

A compact and inexpensive hydrophone with an internal ultra-low-noise preamp

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Abstract - A simple and compact JFET preamp has been built with a gain of 25 dB, a quiescent current of 2 to 3 mA at 12V, and an equivalent input noise voltage of $1.7 \text{ nV/Hz}^{1/2}$ at 1 kHz. This extremely low noise specification was measured with a dummy source impedance that mimics the intended piezoceramic source impedance. Separately, a compact and inexpensive passive hydrophone has been built and measured to have a sensitivity of roughly $-190 \text{ dB re 1V/uPa}$ and a maximum dimension of 28 mm prior to encapsulation. We expect to finish the construction and measurement of an integrated hydrophone and internal preamp soon. This hydrophone should exhibit a noise performance far below Knudsen sea-state zero when completed. The component cost of the preamplified hydrophone is roughly \$25 in small quantities, plus the cost of two simple machined aluminum parts, encapsulation, and cabling.

I. INTRODUCTION

The motivation for this project was originally educational in nature, but the end product may be a valuable hydrophone in its own right. While developing course material for two courses at the Naval Postgraduate School, an analog electronics course and an underwater transducer course, it became clear that a laboratory project that involved the integration of an ultra low noise preamp inside a hydrophone would be very instructive.

A. Traditional Hydrophones

Typical commercial hydrophone designs include those based on thin cylindrical or spherical shells of PZT piezoelectric ceramic material[1]. Both polarization and the generated electric field are usually oriented in the radial direction, so that piezoelectric coupling is between the tangential stress and the generated field, which is g_{31} coupling.

Frequently, the source capacitance of the sensing element is sufficiently high that considerable lengths of cable can be driven without substantial signal attenuation. However, the pressure sensitivity of such simple transducers is not particularly high and the signal quality is can be affected by the cable's electromagnetic environment, the cable's own triboelectric currents caused by cable motion, and grounding issues.

For these reasons, a very low-noise hydrophone is typically built with an internal preamp. A common design is to use two or more thin PZT cylindrical shells as sensing elements and connect them electrically in series in order to boost the sensitivity[2][3]. While the source capacitance of a single cylindrical shell may be high, the net source capacitance of the series-connected unit is much lower. The source capacitance is not sufficient to drive any

significant length of cable, and the internal preamp becomes a necessity.

While the above type of low noise hydrophone is capable of outstanding performance by most measures, the cost of four PZT cylindrical shells alone might exceed \$200, and a typical transducer cost usually exceeds \$2000. Furthermore, the outer diameter of the encapsulated sensing elements range from 3 to 7.5 cm, and the transducer has an overall length of 18 to 30 cm, which is a large device.

B. New Design Objectives

The objective of the work described here is to demonstrate a new design that matches the performance the large commercial transducers in some areas (noise performance in particular), while achieving large reductions in complexity, cost, and size.

II. A LOW NOISE PREAMP

A. A Basic Two Transistor Preamp

The basic design shown in Fig. 1 is a simple N-channel JFET front end, followed by an NPN emitter follower stage that provides a low output impedance.

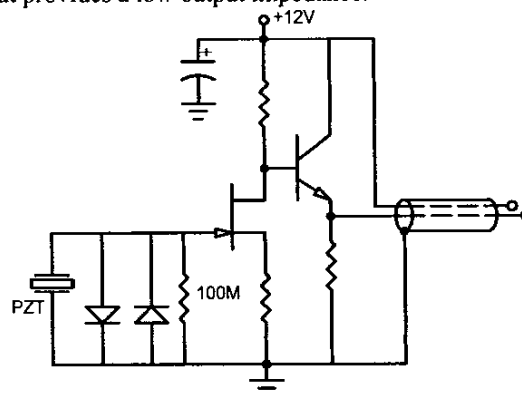


Fig. 1. A simple 2-stage, single-ended JFET preamp.

While traditional internally preamplified hydrophones sometimes use a front end with differential inputs, this is needless if the package is well shielded. Plus, the noise power of the two inputs add to raise the noise floor of the device by 3 dB.

