SPOT POLED REFLECTOR STYLE HYDROPHONE FOR SHOCK WAVE MEASUREMENTS

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Abstract - The membrane style hydrophone commonly used to calibrate lithotripters is found to have a fast rise time, mediocre sensitivity but a very short life span. We propose a new style of hydrophone here that overcomes the longevity problem by employing a spot poled ceramic active element backed by a matched acoustic impedance. This robust hydrophone is shown to have a fast rise time (<50 ns) together with a high sensitivity. It has been successfully used to measure pressures in excess of 100 MPa for over five thousand shots without any serious degradation in sensitivity or pulse shape. Furthermore, it is shown that such a hydrophone reproduces negative (rarefactional) pressures faithfully. By adopting this technique, we also gain the benefit of having well defined and potentially very small (less then 0.5 mm diameter) active areas.

INTRODUCTION

The increasing use of extracorporeal shock wave lithotripsy (ESWL) devices for the destruction of kidney and gall bladder stones calls for an accurate assessment of their acoustic outputs. Hydrophones constructed from the piezoelectric polymer polyvinylidene fluoride (PVDF) are commonly used because of their uniform frequency response and minimal perturbation of the acoustic field. The spot poled PVDF membrane hydrophone [1], however, suffers from a serious drawback in that it exhibits degradation in sensitivity when used to measure pressures in the range 20-100 MPa. The commonly accepted reason for this is that the fragile electrode pattern on the membrane erodes whilst the actual polymer suffers no damage [2]. This is not strictly true if the hydrophone is subjected to pressures as high as 100 MPa. Dents have been observed in the normally taut membrane after only a few shocks at such pressures, which we believe are caused by the cavitation of water. This will adversely affect sensor rise time and reproducibility characteristics. In order to prolong the life of such hydrophones, some researchers have protected the thin membrane by sandwiching it between two layers of glycerine. This step, however, drastically changes the shape of the measured waveform, especially the negative (rarefactional) pressure region.

Several designs have emerged over the past few years that address the robustness of lithotripter hydrophones. Granz [3] has proposed a spot poled electrodeless PVDF hydrophone where the pressure induced charge is capacitively coupled via a dielectric liquid medium to electrodes placed a finite distance away from the sensitive area. A hydrophone 3 mm in diameter was constructed that withstood over 10^5 shocks of 20 MPa. The quoted combined hydrophone/preamplifier sensitivity figure of 20 mV/MPa is rather ambiguous since no mention is given of the amplifier gain or the load impedance. Moreover, the 3 mm aperture is likely to cause appreciable spatial averaging in highly focussed lithotripters where the lateral resolution at the focus is probably less than 1 mm. The aperture of this device is reduced to 2 mm diameter with a correspondingly lower sensitivity of about 6 mV/MPa in a subsequent design [4]. This may still be too large for certain applications.

Cathignol has published a variation on the above design where pressure induced charges on the piezoelectric area are collected via a low resistivity electrolyte [5]. The large aperture size of 1 mm^2 still yields a relatively low sensitivity figure of 12 mV/MPa. The hydrophone is claimed to have withstood over 10^5 focussed shocks of 30 MPa.

We describe below a reflector style hydrophone design which basically consists of a ceramic (or polymeric) active element backed by a matched acoustic impedance. The hydrophones built with a ceramic crystal in this manner have yielded high sensitivities coupled with acceptable rise times. The life span of these hydrophones is a considerable improvement over their membrane style counterparts. The main drawback of this design is the inability of the hydrophone to read negative pressures and the difficulties associated with obtaining a small, well defined active area. By employing a spot poled ceramic active element in our latest design, however, we are able to retain the proven high sensitivity and robustness of the reflector style ceramic hydrophones and incorporate into it the features of fast rise time together with the capability to record negative pressure. We also gain the benefit of having well defined and potentially very small active areas.

