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TITLE

TERFENOL DRIVER FOR THE BARREL-STAVE PROJECTOR

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Terfenol Driver for the Barrel-Stave Projector

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A barrel-stave projector that uses a rod of Terfenol-D for the driving element is described. Radial slots rather than laminations were used to control eddy currents in the Terfenol drive rod. The effectiveness of these slots was studied experimentally and by finite element modelling. The performance of a prototype barrel-stave projector equipped with a radially slotted Terfenol driver was measured and is compared with the performance of a projector powered by PZT-4.

1 Introduction

The barrel-stave is a compact flextensional projector being developed by Defence Research Establishment Atlantic (DREA) for applications in low frequency sonar and underwater communications[1, 2]. To date, stacks of lead zirconate titanate (PZT-4) rings have been used as the driving elements in these projectors. DREA has recently begun evaluating the use of the magnetostrictive rare-earth alloy Terfenol-D as a possible replacement for PZT-4 in the barrel-stave projector. The goal is to increase the acoustic power output of the projector while retaining the same compact size.

The research plan is to proceed with development in three stages: (1) demonstrate use of Terfenol in the barrel-stave with emphasis on eddy current control, (2) develop a low reluctance flux return path, and (3) develop permanent magnet biasing. At this time, only the first stage in this design process has been completed, so the performance measurements presented here must be regarded as preliminary.

2 Projector Design

The projector design was based on the premise that by approximately matching the stiffness and mass of the Terfenol driver to that of the existing stack of the PZT-4 barrel-stave projector, the same flextensional shell could be utilized, and attention could be focused on the design of the Terfenol drive components. Likewise, in this paper only those components related to the Terfenol will be discussed in detail. Fig. 1a is a schematic drawing showing a cross section through the Terfenol-powered barrel-stave projector. The neoprene rubber boot, shell, and stress rod designs are the same as in the PZT-4 version shown in Fig. 1 in [2]. The one-piece slotted aluminum shell acts like a mechanical transformer with a radial to axial strain ratio of 2:1 at the mid point of the shell. Before the application of the boot, the shell of Fig. 1a had an axial stiffness of 6.5×10^7 N/m. This was measured using a hydraulic press equipped with a force transducer and dial indicators. By comparison, the stiffness of the stress rods is 8.4×10^7 N/m, and the open circuit stiffness of the Terfenol is 15.0×10^7 N/m. The components unique to the Terfenol barrel-stave projector are the Terfenol drive rod, the coil, the ferrite inserts in the end caps, and the threaded rings used to couple the

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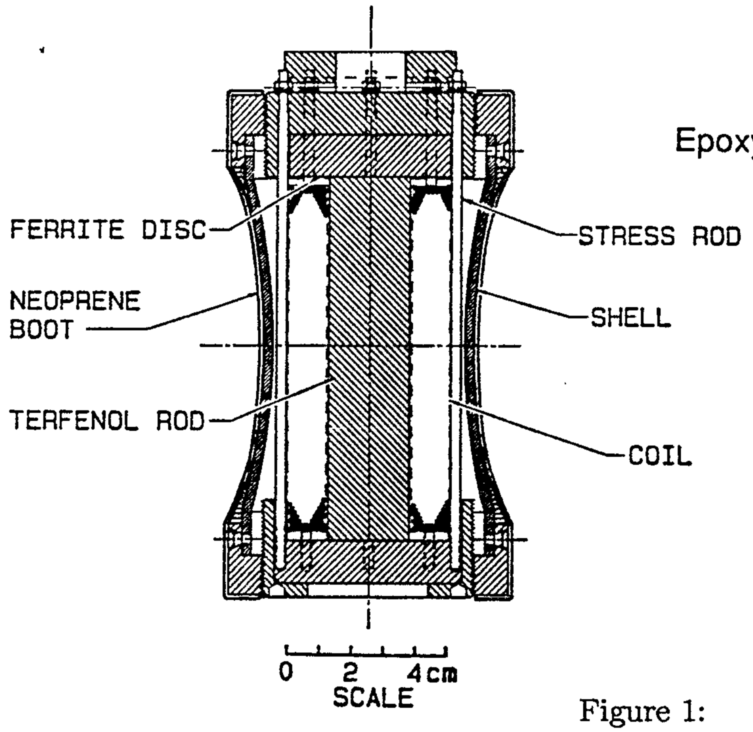

