Cornell Bioacoustics
Brian S. Corzilius
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A Low-Cost Hydrophone Design Using PVDF Film

1. Overview

This technical article documents the design and development of a hydrophone out of PVDF piezo-electric film, including an integral preamp. In order to have a complete and functioning instrument, one should also refer to the technical article Fabrication of the PVDF Hydrophone Design. Note that the test results presented herein were performed quickly with mediocre test equipment. *The results are intended for comparative purposes only (i.e. between prospective designs).*

2. Design Criteria

The primary criteria for this effort was to develop a design that would meet commercial sensitivities and linearity (-168dB re 1V/uPa, +/-6dB 20Hz to 20KHz) and could easily be adapted to static, towed, or structurally-integrated applications. The design must use low-cost materials (available off-the-shelf), and be easy to fabricate.

PVDF Piezo film was chosen for a number of reasons, including cost and malleability. PVDF film also has the benefit of having an acoustical impedance very similar to that of water and a much better FOM (Figure Of Merit) coefficient when compared to traditional ceramic piezo materials.

3. Transducer Design

3.1 PVDF Types and Characteristics

Several types of PVDF piezo film are currently available on the market. For the off-the-shelf types available from Amp Sensors, a table has been constructed below showing the characteristics.

Thickness	**Sensitivity (M_o)** $M_o = (20 \log m_o)-120$	**Capacitance**	**Approx. Cost per**
Thin Film (length-mode)	$m_o = g_{31}t$ [1] $g_{31} = -216 \times 10^{-3}$		DT2 film (w/leads)
28um	-224dB	379pF/cm^2	$ 4.00
52um	-218dB	190pF/cm^2	$ 5.00
110um	-212dB	95pF/cm^2	$ 8.00
Cylinders (hydrostatic/com-pression mode)	$m_o = g_h t$ $g_h = -250 \times 10^{-3}$		Cylinder add $10 for leads
1.07mm	-195dB	18.1pF/cm (length)	$25.00 per inch length
Tiles (hydrostatic/com-pression mode)	m_o, g_h as for cylinders		Tile add $10 for leads
1.0mm	-198dB	13.8pF/cm^2	$25.00/in^2
1.5mm	-192dB	6.9pF/cm^2	
2.0mm	-188.5dB	4.6pF/cm^2	

Note that no matter what physical configuration or mode of operation, sensitivities (and thus open-circuit output voltages) are increased by increasing the thickness of the material.

In working with PVDF film, the following rules apply:

! **Sensitivity** (m_o) can be increased by increasing the film thickness [series connect, concentric windings, etc]. A technique called 'pressure-relief' may also be used which has the effect of amplifying the stress applied to the axis of interest, thus increasing the open-circuit voltage output. See the Powers reference in the appendix (page 25), for additional information.

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[1] m_o is the open-circuit voltage sensitivity. Note that a high-input impedance device must be used to make such measurements (e.g. an oscilloscope).

! **Frequency response** is affected by the compliance of the piezo substrate (e.g. the cable's jacket). Reducing compliance increases the high frequency response.

! **Signal-to-Noise** ratio can be increased by increasing the sensitivity (m_o) and/or the piezo system's capacitance [parallel connections increase capacitance, series connections increase thickness/sensitivity]. It is expressed as a Figure Of Merit (FOM) and defined as:

$$FOM = \frac{m_o^2 C}{\tan\delta}$$

This FOM relates the sensitivity in a form traditionally compared to Sea State Zero[2]. Given that the PVDF value of O is 0.016, PVDF film constructs show a noise figure typically 6dB lower that PZT ceramic constructs.

! **Acceleration Noise** (cable vibration pickup) can be reduced by placing the 2-axis in alignment with the cable axis (g_{31} mode only)[3].

! **Pressure Capability** can be increased by using non-voided construction (cable, film, etc). However, the limit for film seems to be 1000m.

3.2 Acceleration Noise

The presence of cable noise -- also called 'acceleration noise' in the industry -- can be reduced by a couple of considerations during the design. The first consideration must of course be given to the cable construction itself. The cable should be of a solid construction, using a flexible filling compound to penetrate between all cable elements and remove all air voids. This not only creates a water block but also creates a relatively noiseless cable.

