TITANIUM FLEXTENSIONAL TRANSDUCERS

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INTRODUCTION

The idea of using Titanium as a shell material for Class IV flextensional transducers has been published for some time [1] and it has obvious benefits in terms of its low density and high strength. However, no paper has appeared in the literature describing work with this material, possibly because it has a reputation for being forbiddingly expensive to procure and to machine.

As demands grow for increased depth capability, either in operation or for survival, various ingenious variants have been tried, for instance [2, 3] and other types of flextensional transducer investigated [4]. The high strength of Titanium gives it a significant advantage in surviving great depths.

Another advantage of Titanium is its high resistance to marine corrosion, and hence there is no need for a protective coating.

The benefits of using Titanium are such that it is worth investigating, and the cost, although relatively high, is not prohibitive. This paper describes the design processes involved in working with Titanium and shows how they differ from designing with Aluminium. Performance comparisons are also made with Glass-Reinforced Plastic (GRP) shell transducers. Initial results of Titanium transducer build are described.

STRESSES IN FLEXTENSIONAL TRANSDUCERS

There are two fundamental mechanical problems in the use of class IV flextensional transducers underwater: firstly, they are a poor shape for a pressure vessel; secondly, hydrostatic pressure tends to generate tensile stresses on the ceramic stacks. These stresses are counteracted by assembling the transducer such that the shell applies high compressive stress to the ceramics. This in turn generates high tensile stresses in the shell around the inner surfaces at the minor axis and the outer surfaces around the major axis. Flextensional transducers are assembled such that compressive stress in the ceramics is maximum when the transducer is in air and minimum when the transducer is at survival depth.

Stress limitations in operational or survival depth of class IV Aluminium shell flextensional transducers may occur either in the shell or the ceramic stacks. One simple way to increase the survival depth of a given design of flextensional transducer without resort to complex pressure compensation methods is to install "snubbers" which engage on the inner surface of the shell near the minor axis and reduce the moment about the node plane, thus reducing the tensile forces on the ceramic stack. This is illustrated in figure 1. Obviously, the snubbers must not touch the shell while it is vibrating at full amplitude at maximum operational depth. The effect of the snubbers on stress is illustrated in figure 2(a). If the snubbers are to engage in time to provide a significant improvement in survival depth, it is possible that the operational depth may have to be reduced to accommodate engagement of the snubbers at the required shell deflection.

Tensile stress limits for metal alloys commonly used in flextensional shells are well known to Mechanical Engineers, although properties of glass and carbon composites are less reliably defined. Titanium shells are sufficiently strong that the limitation is on the ceramics. However, the stress limits of the ceramics are very ill defined.

BAeSEMA currently use a maximum permitted compressive stress on Navy III ceramic stacks of 12.5 kpsi (83MPa) based on manufacturer's design data [6] and zero tensile stress (although reference [6] suggests small tensile stresses are permissable). This figure appears to be a general rule based on earlier measurements [7] which indicated some reduction in performance under continual cycling over a higher stress range. Recent work [8] has indicated that much higher compressive stresses have been used and demonstrates how ill defined the stress limits on ceramics are.

It has been shown [1] that in practice, depth performance is limited by assembly tolerances. A design is only feasible if the tolerances are practical for machining. If the transducer is not too small and if assembly can be facilitated by means of, for instance a wedge assembly [5], the extra strength of Titanium broadens the tolerance bands and much greater depths can be obtained.

Stresses due to thermal expansion are also encountered. This is rarely discussed, but can be a significant problem. Although the temperature range of the sea at operating depths is small, storage temperature range requirements are often very large, typically -30 to +75 °C. Temperature cycling between these limits should not degrade the performance. The ceramics have a very small coeffecient of thermal expansion, but Aluminium has a large thermal expansion coefficient. A one-degree change in temperature can induce stresses in the ceramic amounting to 0.75MPa, equivalent to 0.9% of the permitted stress range quoted above.