REFLECTOR HYDROPHONES

Unlike the acoustically transparent membrane hydrophones, our hydrophones (as the name implies) *reflect* the incoming acoustic wavefronts. This will only pose a prob-

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lem in lithotripter measurements if the reflection occurs at a boundary with an acoustic impedance less than that of water. The shock wave will invert upon reflection causing the large compressional pressure to turn into rarefactional pressure thereby resulting in the instant cavitation of the water. Conversely, a positive reflection is obtained from a boundary with an acoustic impedance greater than that of water. Thus, it is appropriate to use this type of hydrophone in shock wave measurements. This design is also suitable for pulsed or gated sine wave applications. For CW measurements, only the coplanar membrane or the needle type ceramic hydrophone is suitable. We have observed that even the bilaminate membrane hydrophone is quite an efficient reflector of ultrasound.

The fine apertures desired here are achieved by rendering a small area locally piezoelectric by selective polarisation of the ceramic. Since we need to exceed the ferroelectric switching field of the material in order to polarise it, negligible poling occurs outside the high field region between opposite electrodes. The crystals employed here were 15 MHz Lead Titanate (type EC-97, Edo Corp.). This material is specifically chosen since it possesses negligible coupling to the radial modes. The crystals are then glued to a matched acoustic impedance backing using special bonding techniques and the assembly is encased in a phenolic or steel housing for durability.

SHOCK WAVE MEASUREMENTS

We built an experimental piezoelectric lithotripter for evaluating such hydrophones. The generator was calibrated at full power using Marconi coplanar membrane hydrophones. The sensitivity of these hydrophones was derived at low power by the planar scanning technique and compared with the calibration data provided by National Physical Laboratories (NPL [6]). The power emitted by the source used was measured using reciprocity and independently verified with a force balance measurement. How much faith one has in using low power calibrations for assessing lithotripter output at high power is a subject of ongoing discussion. The ratio between low and high power outputs appears to be affected by design criterion not yet under tight control. Nonetheless, using the low power calibrations for the Marconi hydrophones and other membrane hydrophones we built, the experimental lithotripter was found to produce a peak pressure of about 80 MPa at its focus with a standard deviation of 3 MPa.

Figs.1(a) and (b) compare typical shocks recorded by the Marconi coplanar hydrophone and our spot poled ceramic hydrophone respectively. The hydrophones were iteratively moved in the x, y and z directions at low power to locate the focal region of the lens. The lens was then

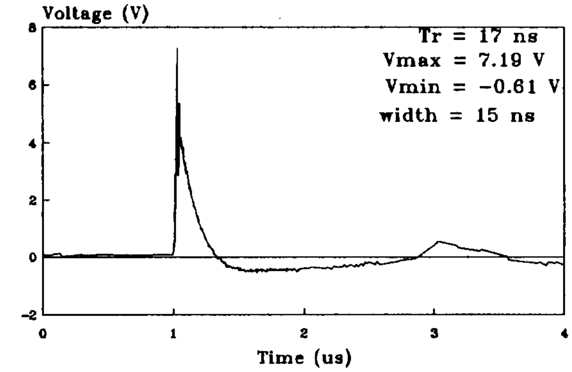

Fig. 1(a) - Shock wave as measured with a Marconi coplanar 1 mm membrane hydrophone.

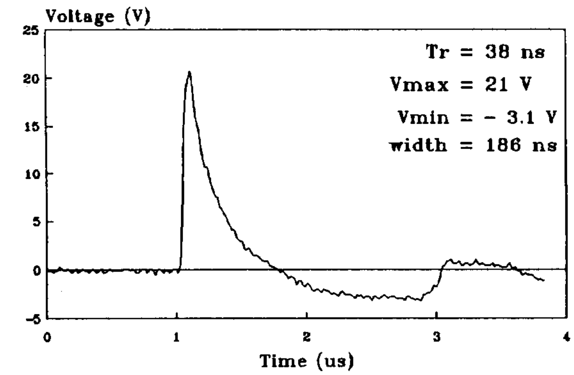

Fig. 1(b) - Same shock wave measured with a 15 MHz, 1 mm spot poled ceramic hydrophone

fired at high power and the resulting voltage captured on a TEK2440 oscilloscope at a sampling rate of 250 Msamples/sec without the use of a preamplifier.

The spikes seen at the leading edge of the Marconi hydrophone were studied in greater detail and found to be spaced by about 16 ns, corresponding to a frequency of 63 MHz. This is caused by the quarter wave resonance of the bulk capacitance of the active element with 0.75 m type RG174 coaxial cable. A notch in the impedance data of the hydrophone, as measured on a HP4194A impedance/gain-phase analyser, appears to confirm this observation. Such a characteristic ringing can therefore have a detrimental effect on the peak pressure computed for the lithotripter and the shock to shock reproducibility behaviour of the hydrophone.