The second consideration is in the transducer design itself. Every piezoelectric-based design has a primary axis of excitation, with 2 or more secondary axes. With traditional PZT (ceramic) piezo designs, a nodal mount approach is often used in which the piezo is gripped in the exact middle. When axial acceleration is applied to this configuration,

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[2]An FOM of $8x10^{-18}$ M^3/Pa is sufficient to detect Sea State 0 (SS0) acoustic pressure levels. A single 28um film of 10.5cm^2 has an FOM of ~$6.93x10^{-18}$.

[3]With PVDF thin films, the 1-axis is the length, the 2-axis is the width, and the 3-axis is the thickness. The coefficient 'g_{31}' refers to the 1-axis usage, 'g_{32}' to the 2-axis usage, etc.

voltages of opposite sign but equal amplitude are produced in the upper and lower halves of the piezo, thus cancelling out a good portion of the acceleration-induced noise. This technique is often referred to as 'acceleration cancellation'.

In the g_{31} mode of operation (as is being considered with the PVDF films), the length is the main excitation axis, with width and thickness (g_{32} and g_{33} modes respectively) being free to move without excitation. If the 2-axis is aligned to the source of common-mode (or 'acceleration') noise, the primary or 1-axis will have a greatly reduced response. In both approaches, the acoustic sensitivity is unaffected.

3.3 Transducer Configurations

Although the thin film material has the lowest sensitivities of the 3 types of PVDF film available to us, several of the thin film attributes are quite attractive for our design work.

From the information presented to this point, we can see that by increasing the thickness (apparent or actual) of the film, sensitivities can be increased greatly. One approach to do such is to wrap the thin film around the cable several times.

If the film is wrapped around the cable in the 1-axis direction, we can also reduce the acceleration noise of the design. And if it is wrapped tightly enough on a relatively non-compliant cable, the frequency response is also enhanced. Finally, if a series-parallel arrangement of several films is employed, the signal-to-noise ratio can be kept within reason.

For the prototypes, variations on concentric wrapping with parallel-series wiring arrangements was chosen. As a comparison point, one unit employing PVDF cylinders in the hydrostatic mode was also fabricated.

Throughout the rest of the document, the following names will refer to the various design approaches chosen (refer to the table in the appendices, page 24 for a full description):

2p2s	2 films in parallel as a set, 2 sets wired in series.
2p4s-cab	" " " " " " " , 4 sets wired in series.
2p4s-tin	" " " " " " " " " " " " , wound around tin flashing over the cable.
110/4s	4 110um films connected in series.
Cyl4p	4 copolymer cylinders connected in parallel.

4. Preamp Design

Due to the high impedance of piezoelectric material, a FET amplifier arrangement was chosen. In order to reduce assembly costs and keep the size of the preamplifier circuit to a minimal, an integrated circuit FET op-amp was desired. For this design, the Texas Instruments TL071 device was chosen. This IC has a good noise figure and output drive capability with good output short-circuit protection.

As a piezoelectric device exhibits the attributes of a capacitor and that its low-end frequency response is dictated by the input load resistance, a 10M Ohm load resistor was chosen, giving a lower cutoff frequency for the amplifier of about 6Hz.

One of the design requirements of our preamp is to be able to run off of a single polarity supply (typically 12VDC). To do this, a resistive voltage divider was employed. The piezo load resistor is then referenced to the divider's midpoint voltage, while the inverting input of the amplifier references the same level through an offset resistor. The resultant amplified signal will then ride a DC offset of roughly 1/2 the supply voltage and swing between ground + 2V and the supply voltage - 2V.

The voltage gain of this circuit is set by a combination of 2 resistor values (see the notes on the schematic included with the document entitled Fabrication of the PVDF Hydrophone Design). Once the voltage gain is known, the gain in decibels can be calculated by the formula: 20log(voltage gain). For the design used in testing, the voltage gain was set at 66, translating into a 36.5dB preamplifier.

The frequency response of the final circuit extends well above 70KHz, with test results included in the appendices, beginning on page 8.

The completed circuit draws less than 2mA across a supply voltage range of 9 to 18VDC. The final circuit, when laid out on a circuit board is <1" by <2" and can easily be integrated onto the cable structure.