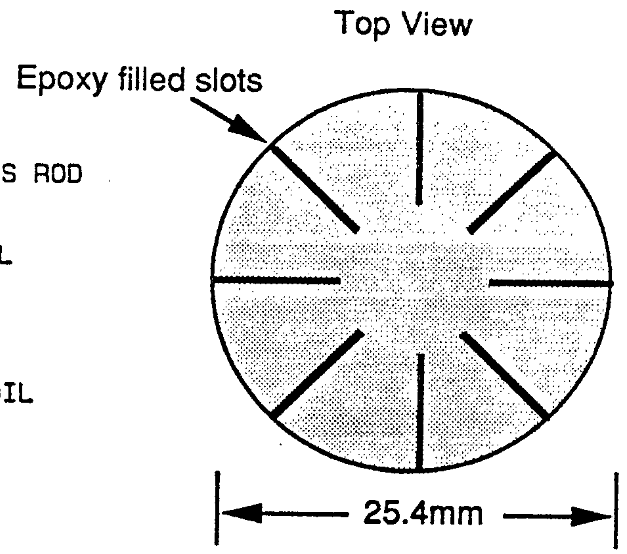

Figure 1:

(a) Cross section of barrel-stave projector with Terfenol driver.

(b) Top view of slotted Terfenol driver.

end caps to the shell. The external dimensions of the PZT-4 and Terfenol projectors are the same, their masses are 2.1 and 2.7 kg respectively.

2.1 Terfenol Drive Rod

Unlike piezoelectric ceramics, Terfenol is a conductive and magnetically permeable metal and so it is subject to eddy current losses. The skin depth, δ, is defined by:

$$\delta = \sqrt{\frac{1}{\pi f \mu \sigma}} \tag{1}$$

where f is the frequency (Hz), μ is the magnetic permeability (H/m), and σ is the conductivity (mho/m). The skin depth, δ, can be taken as a rough estimate for the maximum cross-sectional linear dimension (perpendicular to the applied field) of any Terfenol drive component that will have acceptable eddy current losses. For example, for Terfenol at 1 kHz, $\delta \simeq 6$ mm. At higher frequencies, or larger cross-sectional linear dimensions, the efficiency of the Terfenol driver will diminish because eddy currents dissipate heat in the drive rod. Also, eddy currents cause a spatially dependent phase shift of the magnetic field inside the Terfenol. This can reduce efficiency because not all parts of the driver are being excited in phase.

Terfenol is manufactured in the form of rods, and the usual approach to reducing eddy currents in Terfenol drive elements is to saw the rods into thin laminae and bond these together with insulating adhesive. The insulated laminae interrupt the circumferential eddy currents that would otherwise be generated by an axial magnetic field. At the present time, Terfenol is an expensive material (~\$4000 US/kg) relative to PZT ceramics (~\$40 US/kg). Sawing a rod into thin laminae wastes material because of the kerf of the saw, and because the rod must be ground round after lamination. These losses of material, and the machining and assembly costs are such that the price of a finished laminated rod is approximately double that of the raw material.

The driver rod design in Fig. 1b was developed, in part, with the aim of reducing cost. It is similar to the slotted ferrite rods used in some radio receivers. The purpose of the slots is to interrupt the eddy currents. While there is a loss of Terfenol due to the slot width, the rod does not have to be ground round, which saves material. In addition, less handling is required, which reduces the risk of breakage during assembly. Once the slots are cut, the rod is wound with adhesive tape, and liquid epoxy resin is forced up the slots from one end under pressure and allowed to cure. This is an attempt to restore some of the structural integrity lost by slotting the rod. The resultant thick glue lines in this design were not expected to be a source of acoustic loss. This is because the acoustic stress does not have to be transferred through the glue lines, which are oriented orthogonal to the principal stress direction. The slot width is determined by the minimum practical kerf of the slot cutting process and not by electromagnetic design considerations.

