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PVDF Membrane Hydrophones for the Study of High Frequency and Non-Linear Acoustic Fields

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Introduction

Polyvinylidene fluoride (pvdf) has been shown to be a very useful material for hydrophone construction in underwater applications[1,2,3]. For operation at frequencies well below 1 MHz high sensitivity hydrophones can be obtained by using the pvdf film in planar extension coupling mode. Because the material is available in thin sheets (a few μm thick), however, devices which utilise thickness extension coupling, although having a lower sensitivity, will possess a very broad band frequency response and be useful for operation up to 100 MHz.

The membrane hydrophones developed at the National Physical Laboratory in conjunction with GEC-Marconi Ltd. (Chelmsford) work on this second principle, and this paper reports their development, properties and ways in which they may be used.

The construction of the hydrophones is quite simple. A thin pvdf film is stretched over an annular frame which is large enough (100 mm diameter in the present devices) to allow the acoustic beam from a transducer to pass through its aperture. Each side of the membrane has a metal film lead evaporated onto its surface, and these two leads overlap only in a small central area, which becomes piezoelectrically active when the device is poled. Because the thin membrane is effectively acoustically transparent, and because the supporting ring is outside of the beam, the hydrophone introduces no acoustic perturbations and so senses the free-field pressure at the central element.

When compared with other devices designed to operate in the MHz frequency range, the membrane hydrophone has several advantages. It has a wide frequency response due to the use of the thin membrane, and because the acoustic impedance of pvdf is close to that of water, giving the device a low Q resonance. Radial resonance modes which are a problem with other hydrophone designs are eliminated because of the large size of the membrane compared to the central active element. Because it does not interfere with the acoustic field the hydrophone is free from reverberation effects and so gives accurate reproduction of pulsed fields. The simplicity of the design should mean that it is relatively free from aging problems.

Hydrophone frequency response

The frequency response of the hydrophone is determined by two effects: the resonant build-up of acoustic pressure within the membrane, and the translation of this pressure by the hydrophone's piezoelectric and electrical properties into an end of cable signal which is detected by an amplifier.

For normal incidence, only longitudinal waves are present in the pvdf film and so the ratios of the stress components are the same at all points throughout its thickness. Consequently the size of the piezoelectric coupling is constant and so the voltage across the active element is proportional to the mean acoustic pressure over the membrane thickness. The acoustic pressure at a point in the membrane is determined by the reflections at the surfaces (which have gold electrodes affecting the amplitude and phase of the reflection) and by absorption within the membrane. Calculations based on these considerations were used to predict the frequency response of a membrane hydrophone of a given thickness. The ratio of the frequency responses of hydrophones with 25 µm and 9 µm thick membranes was measured from 5 to 85 MHz and excellent agreement with the theoretical predictions was obtained.

The above considerations are sufficient to predict the ratio of the frequency responses of hydrophones made from different thicknesses of film. In order to predict the absolute frequency response, however, account must also be taken of the frequency variation of the piezoelectric d coefficients (charge sensitivities) and the dielectric constant. Unfortunately, although the behaviour of the dielectric constant is known to the author[4], that of the d coefficients is not. However, as the physical bases of the dielectric and piezoelectric properties are not dissimilar it might be reasonable to suppose that their frequency variation is in some way related. Two possible alternative assumptions are that the charge sensitivity does not vary with frequency, or that it varies in the same way as the dielectric constant. The actual end of cable response of the hydrophone is affected by the loading of the active element by various extra capacitances. Making allowance for this, predictions based on the two assumptions were made and compared with the results of calibrations of hydrophones between 1 and 10 MHz. The results of this comparison were not completely conclusive because of calibration uncertainties at the higher frequencies, but their trend was to favour the charge sensitivity varying with the dielectric constant. As the dielectric constant variation levels off beyond about 15 MHz[4], it seems reasonable to suppose that the piezoelectric coefficients do not change significantly between 20 and 100 MHz, so that the frequency response in this region is determined solely by the acoustic resonance.

Directionality

If the hydrophone behaved as a stiff disc receiver (where the response is proportional to the integral of the free-field plane wave pressure over the plane of the front face of the active element) then its directivity $D(\theta)$ (for angle of incidence θ) would be given by $D(\theta) = \frac{2J_1(Ka \sin \theta)}{Ka \sin \theta}$, where a is the active element radius, K is $2\pi/\lambda$ and J_1 is the first order Bessel function. For a hydrophone that does not reflect all the incident acoustic energy, departures from this behaviour will be caused by the variation of piezoelectric sensitivity with direction of acoustic stress in the pvdf, by possible Lamb wave propagation within the device, or by reflections from parts of the hydrophone other than the active element.