Thermal expansion will also exacerbate the problem of designing snubbers to engage at the required pressure. This is illustrated in figure 2(b). This shows that in practice the use of snubbers may further reduce operational depth while giving no significant increase in survival depth, and so may provide no benefit.

Titanium has a much lower coefficient of thermal expansion: the difference between shell and stack coefficient is thus even lower, amounting to about 0.3% of the stress range quoted above. This gives a further advantage to the use of Titanium beyond its great strength.

DISSIPATING THERMAL ENERGY

The paragraphs above discuss problems arising from thermal energy transfer into the transducer from its environment. There is an entirely different aspect when thermal energy is transferred from ceramic stacks operating at high power to the environment, in order to provide cooling. Aluminium has a much higher thermal capacity and thermal conductivity than Titanium and so is much more able to accept heat from the stacks and dissipate it. However, as Titanium does not require protection from corrosion, it can dissipate the heat directly to the sea without there being a protective layer such as polyurethane to slow the thermal transfer. The high corrosion resistance is a positive benefit both in terms of removing the cost of providing a protective coating but also in terms of assisting heat dissipation. This goes some way to offset the extra cost in using Titanium shells.

BUILDING A TITANIUM FLEXTENSIONAL TRANSDUCER

A Titanium flextensional transducer has been built in order to assess the suitability of the material for flextensional shells. The aim was to triple the survival depth capability compared to an equivalent Aluminium shell design. The design was based on the dimensions of an existing BAeSEMA Aluminium shell transducer, using ceramic stacks of large cross section to meet the depth requirement.

Where possible, existing component designs were used. It was necessary to build new end-plates capable of sustaining the hydrostatic pressures. The transducer was built from existing stocks of large-area ceramic plates remaindered from various projects between 1989 and 1993. This enabled comparison with earlier designs in Aluminium but did not permit design for maximum power. However, the principal aim of the work was to demonstrate the depth capability rather than the power capability of the transducer.

Design work indicated that the requirement could be achieved by a Titanium transducer but it would be necessary to exceed the 83 MPa compressive stress limit on the ceramics for the worst condition. A final figure of 92 MPa was considered to be acceptable.

TESTING

Acoustic testing was limited to in-air measurement of resonant frequency and coupling coefficient and measurement of admittance components around resonance in the test tank at BAeSEMA Filton. The tank is 10m by 6m by 6.5m deep and so is small in terms of wavelength at the relevant frequencies. The effect of standing waves was reduced by taking measurements at five random positions and averaging.

In air, the flextensional resonance had a coupling coefficient of 0.3, slightly higher than a similar Aluminium-shell design. This is not surprising. The very large cross-section stacks are very stiff compared to the shell. Use of Titanium, one-and-a-half times the stiffness of Aluminium, reduces the mismatch.

In-air measurements were also made at the second flextensional and breathing modes. Table 1 shows the resonant frequencies for these modes of the bare Titanium shell and of the shell assembly. These frequencies are within 2% of those obtained for an Aluminium-shell transducer of similar construction.

Ideally, the in-tank measurements should be compared with a transducer of similar design. Admittance measurement at these frequencies in this tank has generally obtained slightly higher values of Q and of maximum conductance (G) than are obtained in free-field conditions. The only single-shell Aluminium transducer of the same dimensions used a different stack configuration although the ceramic plates were the same size and were from same batch as some of those used in the Titanium transducer.

The results are shown in figure 3. In order to make a comparison possible, the G of each transducer was normalised by dividing it by the value of B_0, the susceptance at maximum G. The value of B_0 is proportional to the volume of ceramic and also to the in-water resonant frequency. The ratio of maximum G to B_0 is a function of the Q and the coupling coefficient. The frequency scale has been normalised by dividing in-water resonant frequency of each transducer by its in-air resonant frequency. The position of the peak thus indicates the frequency drop due to mass loading.

It can be seen from figure 3 that the Titanium transducer had a slightly higher in-water resonant frequency: the mass loading effect is less as the shell has a higher mass. The higher conductance peak with respect to B_0 reflects the higher coupling coefficient. This means that the Titanium transducer can give a power output comparable with or slightly higher than the equivalent Aluminium design. There are some signs of a second peak at higher frequency which is probably due to a resonance in the end-plate structure. This requires further investigation.