Because Terfenol is a hard and brittle metal, care must be taken in clamping and fixturing it during machining operations. There is a concern that small chips and surface defects in brittle materials might initiate fatigue cracks. It was found that magnetic fixturing was the safest way to secure Terfenol for machining operations. Rods were machined using diamond sawing and electric discharge machining (EDM). The best results in terms of surface finish, slot width, and cost were obtained with numerically controlled wire EDM, which produced slots of width .25 mm.

Estimates of maximum cross section based on Eq. 1 predicted that eddy currents could be adequately suppressed in a 25.4 mm diameter by 102 mm long Terfenol rod at 1 kHz by subdividing the rod into 8 segments. It was decided for structural reasons to limit the slot depth to 9.5 mm. These estimates were supported by finite element electromagnetic calculations made with MAXWELL 2D software[3]. Because the projector will be operating well below the longitudinal resonance frequency of the Terfenol rod, it is not necessary to consider magneto-elastic interactions[4] in these eddy current calculations.

Fig. 2 shows a contour map of the axial field distribution inside the slotted Terfenol rod at 1 kHz. The calculation assumes the rod is of infinite length, the relative permeability $\mu = 4.5$ and the conductivity $\sigma = 1.7 \times 10^6$ mho/m. The outermost circle in the figure represents the inside diameter of the coil, which is producing a uniform flux density of 1 A/m in the air space between the Terfenol and the coil. The contour values indicate that the field is uniform to within 1.7 % across the rod. A contour plot of the phase showed it was uniform to within 15 deg.

To check these calculations, a small coil whose inside and outside diameters, and length were 27 mm, 38 mm, and 5 mm respectively, and wound with 470 turns of 32 AWG Cu wire, was placed around the middle of the Terfenol rod after each slot was cut. Inductance measurements of the coil were made at three different frequencies: 100 Hz, 1 kHz, and 10 kHz, at zero DC bias. The inductance values were normalized by the inductance of the coil in air at each frequency and are plotted against number of slots in Fig. 3. This figure indicates that the coil inductance at 1 kHz is no longer changing as more slots are added after 6 to

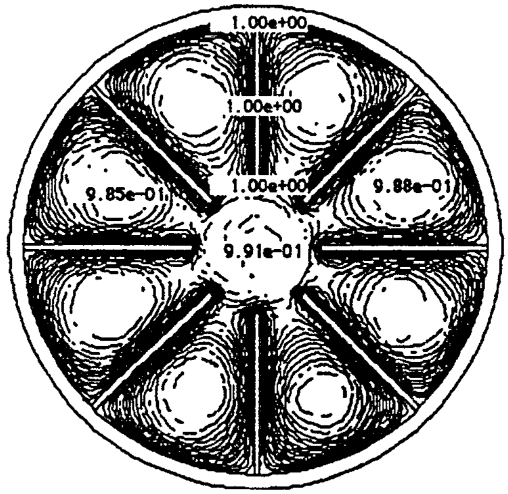

Figure 2: Contour plot of axial field (A/m) at 1 kHz in slotted Terfenol rod. Circle around Terfenol rod represents inside boundary of coil. Contour level 8.5×10^{-4} A/m, 20 levels. Maximum field value 1.0 A/m. Minimum field value 0.983 A/m.

8 slots have been cut. This confirms the conclusion of the finite element modelling, that 8 slots would be sufficient for operation at 1 kHz. The declining inductance seen in the 100 Hz data probably reflects the loss of Terfenol in the slots. The fact that the 10 kHz curve has not stabilized shows that 8 slots are not sufficient for operation at such a high frequency.

A modified Bridgeman Terfenol rod supplied by Etrema Products Inc.[5] and machined as shown in Fig. 1b was installed in the first prototype Terfenol projector. During calibrations in water, the projector coil failed due to overheating. The disassembly of the projector for analysis subjected the Terfenol rod to considerable thermal and mechanical stress. Examination of the rod showed the presence of circumferential cracks linking the innermost ends of the slots. X-ray radiography was unable to determine if the cracks extended the full length of the rod, or if they were just on the surface. Because of a limited supply of Terfenol, it was decided not to subject the rod to destructive testing methods, and instead it was reused in a second prototype. Impedance tests of the rod in the second projector indicated its magnetostrictive properties were unchanged in spite of all that had happened. The calibrations on this second prototype were conducted with frequent monitoring of the temperature of the projector by measuring the DC coil resistance.