Measurements on the directivity of hydrophones with 1, 2 and 4 mm diameter active elements were made between 1 and 10 MHz, and compared with the stiff disc results. The measured beamshapes were about 20% narrower than expected. For the broader beamwidths this deviation was more marked, and for the broadest beamwidth (1 mm diameter hydrophone at 1 MHz) the 6 dB point was obtained at 33° half angle, whereas the stiff disc sensitivity does not reach this point over the whole range of angles. The 1 mm, 1 MHz beamshape shows another anomaly: at higher angles there is a sidelobe which is higher than the peak of the main lobe, whereas a stiff disc sidelobe can never be more than 14% of the peak.

These results were accounted for by a model which used the reported variation of piezoelectric sensitivity with angle[5] and which evaluated the effect on the acoustic pressure at the active element of wave propagation across the membrane. Although resonant excitation of flexural waves (waves where the membrane bends) is not possible for such thin membranes, a Lamb wave with particle displacements symmetrical about the mean plane of the membrane can be excited at the appropriate angle of incidence. The interaction of this wave with the incoming water wave at this angle causes a build-up of energy within the membrane which gives rise to the observed sidelobe. Theory and experiment agree well for the main lobe; for the sidelobe the theory predicts a considerably larger effect than is observed (even when attenuation in the pvdf is included in the model).

The discrepancy may be due to there being a greater Lamb wave attenuation in the film than allowed for in the calculations[6] or to the finite extent of the acoustic beam used in the measurements. The metal electrodes and surface roughness of the membrane may also have had some effect, but this was thought unlikely.

In the calculations it was assumed that the membrane material was elastically isotropic with longitudinal and shear wave velocities of 2.56 and 1.04 km s^{-1} and an attenuation of both waves of 111 Np m^{-1} MHz^{-1}.

Signal Quality

As has been mentioned above, the membrane hydrophone is designed to be free from reverberations in the output signal due to acoustic energy being stored in the device and arriving at the active element some time after the initial wave. This property was tested by placing the hydrophone in the field of a well-damped transducer driven by a single-cycle sine wave. The hydrophone signal obviously depended on the quality of both transducer and hydrophone, but the observed waveform was sufficiently curtailed to indicate that the hydrophone was performing well. The waveform obtained in this way was compared with those obtained by using other hydrophones of different designs. These other waveforms contained a considerable amount of reverberation.

In order to see if any acoustic energy was reaching the active element by propagation within the membrane (which would give rise to delayed contributions to the output signal), an acoustically reflecting "knife edge" was passed in front of the active element for various angles of incidence. As far as could be determined, there was no such propagation present, except near the angle of the large directivity sidelobes. However for this position, the incident wave velocity is equal to the component of plate wave velocity in its direction,

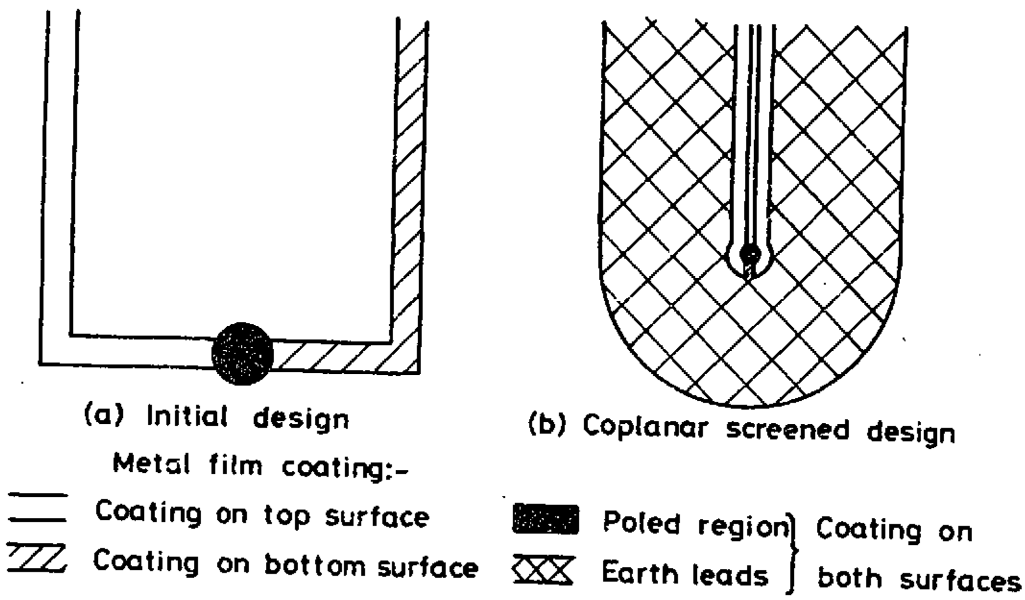

Fig. 1 Hydrophone electrode configurations.

so such propagation should not give rise to delayed contributions to the signal.