The transducer was tested in a pressure vessel. The vessel was surrounded by air and had resonant modes in the operational band so it was not possible to obtain reliable data on the acoustic performance at depth. Designed survival depth was achieved and maintained and the performance reverted to that previously measured after release from survival pressure.

DISCUSSION AND CONCLUSIONS

Transducers have now been built in GRP, Aluminium and Titanium using the same shell dimensions. Their relative performance and design problems are summarised in table 2.

The problem of working with Titanium as a flextensional transducer shell material is financial. The shell costs about five times that of a similar design in Aluminium. However, the shell is only one item, albeit significant, in the price build-up of a flextensional transducer. There is no increase in the cost of ceramic stacks and the cost of any protective coating is saved. Using Titanium for the shell (but not for other components) increases the overall build-and-test costs by a factor of about two. Given that it obviates the need for expensive pressure compensation mechanisms, this increase is acceptable.

The stress limitation in design is the maximum compressive stress limitation of the ceramics. At present, this is ill-defined and there is scope for research on the real performance-limiting effects of high compressive stress on ceramics.

Titanium has a density of 4400 kg/m^3 compared to 2700 for Aluminium, so the weight of the transducer assembly will be higher. Additionally, it may be necessary to use Stainless Steel for some of the components (for instance end plates) in order to take advantage of the extra strength of the shell. Overall weight of the transducer assembly is likely to be about 50% higher than its Aluminium equivalent.

The acoustic performance of the transducer is slightly better than an Aluminium shell equivalent. Stacks of large cross section are needed to sustain the high pressure range and these are very stiff. The increased stiffness of the shell material gives a better match to the ceramic stacks. The design was not optimised for power output. Higher power handling could be achieved by specifiying ceramics of higher coupling coefficient and by using longer stacks containing more ceramic plates. The latter would lower the resonant frequency slightly and improve further the mechanical match between stacks and shell.

The biggest advantage of Titanium is its great strength. The model built has been shown to survive depths three times greater than those obtained for an equivalent Aluminium shell design and to operate deeper than an Aluminium shell can survive.

ACKOWLEDGMENTS

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REFERENCES

[1] J.Oswin and J. Dunn, 1988. frequency, Power and Depth Performance of Class IV Flextensional Transducers. In eds. Hamonic and Decarpigny, Power Sonic and Ultrasonic Transducers Design. Springer Verlag. pp121-133.

[2] P. Dufourcq, J. Adda, M. Letiche and E. Sernit, 1991. Transducer fro Great Depths. Proceedings of Second "Power Transducers for Sonics and Ultrasonics". Springer Verlag pp75-82.

[3] J. Oswin and G. Steel, 1990. Flextensional Transducers with Unlimited Depth Capability Proc IoA, Vol 12, No 4, pp40-48.

[4] D. T. I. Francis, C. Bayliss, J. A. Ahmed, R. F. W. Coates 1994. The Development of a Low Frequency Barrel Stave Transducer for Tomographic Applications Using Finite Element and Boundary Element Modelling. Proceedings, IEEE Oceans, September 1994 Vol 1, pp371-376.

[5] K Ponchaud, 1985. UK patent application 85522652 (also European and US patents)

[6] Vernitron Piezoelectric Division. Piezoelectric Technology. Data for Designers.

[7] H. H. A. Krueger, 1967. Stress Sensitivity of Piezoelectric Ceramics, Part 1. Sensitivity to Compressive Stress Parallel to the Polar Axis. J. Acoust Soc Am Vol 42, No 3 pp636-644

[8] J. L. Butler, K. D. Rolt and F. A. Tito, 1994. Piezoelectric Ceramic Mechanical and Electrical Stress Study. J Acoust Soc Am Vol 96. No 3. pp1914-1917.