2.2 Coil Design

The coil indicated in Fig. 1a was designed using DREA-developed coil design software. The coil consists of 550 turns (.77 kg) of 16AWG magnet wire and has an inside diameter of 27.2 mm, outside diameter of 50.4 mm, and length of 94.6 mm. The DC resistance is 0.84 Ω at 23 °C and the inductance in air is 2.74 mH at 100 Hz. The primary coil

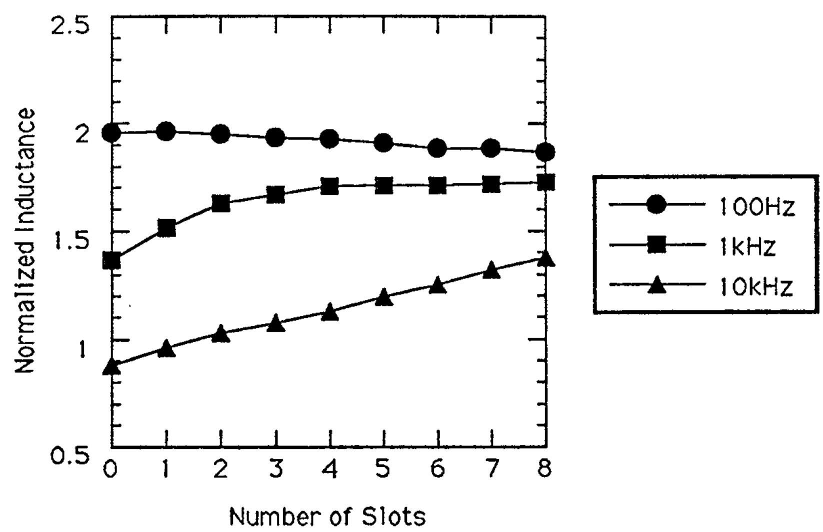

Figure 3: Normalized inductance of coil around radially slotted Terfenol rod versus number of slots, at zero DC bias.

design consideration was that the projector impedance match the available power amplifier (8 Ω) at resonance. This required an estimate based on previous experience of the effective permeability of Terfenol under the operating conditions encountered in the barrel-stave. For example, from the in-water impedance data presented in Section 3, the effective relative permeability near resonance (1300 Hz) can be estimated to be only 1.4. This low value reflects the high reluctance in the magnetic circuit. Another consideration that is easily satisfied by coils of this shape is that the L/R time constant of the coil be sufficiently short so that pulsed calibrations can be done in shallow water without interference from surface or bottom reverberation. The L/R time constant of the projector under operating conditions is 5 ms. This permitted the generation of tone bursts as short as 15 ms to be used for calibrations in the frequency range of interest. To conserve space inside the projector, the coil is self supporting, being wound saturated with epoxy on a removable mandrel. A rubber gasket centers the coil around the Terfenol rod at the midpoint of the rod. The coil is cemented to the end caps with a heat resistant rubber cement applied sparingly to the ends of the coil.

2.3 Ferrite Discs

The use of ferrite discs to shape the flux distribution at the ends of the Terfenol rod, as shown in Fig. 1a, was suggested by Moffett[6]. Finite element modelling of the magnetostatics of the Terfenol rod with and without the ferrite discs indicates they improve the field uniformity along the axis of the Terfenol. However, the modelling also shows there is some risk of saturation of portions of the ferrite adjoining the Terfenol at the highest drive levels.

The ferrite discs are glued into threaded aluminum retaining rings which permit the Terfenol to be prestressed independently of the shell. Following the recommendations of [7], a prestress of 25 MPa is applied to the Terfenol by eight 3.2 mm diameter by 15 cm