Fig. 1(a) shows a very fast rise time of 17 ns. The theoretical rise time of our hydrophone should simply be the time required to completely compress the thickness of the active element assuming a planar shock front. For the ceramic employed, a longitudinal velocity of 4.38 mm/μs [7] gives 34 ns for a 15 MHz crystal. This is in excellent agree-

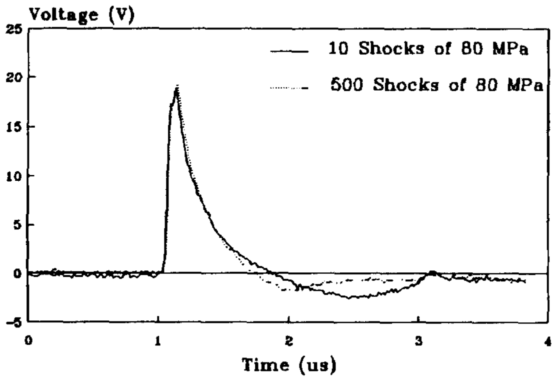

Fig. 2 - Pressure measurement at the focus of a piezoelectric lithotripter before and after 500 shocks of 80 MPa.

ment with the measured rise time of 38 ± 4 ns which is also highly dependent on alignment errors.

We now proceeded to test the durability of the hydrophone by exposing it to the full power of the lithotripter at the focus. After several shocks, the fragile wire soldered to the front face of the active element was dislodged. It was promptly repaired and protected this time by casting a cone of a mixture of 50% by volume ratio of RTV118 and microballoons (Emerson Cummings IGD101). Thus, the active part of the crystal is still exposed whilst the connection is protected by the composite. This action only affected the rarefactional pressure portion of the detected signal. We continued the experiment by noting down the rise time and peak voltage detected by the hydrophone after successive shocks. Fig. 2 compares the output of this hydrophone after 10 and 500 shocks of 80 MPa in degassed water. As can be seen, there is no observable difference between the leading portions of the two waveforms. The standard deviation of the detected peak voltage was well below 2%. The rise time standard deviation was slightly higher at 4%. This hydrophone has since withstood over 5000 shocks of over 100 MPa in field studies and is yet to be tested to destruction

ANGULAR RESPONSE

In order to determine experimentally the effective aperture of the hydrophone discussed here, angular response measurements were made in the far field of a 4 MHz planar source. The above hydrophone could not be used due to the scattering of the incoming waves by the protective cone at certain angles. Thus, more hydrophones of this design were constructed without the protective cone.

Fig. 3 shows a typical angular response measurement in de-bubbled tap water for a nominally 1 mm diameter hydrophone. For comparison, data for two Marconi membrane style hydrophones appear in Fig. 4. The very jagged

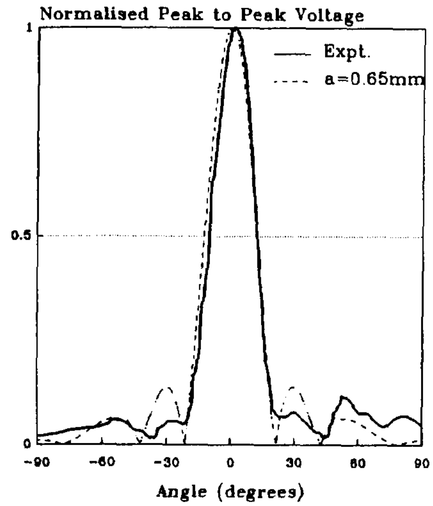

Fig. 3 - Angular response of a 1 mm spot poled ceramic hydrophone at 4 MHz.

response for the 1 mm coplanar hydrophone case may be indicative of the cavitation damage it suffered.