5. Fabrication of the Test Cable

The four film-based designs were fabricated on the same cable while the fifth -- that using the copolymer cylinders (Cyl4p) -- resided on a separate cable since it had been fabricated at an earlier date.

All five configurations were potted in a cylindrical form approximately 1.2" in diameter using 3-M's 82-F1 molds. The cable itself supplied common power and extracted the signals to coaxial cable terminated in BNC-type connectors.

Due to the details required to cover the step-by-step fabrication of the individual elements, fabrication is covered in another document entitled Fabrication of the PVDF Hydrophone Design. Please refer to that document for further information.

6. Test Methods & Results Summary

The test methods used to evaluate the various designs are described in detail in the document Hydrophone Usage and Deployment. The technique is primarily one of 'comparative calibration' where a calibrated reference hydrophone is subjected to the same test conditions and the results of the unknown hydrophones are plotted against those of the known reference.

6.1. Hydrophone Linearity

The hydrophone linearity tests involved examining the response of each of the designs across a frequency range extending from 100Hz to 70KHz. This was then plotted against the reference hydrophone both as a voltage output and as a deviation in decibels. The resultant plots are included in the appendices beginning on page 11.

From the results, it was found that the 2p4s-tin performed the worst, with no response past roughly 12KHz. This may be attributed to either poor construction or the interaction of the metal with the films themselves.

The Cyl4p design had the widest frequency response, but one of the larger response deviations with respect to the calibrated reference (~+/-20dB)

The 2p2s and 2p4s-cab designs showed the smallest variance in respect to the calibrated reference, although both responses fell off at about 25KHz. This again may be attributed to the films not being wrapped tightly enough, etc.

6.2. Hydrophone Sensitivity

The sensitivity of each design was calculated by taking the average gain of the transducer-preamp combination over the reference, converting this to decibels, then adding it to the calibrated reference hydrophone's known sensitivity.

Working from a design goal of meeting or exceeding commercial hydrophone sensitivities of -168db, all designs except the 2p4s-tin met the goal. The 110/4s and the Cyl4p had the highest sensitivities which is to be expected due to the materials used (thickness and base sensitivities). Again, all preamplifiers employed the same gain factor.

6.3. Signal-to-Noise (SNR)

The signal-to-noise test involved dividing the recorded output (at a specific frequency) by the ambient noise level for each design. For comparison purposes, only the 4 film-based designs were compared. Of these, the 2p2s design gave the highest signal-to-noise figure.

6.4. Cable Noise Susceptance Test

Since the test elements were built onto a particularly noisy cable (internal mylar layers against Kevlar), it was relatively easy to generate cable movement noise over a small section of the cable. Only one of the group did not get tested -- that of the cylinder construction. Testing was performed by monitoring the element under test with an oscilloscope and applying a rotational force to the cable just above the element being monitored. The same force was applied to each element in-turn and the level seen on the oscilloscope noted for comparison. This was followed by the same procedure but using headphones to monitor the output, providing a human factor to the result biasing.

The testing showed that the groupings of 4 sets of parallel films in series (2p4s designations) showed the lowest cable noise, the 2p2s design came in second, while the 4 singular series connected films (110/4s designation) performed worst.

6.5. Maximum Operating Depth

Pressure testing was not performed at this time due to facilities being unavailable.

7. Summary

In the appendices, page 24, a table is included that summarizes the final characteristics of the various design approaches discussed in this document.

Of the five designs, the 2p2s had best SNR, good cable noise rejection, and good response and sensitivity. It was also the lowest cost, smallest, and easiest to fabricate. Based on these factors, this design is the author's preference, although the other designs -- specifically the 2p4s-cab -- have potential future applications.

Since these tests were performed, another 2p2s-based design was fabricated for use in the field in research. The calibration plots for this hydrophone showed that, with care in fabrication, quite respectable specifications could be reached. In this case, a sensitivity of -166dB was achieved with a frequency response of +/-6dB from 10Hz through 25KHz (+/-10dB through 35KHz).