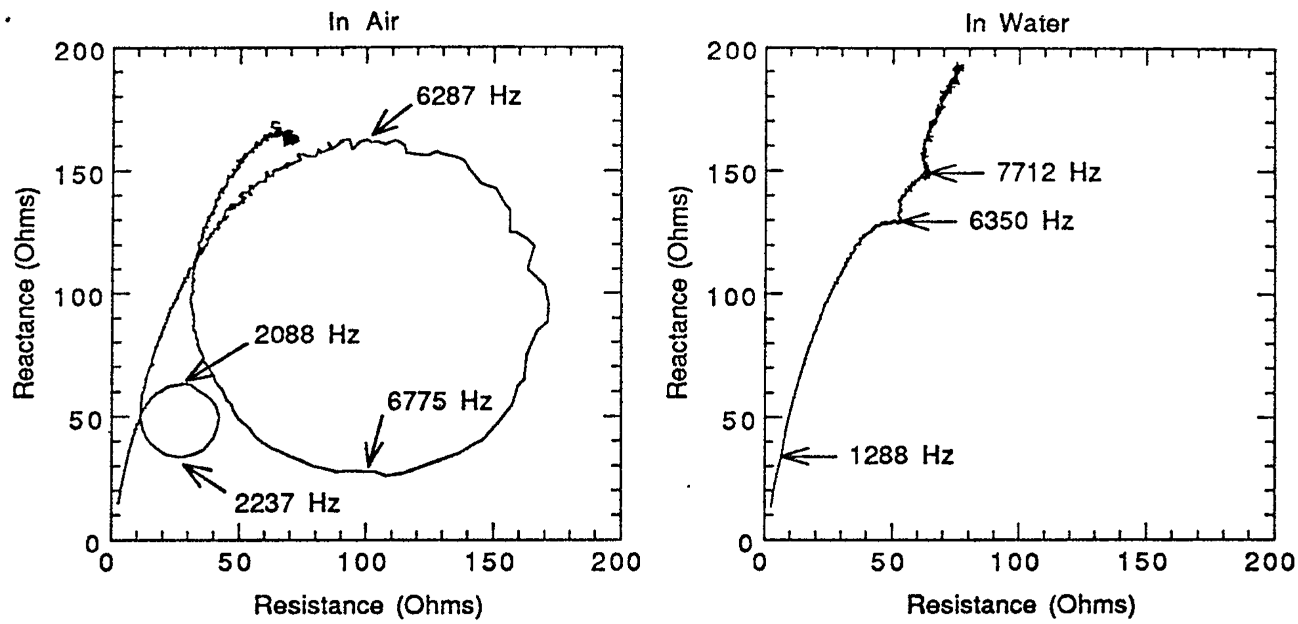

Figure 4: Impedance of Terfenol barrel-stave projector in air and water, 20 A DC bias.

long Type 316 stainless steel stress rods. All threaded components are coated with epoxy at assembly to improve coupling, and the Terfenol is glued to the end caps for the same reason.

3 Projector Performance Measurements

The Terfenol barrel-stave projector was calibrated at the DREA Acoustic Barge, in Bedford Basin, N.S. in 42 m of sea-water. Calibrations were done with the projector and a Bruel and Kjaer model 8101 hydrophone mounted on stations 4 m apart at 14 m depth, and at a water temperature of 0.5 °C. Impedance measurements were conducted using a Hewlett Packard 3562A Dynamic Signal Analyzer, with a Tecron Model 7560 2kW Power Supply Amplifier to energize the coil with both AC signal and DC bias. Transmitting current responses were recorded using a microcomputer controlled pulsed calibration system[8] that permits measurements to be made before surface or bottom reverberations reach the hydrophone. The requirement for provision of DC bias complicated the calibration of the projector, and, in particular, power testing the projector. It proved most expeditious to power test the projector using the frequency doubling mode, where the projector was driven with zero DC bias and at one half the resonance frequency, from a CML Wide Band 5kW power amplifier through a series matching capacitor.

Fig. 4 shows the impedance of the projector in air and in water at 20 A DC bias. In air, the large circle corresponds to the longitudinal mode of the Terfenol rod and the small circle corresponds to the breathing mode of the shell. The transmitting current response (TIR) in Fig. 5 shows the effect of DC bias up to the 20 A maximum obtainable from the Tecron power amplifier. The overall shape of the TIR of the Terfenol barrel-stave resembles the shape of the transmitting voltage response of the PZT-4 barrel-stave[2]. The directivity was omnidirectional to within $\pm 1dB$ at the low frequency resonance (1300 Hz). Fig. 6 shows the efficiency (AC power only included) versus frequency for the 20 A DC bias condition.

