# Ellipsoidal hydrophone with improved characteristics

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*Abstract* - A new style of hydrophone is being developed to meet or exceed the new recommendations set forth in the AIUM Acoustic Output Measurement Standard [1] as they apply to ultrasound measurements for submission to the U.S. FDA. The device can be calibrated and used over a frequency range extending from below 200 kHz to above 40 MHz. The new hydrophone is basically a membrane style hydrophone; however, the membrane is bonded to and backed by the small radius end of an ellipsoid of acoustically lossy epoxy. The active element in the device is defined by the end of an axial wire that comes away perpendicular to the membrane, which is a small disk of 4 or 12-μm thick copolymer film. This configuration has the advantage of minimal shunt capacitance, excellent shielding, and the reduction of spurious artifacts in the frequency response due to surface waves. Surface waves are inevitably generated by ultrasound incident upon a hydrophone, but with this design they carry on around the elliptical cross section with little or no reflection. The large size of the device (in wavelengths) also avoids a 6 dB step in the frequency response due to the transition from a free field pressure sensor at low frequency to a mirror at high frequency. This is an inherent problem with needle type hydrophones as discussed by Fay et. al. [2]. We are also addressing this mode transition issue (and other problems) by choosing materials for casting the ellipsoid that have acoustic impedances close to water.

A major advantage of this design is the fact that it can be well shielded electrically without loss of sensitivity, as is often the case with membrane hydrophones. The shielding currently in use is an evaporated gold film over the front end of the device. This gives them the appearance of being a "golden lipstick" which has become the nickname used to refer to these things in the shop. Active element sizes as small as 25 μm have been tested, typical active element sizes are 85 – 400 μm, and larger apertures are also possible. The hydrophones can be made with high input impedance preamplifiers cast in the backing directly behind the active element in order to achieve very high sensitivities relative to other types of hydrophones. The hydrophone's freedom from artifacts yields frequency responses that are flat to ±1.5 dB over the entire calibration range (200 kHz to 40 MHz). Some theory of operation and experimental results obtained with these new devices will be presented.

## INTRODUCTION

Membrane hydrophones have set the standard for ultrasonic measurements in the past due to their flat frequency response and freedom from many of the artifacts that typically degrade the performance of needle type hydrophones. Aside from their inconvenient form factor, they suffer from two major drawbacks, i.e., their lack of sensitivity and their susceptibility to electrical noise. These drawbacks are caused mainly by the electrical leads to the small, spot-poled acoustic element at the center of the membrane. Typically these leads either have a significant shunt capacitance to ground, often orders of magnitude higher than the capacitance of the active element itself, or else they are unshielded. Additionally, the leads and shielding employed over them have non-zero resistivity and hence are likely to pick up RF noise from sources like radio stations and nearby monitors. Lum et. al. [3] have attempted to alleviate some of these shortcomings by placing active circuitry directly upon the membrane, as close as possible to the active element. While this helps, the resulting device still lacks the noise immunity necessary for many applications due to the exposed "hot lead" between the active element and the preamplifier input. This idea is fully described in a US patent [4].

Our approach to solve these basic problems has been to build an ellipsoidal backing for the membrane and replace the signal trace of the conventional design with a "flying lead" as described in the abstract. A "flying lead" normal to a ground plane is a one of the lowest capacitance structures possible for making connection to the active element of a hydrophone, and it can still be completely shielded. Figure 1 shows the construction in detail.

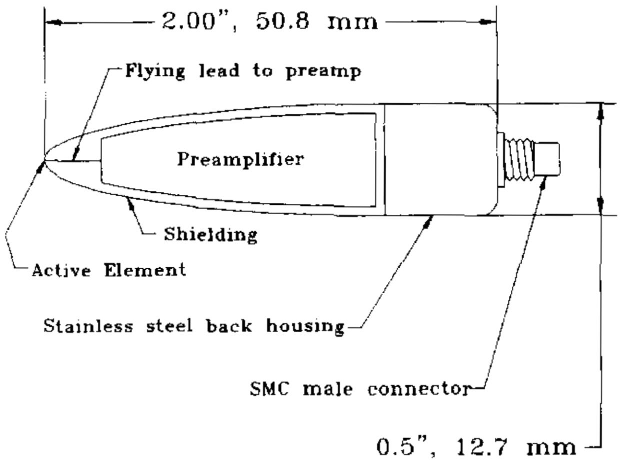


Figure 1. Construction of new hydrophone

For the experimental results shown in this paper, the preamplifier was actually outboard of the SMC connector, as we are still developing the internal amplifier.