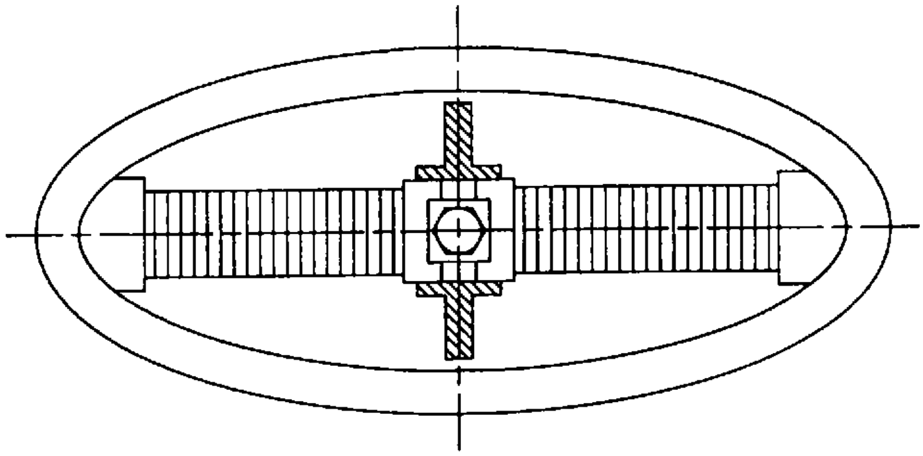

Figure 1. Flextensional transducer with snubbers

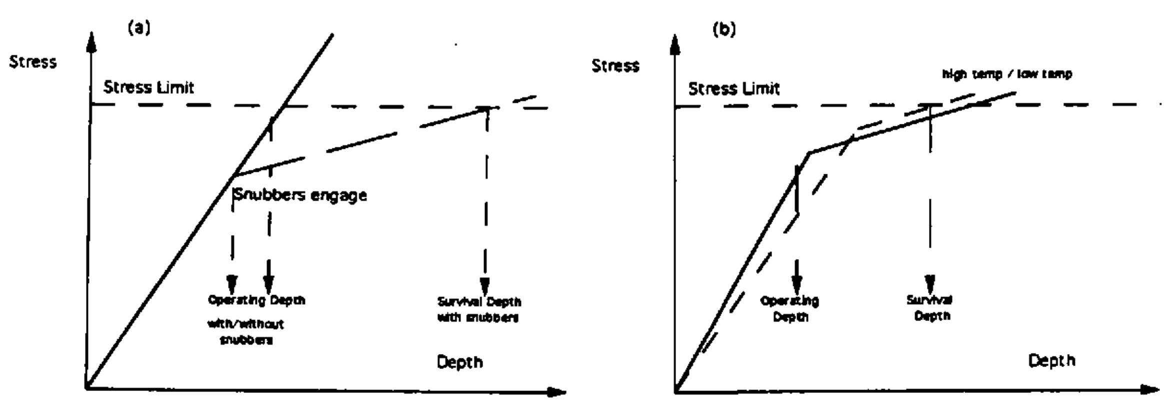

Figure 2. Stress vs. depth. 2 (a) Effect of snubbers. 2 (b) Effect of snubbers and thermal expansion.