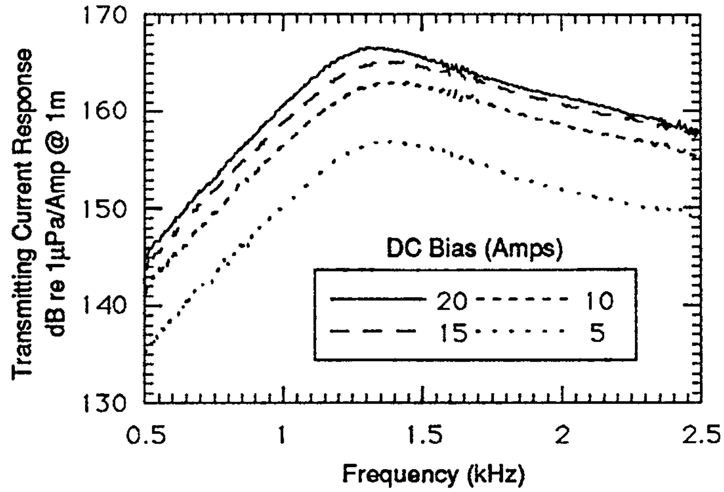

Figure 5: Transmitting Current Response of Terfenol barrel-stave projector.

The efficiency at the 1300 Hz resonance is very low compared to the PZT-4 version of the projector, which achieves 70 % efficiency at resonance. Fig. 7 shows second harmonic power output versus rms current input. The projector was driven at 650 Hz without DC bias, and the output measured at 1300 Hz. The dependence of acoustic power on drive current should be fourth order assuming a quadratic dependence of strain on magnetic induction in the Terfenol[9]. Fig. 7 indicates the dependence is somewhat more than fourth order at low drive levels changing to somewhat less that fourth order at the higher drive levels. As indicated in the figure, a least squares fit over the entire range gives 3.45 for the exponent. While this may be due to the shape of the Terfenol strain versus field curve, a similar effect seen in the PZT-4 barrel-stave has been attributed to effects of the rubber boot[10]. It was not possible to obtain a source higher that 187.8 dB re $1\mu Pa$ @ 1 m at 1300 Hz at the 14 m depth. The projector did not appear to be cavitating. The observed sudden increase in third and higher order harmonics at this source level is thought to be due to boot flapping[10]. The boot is not cemented to the shell, but held in place by tension and water pressure. The PZT-4 barrel-stave has a similar limit on its output power at this depth. It is also possible that the ferrite end caps are saturating. Calibrations at greater depth should distinguish between these two alternatives.

4 Thermal Measurements

The problems of over-heating encountered with the first Terfenol barrel-stave projector prompted thermal resistance and thermal capacitance measurements. The temperature of the coil was monitored by measuring its resistance and assuming a linear variation of resistance with temperature. DC current was applied continuously until the resistance of the coil stabilized while immersed in the 0.5 °C water. A value for the thermal resistance between the coil and the water of 2.0 K/W was estimated using the steady state power input of 20 W.

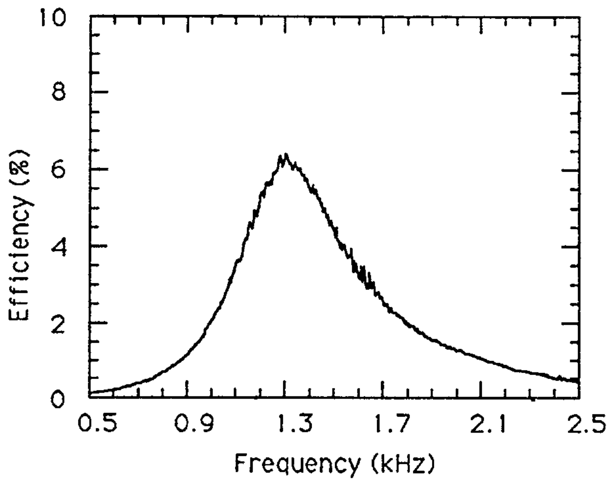

Figure 6: AC Efficiency of Terfenol barrel-stave @ 20 A DC bias.

