermediate frequency. The comparison between the two designs is shown in this table:

	6.5KHz	75KHz
Ratio of stack to Diaphragm area	5	4
$\frac{2\pi a}{\lambda}$	1.5	1.8
Single element Q in water	5	7.5

The 75KHz element used a titanium radiating head to avoid the corrosion problems of the aluminium of the 6.5KHz element, it also employed standard ceramic discs instead of specials. Intermediate designs have been constructed at 10KHz, 36KHz, 42KHz and 54KHz, all with very similar properties.

All these designs feature a central pre-stressing bolt to keep the ceramic in compression through the acoustic cycle, and an integral flange around the front of the radiating cone for mounting purposes. This gets round the problem of sealing the front face which bedevils nodally mounted transducers, and thus contributes very substantially to the high efficiency of the design.

On the other hand both of these features introduce their own problems when the design is scaled for high frequencies. The pre-stressing bolt necessarily displaces useful ceramic volume and if it is of too large a diameter it may cause alterations in stack impedance as well as power handling capability. However the peak acoustic strain at maximum power is known and this fixes the minimum bias stress in the ceramic to maintain the stack in compression, with the result that the necessary bias stress levels in the bolt and ceramic are inversely proportional to their respective areas. The limit on the minimum bolt diameter is the fatigue limit for the steel for the known acoustic strain superimposed on the steady bias strain. The result is that one needs very high quality material for the bolt if the effect of its presence on the transducer is to be small. The scaling problem arises because the bolt has to be threaded and in order to maintain the fatigue safety factor as the attainable manufacturing tolerances become relatively coarser a large proportion of the stack area has to be set aside for the pre-stressing bolt. The problem is aggravated by the fact that the practical fatigue limit is set by the 'notched' condition of the bolt due to the thread, which may be nearly an order down on the limit for the equivalent bar material. The pre-stress is applied by clamping the transducer front face to a datum surface and tightening the tail nut until a specified elongation of the bolt has occured. In this design the required elongation was 0.023mm but because of creep in the glued joints this had to be applied as an initial stretch of 0.028mm followed by a relaxation and a re-application of 0.023mm before locking the nut. It is felt that the problems of correctly pre-stressing a smaller stack within the fatigue limit of even the best quality bolt would be very severe. Due to the fatigue limit of the bolt the measured power handling capability of the 75KHz element at a normal duty cycle is limited to 16 watts i.e. 14watts/cm^2 (under a hydrostatic pressure of 3.5 bars). When run continuously the limit is again 16watts, due equally to the unaltered bolt strain and the now increased dielectric heating which produces a measured internal stack temperature of 60^oC above ambient.

The other main problem of scaling was also caused by tolerance effects and concerned the supporting flange. This flange has to support the whole hydrostatic thrust on the front face, with the a.c. acoustic deflection superimposed on the static one. Again the calculation involves a fatigue limit, that of the titanium flange. Because of the small area of each element the 40 x 40cm array required 729 elements each 12mm in diameter. The only way to get these closely enough packed was to start with a solid plate of titanium and to machine the radiating cones and their flanges from the back. The 50cm square plate 12mm thick had to be machined 729 times across a 40cm square to within 0.5mm of the front surface, and the tolerancing led to a rather thicker flange than optimum. This meant that the elements were rather more tightly coupled to the surrounding matrix of material than was desirable.

The practical difficulties of wiring, testing and sealing the array proved far less trouble than was originally feared, and the uncertainties in pre-stressing,bolt fatigue and flange-mounting would be the likely limits to further frequency scaling.

The ceramic stacks and tail masses were pre-assembled in a special jig and tested to ensure suitable activity and quality. Meanwhile the plate was machined (during which process only one element station was lost), and the threaded studs were inserted in tapped holes in the cones. Next the stacks were glued in and pre-stressed as described above. An admittance measurement of the whole array in air would be meaningless because of the frequency spread and high Q values, but the individual elements were all tested for resonant frequency and Q. Q values ranged from 35 to 90. The elements were wired in parallel in rows and the rows were connected through fuses to a single bus bar. The fuses would allow a faulty row to be cleared with a d.c. current pulse.

Results

The admittance circle in water revealed that the mechanical Q had increased from the prototype single element value of 7.5 to 13.8 for the full array after the titanium was fully wetted (a test array of 9 elements had previously given a Q of 9.5). The explanation for the higher Q in an array seems to lie in the interaction between the elements and the baffle, and/or the interaction of elements through the baffle. The active portion of the transducer face amounted to about 45%, and the effective volume of baffle available to each element is about $1200mm^3$ whereas the volume of the titanium radiating cone is $270mm^3$, so the baffle mass is only 4.5 times the vibrating mass, and as well as the acoustic coupling there is a fairly stiff compliant coupling due to the diaphragm as mentioned earlier. The resonant frequency of the baffle mass driven by the diaphragm coupling can readily be calculated as about 42KHz, so the elements are fairly tightly coupled to a system with a resonant frequency less than one octave removed from their own.