The preamp in Fig. 1, uses a pair of diodes to protect to protect the gate of the JFET from damage when handling the transducer, and the high value gate resistor maintains a gate DC bias voltage level at ground potential. In our

preamp the first stage can have a voltage gain as high as 30, and the second stage has a voltage gain very near unity.

B. Preamp Noise Measurements

Through careful selection of transistors, resistors, and diodes; extremely low noise performance is possible. In particular, the JFET used has a specified equivalent input noise voltage of $1 \text{ nV/Hz}^{1/2}$ at 2 kHz. This is a large improvement over other discrete and op-amp FET preamps that have equivalent input noise voltages in the range of 6 to $10 \text{ nV/Hz}^{1/2}$. In practice, the preamp used in the transducer described below has a measured noise voltage of $1.67 \text{ nV/Hz}^{1/2}$ at 1 kHz with a zero input impedance.

As a final test of the preamp prior to permanent installation into the transducer, the noise performance was measured with a dummy input load impedance consisting of a 789 pF polypropylene capacitor in parallel with the $100 \text{ M}\Omega$ gate resistor. This capacitance roughly matches that of the PZT at low frequencies. While the high quality plastic film capacitor is quite noiseless, unlike the PZT, its virtue is that it has no sensitivity to mechanical forces and vibration, allowing a simple and clean measurement.

It is useful to understand the basic noise source of a parallel capacitor and resistor combination that appear at the preamp input in Fig. 1. The high value gate resistor R_g has a large Johnson noise voltage which is strongly attenuated by the smaller shunt impedance of the capacitor C . The resulting source noise voltage e_s is,

$$e_s = \sqrt{\frac{4kTR_g}{1 + (\omega R_g C)^2}} \quad (1)$$

where kT is the Boltzmann thermal energy at room temperature T and ω is the radian frequency of the noise spectrum measurement. The numerator in (1) is the standard Johnson noise voltage of the resistor and the denominator is the attenuation caused by the low pass filter characteristic of the RC combination. For values of $\omega R_g C \gg 1$, e_s is proportional to $1/R_g^{1/2}$, so that larger value resistors produce less noise, as do larger value capacitances and higher frequencies.

The measured noise performance with a plastic film capacitor connected to the preamp input, is shown in Fig. 2.

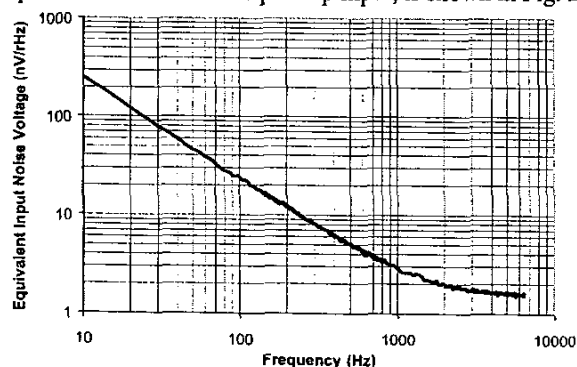


Fig. 2. Equivalent input noise voltage with a plastic film input capacitor.

At lower frequencies the source noise voltage given by (1) dominates the measurement in Fig. 2, and at higher frequencies the noise of the JFET circuit dominates.

While the raw noise voltage numbers shown in Fig. 2 may not be meaningful to all, these same noise values are re-plotted in Fig. 3 below. In Fig. 3, we anticipate the measured hydrophone open-circuit-voltage sensitivity (OCV) discussed in Sec. III, and use it to convert these noise voltage values into an indirect equivalent noise pressure estimation.

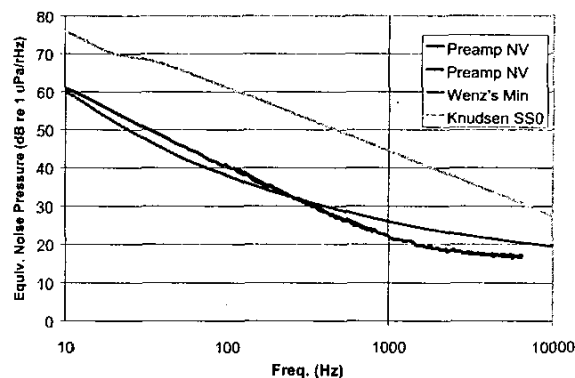


Fig. 3. An indirect measurement of hydrophone equivalent input noise pressure response (black curve) using a plastic film capacitor as a dummy source load. Also plotted are Knudsen sea-state zero, and Wenz's minimum ocean noise pressure levels.