## CONSTRUCTION DETAILS

Early attempts to build the "golden lipstick" style hydrophones with small diameter active elements (25-75 μm) using corona poled films produced devices with great sensitivity, but with much larger effective element sizes than expected. While the exact physics of this effect remains a mystery, it is believed to be the result of charges deposited on the hot lead by conically shaped electric fields between the exterior ground plane and the active element lead. In the latest series of hydrophones, this problem has been solved by spot poling the film after bonding it to the backing.

An important detail to be noted with this design is the possibility of using two different thicknesses of metal shielding. In the design typically built, we evaporate a 1700 Å Cr/Au metal film directly over the active element. About 1 mm away from the active element, however, we increase the shielding thickness to about 1 μm. This results in a very low electrical impedance shield, which is still acoustically thin where it matters. 1 μm of shielding would have very definite, adverse effects on frequency response above 30 MHz if used directly over the active element. A thin coating of parylene, typically 10 μm thick or thinner is usually applied over the gold metalization to make the hydrophone more robust and stable. The effect of this film will be shown in the next section.

Another important advantage of the ellipsoidal hydrophone design is the close proximity between our active element and the first stage of preamplification. The amplifier is built using a specially shaped board to match the contour of the ellipsoid. The amplifier is encapsulated within the tapered section of the hydrophone housing. This allows the lead between the PVDF active element and the first stage of the amplifier to be very short, about 5-mm, thereby increasing significantly the amplitude of the signal received at the amplifier. A JFET first stage provides the sensing element with a high impedance, 3.3 pF input capacitance, attempting to match the PVDF active element. The JFET then drives a wide band, low noise operational amplifier, which is the primary gain stage. Finally, a buffer amplifier couples the output of the op amp to the 50-Ω impedance of the output cable.

## THEORY

The theoretical capacitance for the active element of a PVDF copolymer hydrophone, assuming an 85 μm aperture size and a 4 μm thick film is only 52.7 fF. This is about 1/20$^{th}$ of a pF. This calculation assumes a dielectric constant of $4.12\varepsilon_0$. Indeed, the actual dielectric constant of the copolymer appears to be a function of frequency (decreasing with frequency). This was deemed a reasonable approximation for frequencies around 20 MHz. The theoretical stray capacitance of an 85 μm diameter wire, positioned 4 μm away from and perpendicular to a ground plane, 5-mm long, is still under investigation; however, it is believed to be on the order of 1 pF. The capacitance of a wire passing completely through the structure, from the SMC connector to the active element inclusively, was 11.3 pF at 20 MHz. A KLM model analysis has verified the intuitive concept that the input voltage to a preamplifier is proportional to the capacitance ratio of the active element of the hydrophone and the total capacitance of the preamplifier input and the stray capacitance connecting the two.

The same model predicted that given an active element diameter of 85 μm, a film thickness of 4 μm, material properties for the copolymer film as listed in [5] (specifically $Z^D$ = 4.13 MRayl, $Q_m$ = 25.0, $\varepsilon_r$ = 4.12, tan $\delta$ = 0.20, $v_3^D$ = 2.32 mm/μs, and $k^2$ = 0.05), a shunt capacitance of 11.3 pF and an input capacitance of a preamp of 3.3 pF, a gain in the preamp of 13.8 dB, then a flat sensitivity of –25.4 dB re. 1 V/MPa is expected. Assuming no electrode or parylene layer, the model predicts this sensitivity to be flat out to about 60 MHz, at which point it slowly increases to a gentle peak of about 3 dB around 120 MHz and then cuts off around 200 MHz. The heavy solid line in Figure 2 depicts this behavior.