Electrical RF pick-up (mainly at MHz frequencies) was experienced in hydrophones with the original electrode configuration (Fig 1a)[7]. Reduced pick-up was obtained by using coplanar screening of the active element (Fig 1b) where the earthed electrode was evaporated onto both sides of the film, leaving a 1 mm gap between it and the live electrode. The earth lead was connected to a pin on the hydrophone mounting ring as well as to the shield of the co-axial cable, and pick-up was further reduced by connecting this pin to a metal surface immersed in the water bath. Used in this way, the pick-up was about 1 mV peak to peak (pp). For a 1 mm diameter hydrophone of 0.1 μV/Pa sensitivity this corresponds to a RMS acoustic pressure level of 3500 Pa.

Another approach to the screening problem (called the bilaminar design) involved trying to screen the live lead completely. Two sheets of pvdf film were stuck together, with the live electrode in the centre of the sandwich. The external surfaces of the device were almost completely coated with metal film and were connected to earth. To reduce the amount of extra capacitance loading the active element, the live lead from it was made as thin as possible (0.1 mm). Poling was performed in such a way as to pole only the active element. The pick-up obtained with this design was too small to be measured with the available equipment (less than 0.1 mV pp at RF frequencies) and such a device should therefore be very useful in the detection of very small acoustic pressures.

If low pick-up is required and the hydrophone is being used in a moderately sized tank, some form of metal screening placed round the walls of the tank could obviously be used, thus eliminating the need for a bilaminar device.

Because the hydrophones have good frequency responses, they give accurate reproduction of waveforms up to high frequencies. However, when using a hydrophone made from 25 μm film to observe non-linear fields with frequency components up to 100 MHz, it was possible to see the effect of the 40 MHz resonance on the waveform (Fig 2a). When a 9 μm hydrophone was used instead (Fig 2b), it gave a smooth output because of its higher resonance frequency.

Electrical properties

The hydrophone's output signal is determined by the way in which the active element is loaded electrically. If the cable is connected directly to an oscilloscope for example, one might expect the signal to be reduced because of the cable and oscilloscope input capacitances. The capacitance of the hydrophone can be measured in air at 10 kHz and this measurement should enable the size of these loading effects to be predicted. Measurements in the MHz frequency range with the hydrophone immersed in water (using extra cable of

a) b)

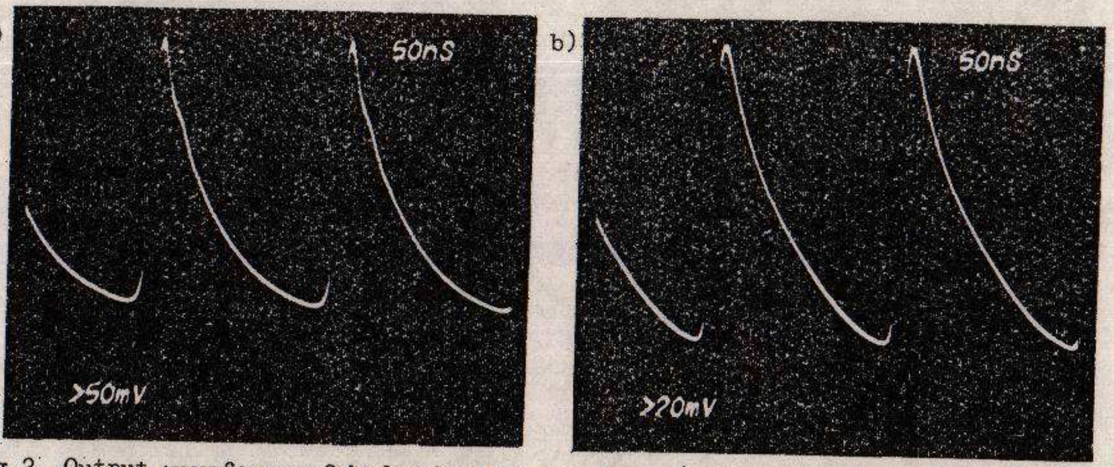

Fig 2. Output waveforms of hydrophones made from a) 25 µm film and b) 9 µm film.