Note that these noise levels are well below Wenz's minimum at higher frequencies, and that a more traditional preamp would raise these noise levels above 1 kHz by 12 dB or more.

C. Other Basic Preamp Specifications

The other important preamp specifications used in the hydrophone discussed below are the following: A voltage gain of 18.7 or 25.4 dB; a supply current of 3 mA at +12 V; a low frequency cut-off at 2 Hz; and an input capacitance of 95 pF.

The input capacitance value is surprisingly high and is mostly the result of the Miller capacitance effect which is related to the high voltage gain of the JFET stage and a moderately high reverse-transfer capacitance for the JFET. Future transducer work will likely employ voltage gains in the range of 15 dB, which should reduce the total input capacitance to 40 pF.

III. THE MINICAN HYDROPHONE

A. The Transducer Structure

The introduction discusses hydrophones that boost the voltage sensitivity by connecting multiple ceramic pieces in series. However, the one-dimensional compression of a piece of PZT can exhibit ever larger voltage responses simply by increasing the thickness and distance between electrodes. Doubling the thickness will double the output voltage and reduce the capacitance by $1/2$ in a manner that is entirely analogous to two series-connected parts. But a

single thick PZT part is simpler and cheaper than many series-connected parts.

Such a thick ceramic hydrophone structure is shown below in Fig. 4 and is similar to one described by Anan'eva[4].

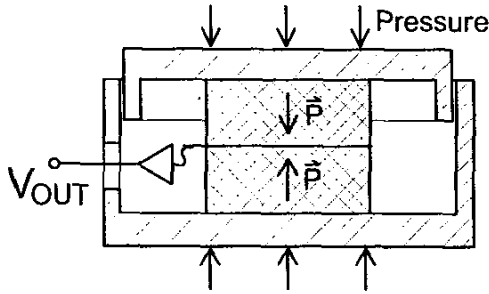


Fig. 4. The MiniCan hydrophone geometry.

It consists of two back-to-back cylindrical plugs of PZT bonded internally to two cylindrical aluminum parts with flat end plates. The aluminum parts partially nest within one another, so that the resulting structure looks like a metal can, which we call the "MiniCan." The outer diameter is 2.8 cm. The cable, preamp, aluminum parts, and two outer PZT electrodes all form a common electrical ground. The middle electrode joining the two PZT parts is the sensing electrode that is connected to the preamp input.

The two aluminum parts are separated by a clearance of 100 to 200 μm , which is filled with a very soft silicon rubber, and the entire structure is encapsulated in urethane rubber. This allows all of the pressure generated forces to be exerted on the PZT. A photo of the partially assembled parts and a completed unit are shown in Fig. 5.

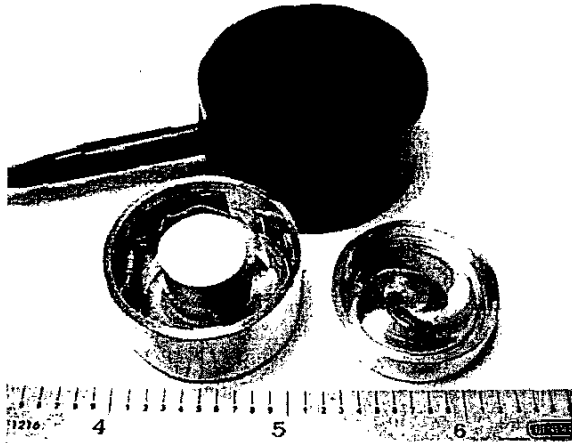


Fig. 5. An opened hydrophone and a completed unit. The opened unit shows the aluminum, PZT, and preamp wrapped along the inner diameter. An inch scale ruler appears at bottom.