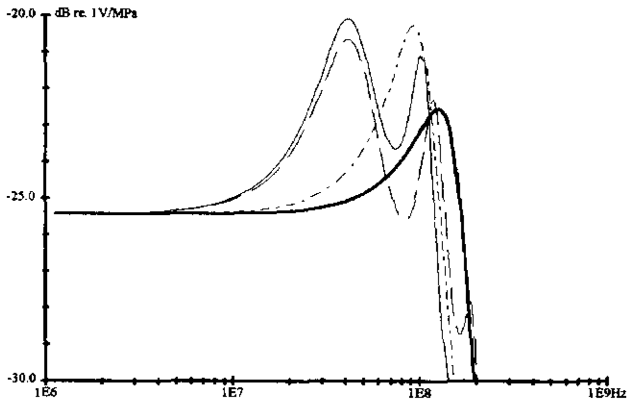


Figure 2: Broadband theoretical calibration data for 85 μm active element hydrophone.

Next, the effect of a 1700 Å thick gold electrode over the active element is modeled using the dash-dot line. Here we can see a stronger, 5 dB peak around 100 MHz. A 10 μm thick parylene coating is often used to protect the fragile gold electrode and has a much more dramatic effect on sensitivity, as seen by the dashed line. Finally, the effect of both the gold and the parylene is modeled and graphed as the thin, solid line. The parylene or parylene with metal results in a 5 dB peak around 42 MHz. The parylene impedance is assumed to be 3.00 MRayl, with a velocity of 2.15 mm/μsec.

## EXPERIMENTAL RESULTS

Figure 3 shows the calibration data from 200 kHz to 40 MHz obtained from an 85 μm active element hydrophone by comparing it to a membrane hydrophone calibrated by NPL in the UK. (Actually the calibration data above 20 MHz and below 500 kHz is "home made" by reciprocity and planar scanning and not actually traceable.) From this data it is clear that the sensitivity is very flat and will comfortably meets the AIUM specification of ±3 dB.

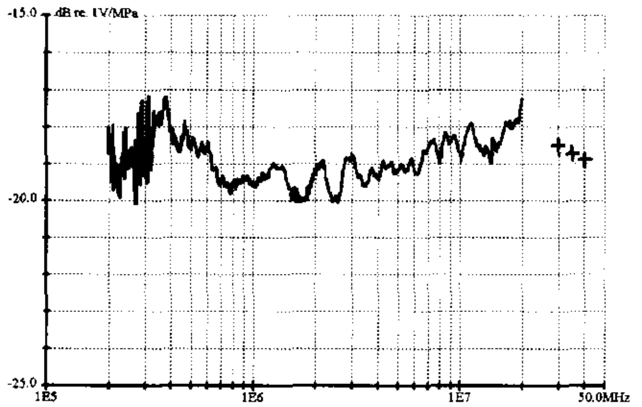


Figure 3: Broadband experimental calibration data for 85 μm active element hydrophone.

It would appear that this hydrophone has an average sensitivity of about –19 dB re. 1V/MPa. This is about 6 dB higher than what was predicted with the KLM model.

Figure 4 shows the angular response of this same hydrophone at 6 MHz.

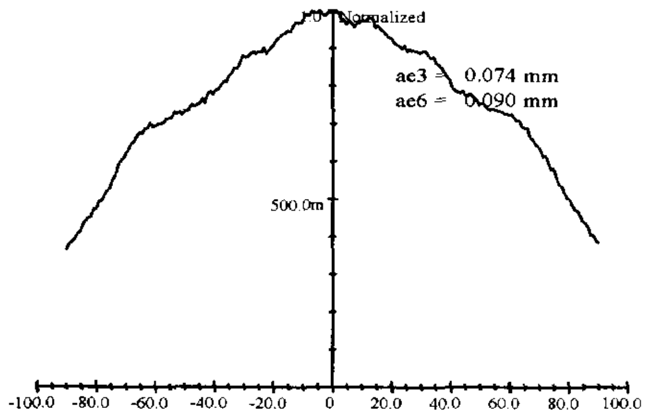


Figure 4: Angular responses of hydrophone at 6 MHz. Horizontal axis units are degrees of angle from normal incidence.