The dotted lines on the graphs represent the theoretical response for a circular aperture in a rigid baffle generated by using the following expression [8,9],

$$2J_1(\nu)/\nu \qquad \text{where } \nu = (2\pi/\lambda)\, a \sin\theta \qquad (1)$$

where λ is the desired wavelength, a is radius, θ the angle and J_1 is a first order Bessel function. The effective aperture of the hydrophone is then evaluated by calculating the full width at half maximum (fwhm) on the measured data and generating a theoretical plot with an appropri-

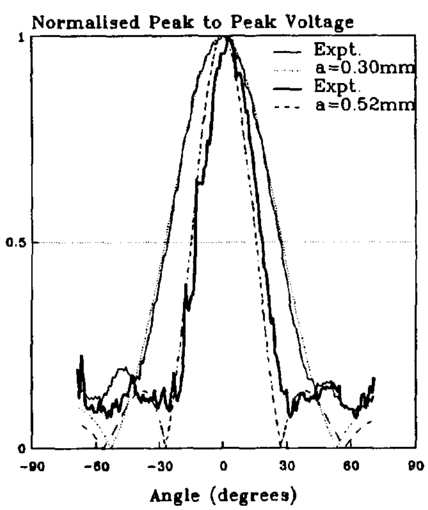

Fig. 4 - Angular response of a 1 mm coplanar and 0.5 mm bilaminate Marconi hydrophone at 4 MHz.

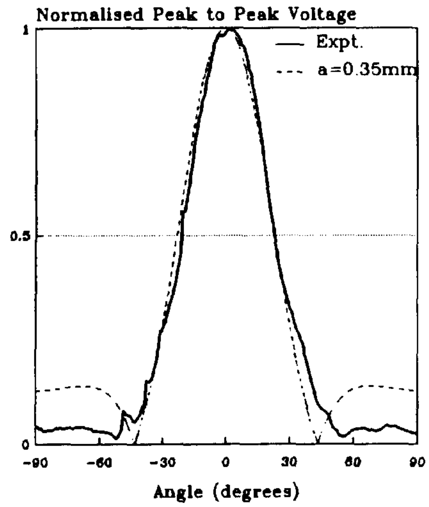

Fig. 5 - Angular response of a 0.5 mm spot poled ceramic hydrophone at 4 MHz.

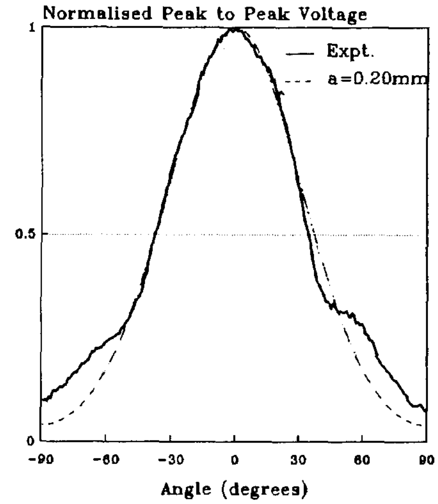

Fig. 6 - Angular response of a 0.25 mm spot poled ceramic hydrophone at 4 MHz.

ate value for radius that matches most closely to the measured datum.

With a growing demand for hydrophones with improved spatial resolution to characterise highly focussed, high intensity transducers, we now exploit the flexibility of this design by building hydrophones with smaller apertures. In order to reduce spatial averaging errors, the effective size of the active element must be less than a wavelength in the ultrasonic field. This cannot be chosen arbitrarily by reducing the diameter of the electrode to be polarised as the active region will ultimately be determined by the fringe poling fields rather than the electrode pattern itself. With this in mind, we constructed hydrophones with nominal electrode diameters of 0.50 mm and 0.25 mm though even smaller hydrophones should be possible. The crystals employed here were half wave resonant at 30 MHz for a wider frequency response. The resulting directional responses for the 0.5 mm and 0.25 mm hydrophones are depicted in Figs. 5 and 6 respectively. Pertinent data relating to all four hydrophones are collated in

TABLE 1

Hydrophone	fwhm (°)	a-physical	a-effective
Marconi 1 mm coplanar	31	0.48mm	0.52mm
Marconi 0.5 mm bilaminate	53	not measured	0.30mm
SEA 1.0mm	22	0.59mm	0.65mm
SEA 0.5mm	45	0.27mm	0.35mm
SEA 0.25mm	74	0.15mm	0.20mm

Table 1, where *a-physical* is the measured radius of the electrode and *a-effective* is the effective radius deduced from Eq.(1).

As can be seen from these data, the effective aperture is always greater than the physical dimensions of the electrode pattern.