While the MiniCan structure could be built with a single PZT plug and an insulating dielectric disk, it was decided that doubling the capacitance with two PZT parts would improve the noise performance with a minimal increase the cost and height of the device. The resulting low frequency PZT capacitance was designed to be 780 pF, but was measured to be roughly 900 pF because of PZT manufacturing tolerances.

The total cost of the PZT and preamp parts is \$25 in small quantities. The PZT cost is \$19 and most of the electronic component cost is in the precision metal film 100 M Ω gate resistor. In reality, the cost of assembly labor and possibly the aluminum machining cost would likely dominate the above costs.

B. A Simple Voltage Sensitivity Theory

An advantage to the MiniCan compared to a thin cylindrical or spherical shell hydrophone is that the force-to-voltage transduction results from stress and polarization effects that are largely co-aligned. The resulting OCV for the pressure applied to the PZT is thus approximately given by

$$\text{OCV}_{\text{PZT}} = g_{33} t, \quad (2)$$

where g_{33} is one of the piezoelectric voltage coefficients and t is the PZT thickness between electrodes. This type of piezoelectric coupling is more sensitive than the traditional shell coupling mentioned in Sec. I by a factor of $|g_{33}/g_{31}| \cong 2.4$.

Another advantage to the MiniCan is geometrical pressure "leverage" created by the larger area aluminum part pressing on the smaller area PZT part. If the effective piston area of the aluminum can is A_{AC} and the electrode area of the PZT is A_{PZT} , then the pressure leverage is given by A_{AC}/A_{PZT} ($= 4.08$ for the hydrophone here) and the net MiniCan sensitivity is given by,

$$\text{OCV}_{\text{MC}} = (A_{AC}/A_{PZT}) g_{33} t. \quad (3)$$

For the unit discussed here, (3) evaluates to an un-amplified sensitivity of -185.4 dB re $1\text{V}/\mu\text{Pa}$ for Navy Type II PZT. Coupling the PZT to the input of the preamp and its capacitance reduces this value by -0.88 dB to -186.3 dB re $1\text{V}/\mu\text{Pa}$. Factoring in the preamp gain yields a net sensitivity of -160.8 dB re $1\text{V}/\mu\text{Pa}$.

The above theory simplistically assumes that the PZT stress in the 1-direction is zero. Because two of the PZT electrodes are bonded to the aluminum, the aluminum will resist and reduce the PZT strains in the 1-direction partially, and thus reduce the sensitivity given by (3) by a few decibels. Rather than pursue more elaborate PZT theory at this point in time, we are focusing our energies on building and calibrating some new hydrophones with variations in construction that should help establish the exact sensitivity loss, and ways to ameliorate it.

IV. ACOUSTIC MEASUREMENTS

A. Passive MiniCan Resonance

An initial MiniCan hydrophone was built without a preamp so that passive electrical measurements could be made. A short coax cable added 208 pF of capacitance to that of the PZT. An obvious concern for the MiniCan structure is the possible existence of spurious resonances in the aluminum parts or combined structure that may be relatively low in frequency. A sweep of the passive electrical impedance showed a fundamental resonant

frequency of 77.5 kHz in air, which is far above the useable frequency range based on anticipated frequency response variations caused by "diffraction effects"[5]. Various sensitivity measurements were also performed on this hydrophone, with results very similar to those described in the next sub-section.

B. Preamplified MiniCan Sensitivity

The partially assembled hydrophone shown in the lower part of Fig. 5 contains the preamp discussed in Sec. II. The assembly of this unit was completed and various sensitivity measurements were performed. The final frequency response curve is shown at the end of this subsection.

The first simple calibration performed prior to the final urethane encapsulation involved mounting the MiniCan on a vibration exciter designed for calibrating small accelerometers [6]. The exciter produces a known and stable amount of AC acceleration. Various known small masses were then attached to the top of the MiniCan while vibrating. The various output voltages of the MiniCan were then divided by the effective pressures generated by the acceleration of the known small masses. In the case of the preamplified MiniCan these sensitivity results were in agreement with the subsequent calibrations to within 0.7 dB.