The numbers "ae3" and "ae6" printed on the graph correspond to the effective aperture radius as defined by the AIUM Standard [1], which are based on angular widths at –3 and –6 dB below the peak on axis response, respectively. It is interesting to note that the response is non-zero at ±90°, indicating a plane piston receiver in a rigid baffle. Also note that there are no significant bumps in the response, as can be produced by Lamb wave propagation on membrane hydrophones (see Figure 8 of Lum [3]). Table 1 summarizes the angular response data, which was collected at 4 different frequencies.

| Frequency (MHz) | ae3 (mm) | ae6 (mm) |
|---|---|---|
| 20.000 | 0.058 | 0.054 |
| 15.000 | 0.063 | 0.061 |
| 10.000 | 0.062 | 0.059 |
| 6.000 | 0.074 | 0.090 |
| Mean Values: | 0.064 | 0.066 |

Table 1: Effective hydrophone element radii as determined by angular response measurements.

From these measurements it is clear that the effective hydrophone diameter is about 130 μm.

## DISCUSSION

The 6 dB discrepancy between the predicted and the measured sensitivity of the hydrophone is likely due to the fact that the effective hydrophone diameter is larger than the physical diameter defined by the end of the wire used as an electrode. In fact, if the theory is "force fitted" to the experimental data, an effective size of about 120 μm is obtained. This matches the angular response values nicely. We also note that the theory, which includes the parylene, is supposed to have a 4-dB peak in sensitivity around 40 MHz, which does not appear experimentally. This is believed to be due to one or more of several possibilities, which include: 1) The theory is inaccurate due to the properties of the copolymer changing with frequency; and 2) The experimental data underestimates the sensitivity due to shortcomings in the planar scanning techniques used. More work will be required to clarify this.

The lack of lumps in the angular response curve may be attributed to an absence of propagating Lamb waves. This is probably due to the absence of a planar interaction region, given the ellipsoidal shape of the membrane in this design. In addition, it is possible that the generated surface wave "trash" dissipates harmlessly into the interior of the ellipsoid.

## CONCLUSIONS AND FUTURE WORK

The new design of hydrophone described above has desirable characteristics that will make it useful for measuring broadband acoustic fields. These devices have been shown to meet and exceed the AIUM specifications for hydrophones to be used for measuring the ultrasonic fields produced by medical diagnostic equipment, and yet they still maintain a compact and convenient form factor.

The sensitivity of the hydrophones has been shown to be very flat with respect to frequency, and relatively high for hydrophones with such small effective apertures.

Future work includes making the ellipsoid material match the impedance of water. We also look forward to making these devices about a factor of 2 smaller, with hopefully little or no degradation in their performance characteristics.

## REFERENCES

[1] Acoustic output measurement standard for diagnostic ultrasound equipment, Am. Inst. of Ultrasound in Med., Laurel, MD; Nat. Electr. Manu. Assoc., Rosslyn, VA (NEMA Pub. UD 2, Rev. 2), 1998.

[2] B. Fay, G. Ludwig, C. Lankjaer and P. A. Lewin, "Frequency Response of PVDF Needle-Type Hydrophones," Ultrasound in Med. & Biol., vol. 20, No. 4, pp. 361-366, 1994.

[3] Paul Lum, Michael Greenstein, Charles Grossman, Thomas L. Szabo, "High-Frequency Membrane Hydrophone," IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 43, No. 4, July 1996. This is also readily accessed, in slightly shortened form at: http://www.hp.com/hpj/98aug/au98a1.htm

[4] U.S. Patent 5,479,377 "Membrane-Supported Electronics for a Hydrophone" December 26, 1995.

[5] Ultrasonic Devices Inc. and Specialty Engineering web site: http//:www.ultrasonic.com /tables/long_bottom.htm