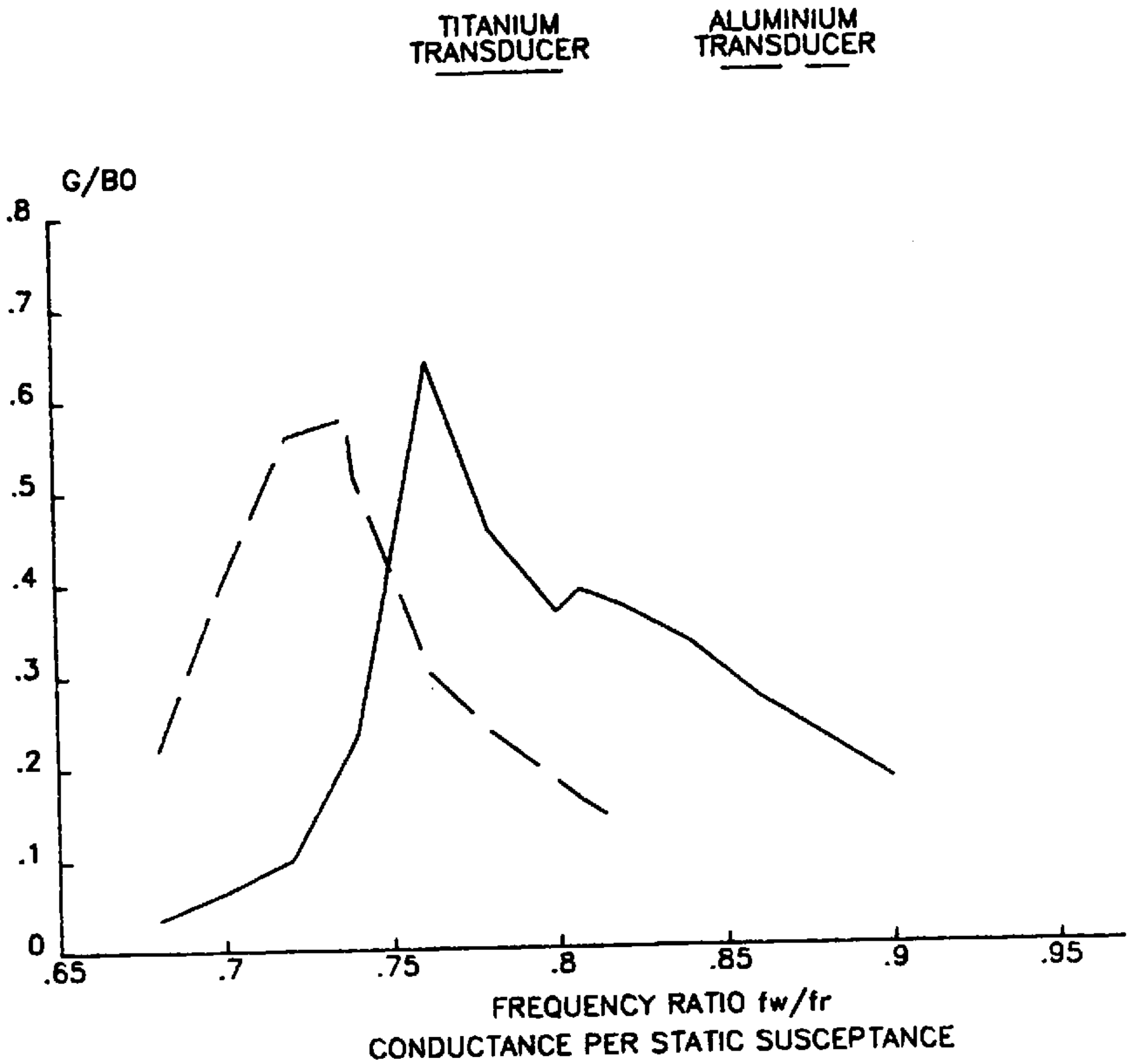

Figure 3. In water characteristics, Titanium and Aluminium transducers

Mode	Bare Shell	Shell Assembly
Flextensional	f_s	$f_a = 1.6 \times f_s$
Second Flextensional	$5.1 \times f_s$	$3.5 \times f_a$ $= 5.6 \times f_s$
Breathing	$6.35 \times f_s$	$3.8 \times f_a$ $= 6.1 \times f_s$

Table 1. Resonant frequencies in air

Property	Titanium	Aluminium	GRP
Frequency	Medium	Medium	Low
Fractional Bandwidth	Medium	Medium	Wide
Depth Capability	Best	Medium	Lowest
Power Handling	Highest	Medium	Lowest
Thermal Dissipation	Medium	Highest	Lowest
Thermal Stress	Medium	Highest	Lowest
Weight	Highest	Medium	Lowest
Cost	Highest	Medium	Medium

Table 2. Relative merits of Titanium, Aluminium and GRP flextensional transducers.