Further attempts to calibrate the sensitivity involved three variations on the comparison calibration method, where the MiniCan response is measured side-by-side with a reference sensor.

The first method used the anechoic chamber facility at NPS, a small loudspeaker sound source, and a precision 12.7 mm diameter condenser microphone[7] used as a reference. The reference microphone was calibrated with a pistonphone device. Dual channel swept-sinewave ratio measurements were performed and good response data was obtained from 50 Hz to 1 kHz, above which diffraction effects became severe. These low frequency sensitivity results agree with the second and third comparison methods to within 0.2 dB.

Next, the same type of comparison calibration was performed in the NPS underwater tank facility, again using a swept-sine ratio measurement system. The tank dimensions are 7.7 m x 1.85 m x 2.15 m. A custom low frequency projector consisting of two trilaminar PZT flex disks was used. The projector is 15 cm in diameter, has a fundamental resonance of 1.6 kHz under water, and useable sound power down to 100 Hz. A precision calibrated PZT hydrophone with a flat response out to 45 kHz was used as a reference[8]. The results here were good from 100 Hz to roughly 2 kHz where again diffraction effects as well as sound pressure nodes in the reverberant tank were a problem.

Finally, a third underwater tank comparison calibration was performed in order to resolve the higher frequency response of the preamplified MiniCan. The same reference hydrophone as before was used. A 5 cm diameter cylindrical PZT projector, with a 30 kHz resonance, was used. The projector was driven with a single-pulse impulse signal and a dual channel FFT ratio, with averaging, was

performed on the signals from the two receivers. Waveform traces were carefully adjusted to avoid capturing any tank wall reflections. The MiniCan hydrophone was oriented so that the incident sound wave propagation direction was parallel to its two flat faces. (Direct incidence onto a flat face of the MiniCan causes a response roll-off starting at 13 kHz and a deep notch at 23 kHz.)

The results of the impulse measurement appear to be very good, except that we had trouble getting enough sound power into the water with spectral content below 3 kHz. The signal from the small passive reference hydrophone was buried in noise in this frequency range.

The combination of the two underwater tank calibrations is shown in Fig. 6.

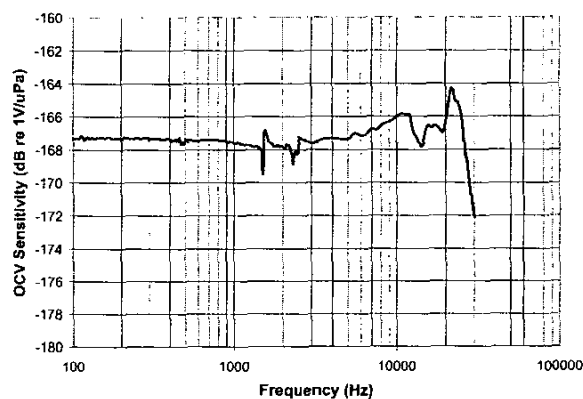


Fig. 6. Frequency response of the preamplified MiniCan with under water sound source incident perpendicular to MiniCan cylindrical axis.

The absolute low-frequency OCV sensitivity is measured to be $-167.45 \text{ dB} \pm 0.2 \text{ dB re } 1\text{V}/\mu\text{Pa}$. The frequency response variations located in Fig. 6 around 1.5 to 2.5 kHz are probably the result of problems with the swept-sinewave measurement and reverberant tank and not indicative of the actual MiniCan response. The response variations above 8 kHz, while likely diffractive in nature, probably represent the actual free field response of the MiniCan hydrophone.

Note that the low frequency sensitivity measured in Fig. 6 is 6.7 dB less than the value quoted at the end of Sec. III B. While the actual sensitivity was expected to be a few decibels less than the simple theory, the final result was lower than expected. After combining measured values for the PZT capacitance and d_{33} , the resulting g_{33} value was found to be lower than nominal by 0.5 dB. During fabrication, low melting point solder was used to join the two PZT parts, and we suspect that the heating over an extended time may have reduced the sensitivity of the PZT by a couple of decibels.