As it happens the degradation of Q is not serious since the elements were not voltage limited at the required drive level so it was possible to compensate for the loss of power factor at the two primary frequencies of 70 and 80KHz by increasing the drive voltage.

In all other respects the transducer behaved as predicted, it being possible to transmit 6KW of peak envelope power with an efficiency of 80%, at a depth of 30 metres before the onset of cavitation. The array was cycled more than 10^7 times at full power without change of characteristics so there are grounds for believing the fatigue calculations to be good.

References

1. J.S.M. RUSBY — Investigation of a mutual impedance anomaly between sound projectors mounted in an array. Acustica, 14, 1964, pp. 127-137.

2. HEUTER and BOLT — Sonics. Wiley and Sons, New York, 1954, p.106.

3. D.J. SMALL — Design of a Low Q Transducer, Ultrasonics, July 1971.

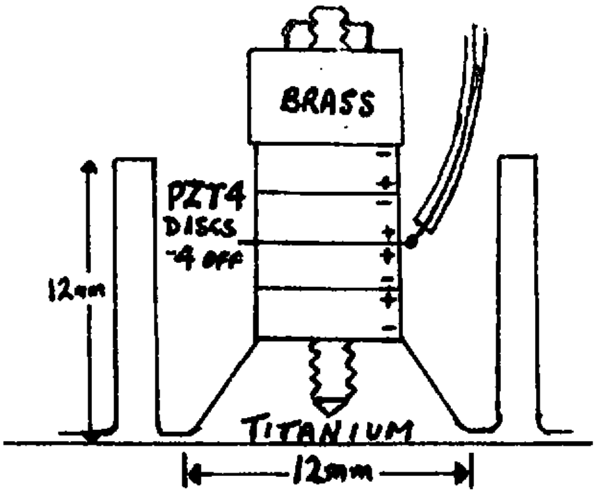

FIG 1 CROSS-SECTION OF 75 KHz ELEMENT

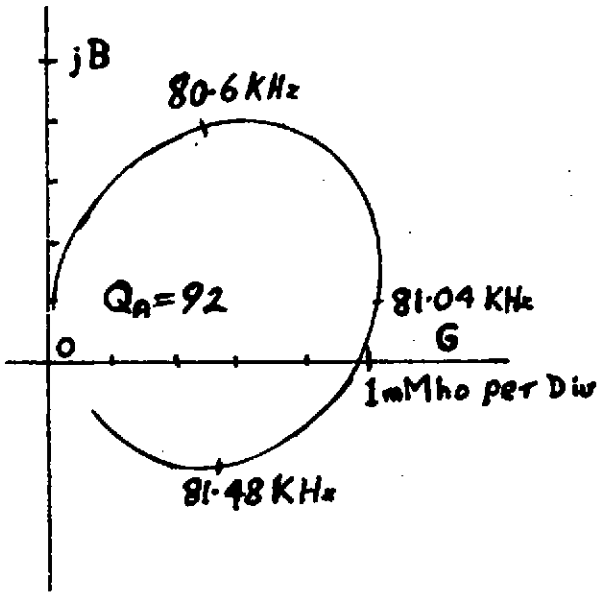

FIG 2 ADMITTANCE OF SINGLE ELEMENT IN AIR

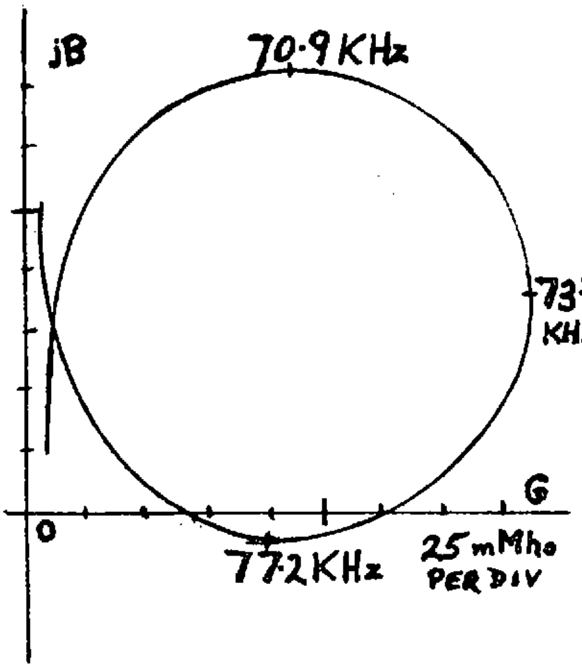

FIG 3 ADMITTANCE OF ARRAY IN WATER WITH 200 M OF CABLE

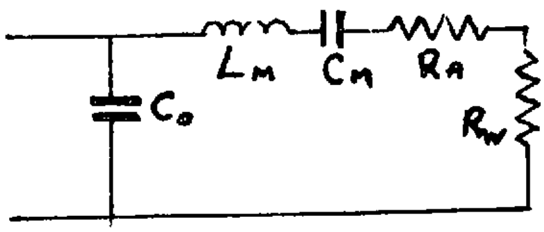

FIG 4 EQUIVALENT CIRCUIT