Using a value for the thermal conductivity of neoprene[11] of .0065 W/(m·K), a surface area of 327 cm^2 and thickness of 1 mm of the boot, a thermal resistance of 0.5 K/W was estimated for the boot. From this estimate it appears that the boot is not the main impediment to cooling the projector.

The heat capacity of the projector was determined by measuring its thermal time constant from the exponential recovery of the coil resistance to its ambient value with the power turned off. The time constant of 1100 s was then used to calculate the heat capacity of the projector as 550 J/K. For comparison, the copper coil has a heat capacity of 296 J/K. Because of its proximity to the coil the Terfenol rod probably contributes its heat capacity to the total effective heat capacity of the projector. The heat capacity of the Terfenol was estimated as 165 J/K using a specific heat for Terfenol of 350 J/(kg·K)[12].

5 Discussion

The PZT-4 version of the barrel-stave projector[2], provides a field-limited source level of 191 dB re 1 μPa @ 1 m @1200 Hz, a bandwidth of 300 Hz, and an efficiency at maximum power of 70 % from a cylindrical package of length 120 cm, diameter 80 cm and mass 2.1 kg. Since there is room in the projector for more ceramic, the ultimate power capability of the design has not yet been reached. The Terfenol barrel-stave projector described above has to date yielded a source level of 187.7 dB re1 μPa @ 1 m @1300 Hz, a bandwidth of 600 Hz, and an AC efficiency of 7 % from a package of the same size as the PZT-4 projector, and with a mass of 2.7 kg.

The next version of the Terfenol barrel-stave projector, now under construction, will have a low reluctance magnetic flux return path to improve the efficiency. This will take the form of a cylindrical shell of magnetically permeable metal foil, surrounding the coil. The attractive idea of a flux return path through the flextensional shell is being investigated,

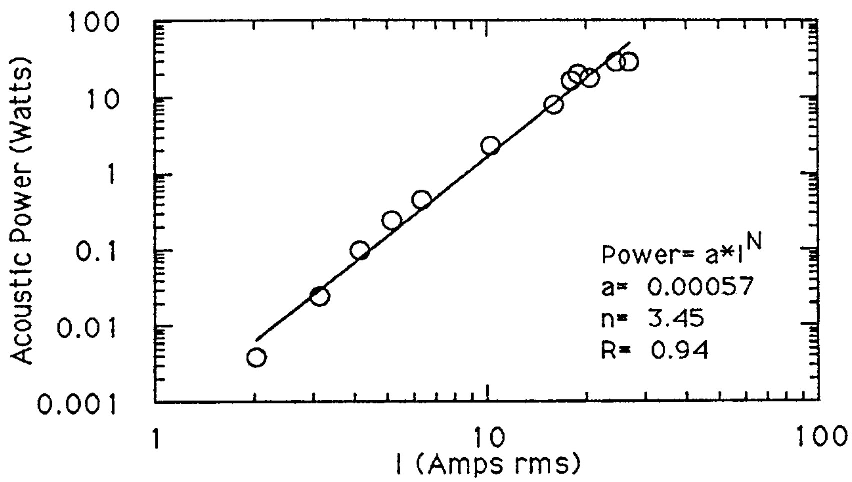

Figure 7: Power output at second harmonic versus rms current input.

but at 1200 Hz, there are no obvious choices for shell materials that have the required electromagnetic and mechanical properties.

To make room for the flux return path, the eight stress rods used in the first design will be removed, and replaced with a single stress rod through a central axial hole in the Terfenol. This rod will be of a high strength alloy and designed to have less stiffness than the stress rods of the present design. The hole for this stress rod will be sized to intersect the ends of the slots in the Terfenol rod. This will remove the stress raisers at the ends of the slots in the rod design of Fig 1b, and should prevent the occurrence of cracks like those observed.

The high thermal resistance between the coil and water is an impediment to continuous high-power operation of the projector, and ways to reduce this resistance are being studied. The barrel-stave projector is a challenging test of the utility of Terfenol, because of the heat dissipation problems, and because of the limited space available for the coil, flux return path, and permanent magnets. However, the potential for increased power is a strong incentive for continued design work.

6 Acknowledgements

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