C. Calculated and Measured Noise Performance

The noise performance of the MiniCan hydrophone was measured in air in a relatively quiet laboratory while mounted on a vibration isolator. The equivalent noise pressure of the hydrophone is shown in Fig. 7.

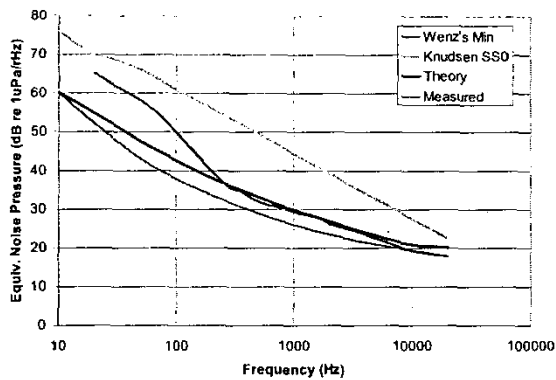


Fig. 7. Equivalent noise pressure of the preamplified MiniCan.

The measured data shown in Fig. 7 represent the noise floor after a few narrow higher frequency peaks caused by air-borne sounds and EMI were removed. The measured noise levels below 200 Hz are believed to be anomalously high because of broadband or random sources of air-borne sounds. We suspect that the measured noise levels shown in Fig. 3 are a more accurate representation of the true performance below 100 Hz.

Figure 7 also shows a theoretical noise response curve where the actual measured sensitivity was used to generate the equivalent noise pressure values. The latter part of the calculation is essentially the same as the filtered Johnson noise calculation given by (1). However, the more difficult task is to determine the exact value for the equivalent parallel resistance that will be used in place the variable R_g in (1).

The "fluctuation dissipation theorem"[9] tells us that any physical effect in a transduction system that dissipates energy will also produce random noise. These dissipative mechanisms can be re-cast as contributions to the aforementioned equivalent parallel resistance. The important sources of dissipation include: the actual resistor R_g ; the low frequency dissipation factor of the PZT; the acoustic radiation under water; and any mechanical dissipation caused by adhesives or elastomers used in the construction of the transducer. This last dissipation source is quite difficult to estimate theoretically and is absent in our calculations. Another source of underwater noise is the thermal molecular motion of the water, but this effect is not significant below 30 kHz.

In our calculations the acoustic radiation noise source just begins to have a substantial contribution at a frequency of 10 to 20 kHz. Inspection of Fig. 7 shows the curious result that the measured noise level is slightly below the theoretical level in the 10 to 20 kHz range. This is because the measurements were performed in air and the theoretical curve includes the underwater radiation resistance.

V. FURTHER WORK

New versions of the MiniCan hydrophone are being built. Another passive unit is being built in order to determine if some of the sensitivity loss can be recovered. A version that is roughly half the size of the unit discussed

here is also being constructed. It should have a flat frequency response out to 40 kHz. Also, efforts will be made to shape the exterior of the hydrophone in order to determine if the diffraction effects can be reduced.

A professional calibration of the preamplified MinCan is currently being performed, and improvements in the techniques used in the sensitivity frequency response measurements and noise measurements are being pursued.

VI. CONCLUSIONS

A simple, compact, low-cost hydrophone has been demonstrated to have a relatively high intrinsic OCV sensitivity. The intrinsic OCV sensitivity is -192.9 dB re $1\text{V}/\mu\text{Pa}$, (-167.4 dB including the preamp gain) and there is hope that a few more decibels of sensitivity can be gained with future improvements. The sensitivity has a flat frequency response from 10 Hz to 20 kHz ($+1.5/-0.5$ dB). An extremely low-noise preamp is integrated inside the compact hydrophone and the overall equivalent noise pressure is well below Knudsen sea-state zero from 10 Hz to 20 kHz. Furthermore, these noise pressure response values are within a few decibels of Wenz's minimum ocean noise levels above 200 Hz, and may prove to be within a few decibels of Wenz's minimum down to 10 Hz as well, with improved test measurements.

Acknowledgments

We acknowledge the efforts of Lt. John Stokely USN with initial development work and noise measurements on the preamp. This work was performed as part of a course project, course development work, and partially by NavSea funding to the NPS Physics Department.

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