known capacitance and noting its effect on the signal) gave a higher value for the hydrophone capacitance however, because of the capacitative loading of the water. This result means that the hydrophone frequency response will depend mainly on the charge sensitivity (rather than voltage sensitivity) of the active element. The capacitance measured in this way will determine the signal reduction due to any extra loading, and it is obviously important that the detection electronics have a high input resistance and low capacitance to give accurate waveform reproduction and preserve signal strength. This high input impedance, however, means that the hydrophone cable will act as a resonant cavity and so cause signal distortion at high frequencies (centre frequency 70 MHz for 65 cm cable). It is therefore necessary to use a short cable (2 or 3 cm) feeding into an auxiliary amplifier when operating above about 20 MHz.

Applications

The good frequency response of membrane hydrophones obviously makes them useful in measuring any fields containing high frequency components. For measuring non-linear fields, the acoustic transparency of the hydrophone is an additional important factor. Because the principle of superposition does not apply in this case, any acoustic waves reflected from the hydrophone back towards the source will interfere with the incoming wave. A hydrophone that reflects acoustic energy may consequently not have a response proportional to the free-field acoustic pressure even if its response to the pressure at its surface is linear. A 1 mm diameter membrane hydrophone has been used to investigate a non-linear transducer field in order to verify its usefulness. The transducer was operated at 5 MHz and measurements of 20 harmonic components were possible at the highest powers (Fig 3). The variation in harmonic amplitudes, both along the transducer axis (in and outside the nearfield) and in the radial direction and the approach to acoustic saturation at a point in the far-field, were all measured in this way, yielding a considerable amount of information for analysis.

The sensitivity of the membrane hydrophones has been stable over the year and a half that they have been in use, and so they can be used to calibrate other hydrophones. A simple replacement technique can be used, or the acoustic transparency of the membrane hydrophone can be utilised and the unknown hydrophone placed behind it in an acoustic field. In this second case the extent to which the unknown hydrophone perturbs the field can be monitored. If the unknown hydrophone has a linear response, a non-linear acoustic field can be used in its calibration. Comparison of the outputs of the two hydrophones as displayed on a spectrum analyzer can then give the frequency response very quickly and easily.

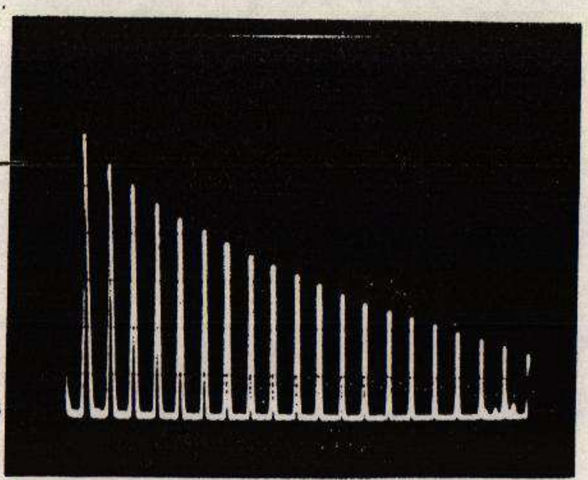

Fig 3. Harmonic content of a non-linear field measured by a hydrophone made from 9 μm film

The hydrophones reported in this paper have not been used extensively at frequencies below the MHz frequency range. The dielectric constant of pvdf does not change significantly below about 0.5 MHz[8], so the hydrophone should have a good frequency response in this range. When detecting large amplitude sound waves at these lower frequencies it is possible that the element may no longer operate simply in thickness extension mode, thus introducing a component into the output signal of twice the acoustic frequency. In order to accommodate the larger acoustic beams used at these frequencies, the membrane and supporting ring would have to be made larger. Greater sensitivity could be achieved as larger active elements could be used without significantly affecting the directivity.

Conclusion

The performance of the membrane hydrophones between 1 and 100 MHz has been described. They have good frequency responses, are free from reverberations and give fairly low electrical pick-up. Except for the widest beamwidths, the directionality corresponds fairly closely to that of a stiff disc.

Sensitivities of about 1 μV/Pa for a 4 mm diameter active element and 0.1 μV/Pa for a 1 mm diameter element have been achieved, which are quite adequate for the applications described. With the correct cables and amplifiers they can be used reliably to detect high frequency and non-linear fields. At the NPL they have been used for measuring complex fields from scanning equipment as well as in the calibration of other hydrophones, and they seem to have potential for other applications, particularly where good bandwidth is required.

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