SENSITIVITY

Typical sensitivities of some of the hydrophones described here are now presented along with data for some commercial hydrophones encountered frequently. For comparison purposes, results are presented in units of dBs rel. 1 V/μPa when the hydrophone is loaded by an equivalent impedance of 1 MΩ in parallel with 30pF. Where necessary, calibration data were converted to this format and plotted at 1 MHz intervals, see Fig. 7.

The 0.25 mm and 0.5 mm 30 MHz SEA hydrophones were calibrated by International Sonic Technologies [10] using a time delay spectrometry method. The membrane hydrophones were calibrated by NPL [6] and data on the 1 mm PVDF needle type hydrophone were provided by Medicoteknisk [11]. The 1 mm SEA hydrophone sensitivity was measured against the calibrated Marconi bilaminar hydrophone in the far field of a broad band source.

As expected, the 1 mm ceramic hydrophone exhibits the highest sensitivity of all the hydrophone shown in Fig. 7. The 0.25 mm hydrophone is seen to be more sensitive than our 0.5 mm hydrophone. This is simply due to the different housings employed. In this embodiment, the overall diameter of the crystal was reduced from 8 mm to

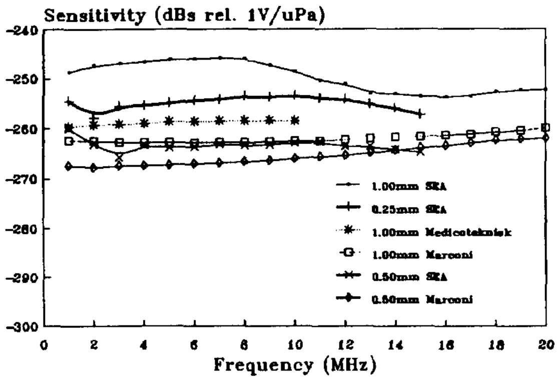

Fig. 7 - Hydrophone sensitivities when loaded by an equivalent impedance of 1MΩ in parallel with 30pF.

2.25 mm in order to reduce the capacitance that is electrically in parallel with the active region and acting as a voltage divider. This particular housing was specifically chosen to boost the sensitivity of the hydrophone for measuring the intensity and spatial distribution of highly focussed transducers. For lithotripter applications, the sensitivity was not an issue.

It can be seen that the hydrophones presented here are not as flat in frequency response as their membrane counterparts. Some hydrophones even exhibit a resonance behaviour at low frequencies (< 2MHz) which is not fully understood yet. This will only affect the rarefactional pressure reading in lithotripter measurements. The peak pressure and rise time characteristics will be replicated reasonably accurately. Work is currently in progress to investigate this low frequency behaviour which is most likely to be some type of assembly resonance. Nevertheless, as demonstrated by Fig. 7, these hydrophones possess a flat frequency response in the 3-15 MHz range and should prove useful in lithotripter and other pulsed high pressure applications.

CONCLUSION

A new type of inexpensive and robust spot poled ceramic hydrophone was presented for applications involving the reliable mapping of high acoustic pressures. It was shown that the unprotected hydrophone reproduces rarefactional pressure faithfully. The protected version was shown to withstand over 5000 exposures of 100 MPa with an excellent shock to shock reproducibility. Furthermore, it is possible now to probe the focus of a lithotripter with a hydrophone with an effective aperture < 0.5 mm and specifically designed to withstand such pressures.

In order to achieve results similar in shape to the membrane style hydrophones, the arriving shock wave must not be perturbed in any way (i.e. by protection layers etc.). The effect of such layers on the shape of the measured waveform can be limited somewhat by protecting only the electrical contact point itself, which we have implemented with the RTV118/microballoon composite.

The flexibility of the design was demonstrated by constructing hydrophones with apertures less than 1 mm in diameter without having to compromise with sensitivity considerations, as is the case for the polymer hydrophones.

The current hydrophones should prove extremely useful in pulsed or gated sine wave applications for determining the spatial distribution and intensities of highly focussed transducers in the 3-15 MHz frequency range. The large aperture hydrophones often used may lead to appreciable inaccuracies due to spatial averaging. The flat frequency response in this range also enables the temporal variation of the field to be assessed accurately.

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