Appendix A. Preamp Response Curve

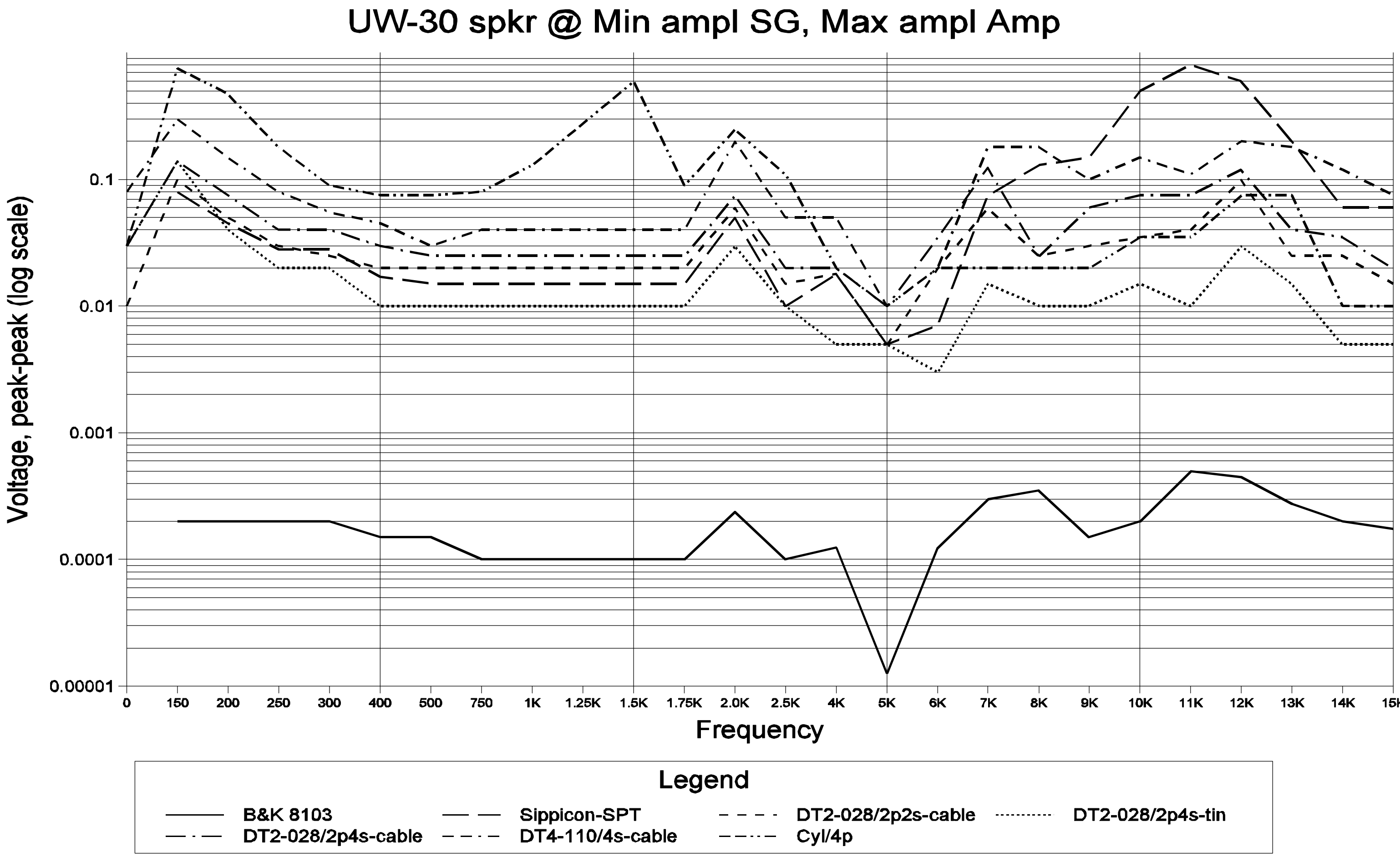
The preamplifier circuit was tested by placing it in a box with BNC connectors on either end and using it to amplify the B&K reference. This amplified reference was then compared against the unamplified reference to generate information on linearity and sensitivity of the circuit itself. On the following pages, spreadsheet data and a graph of the results are presented.

Appendix B. Transducer Response Curves

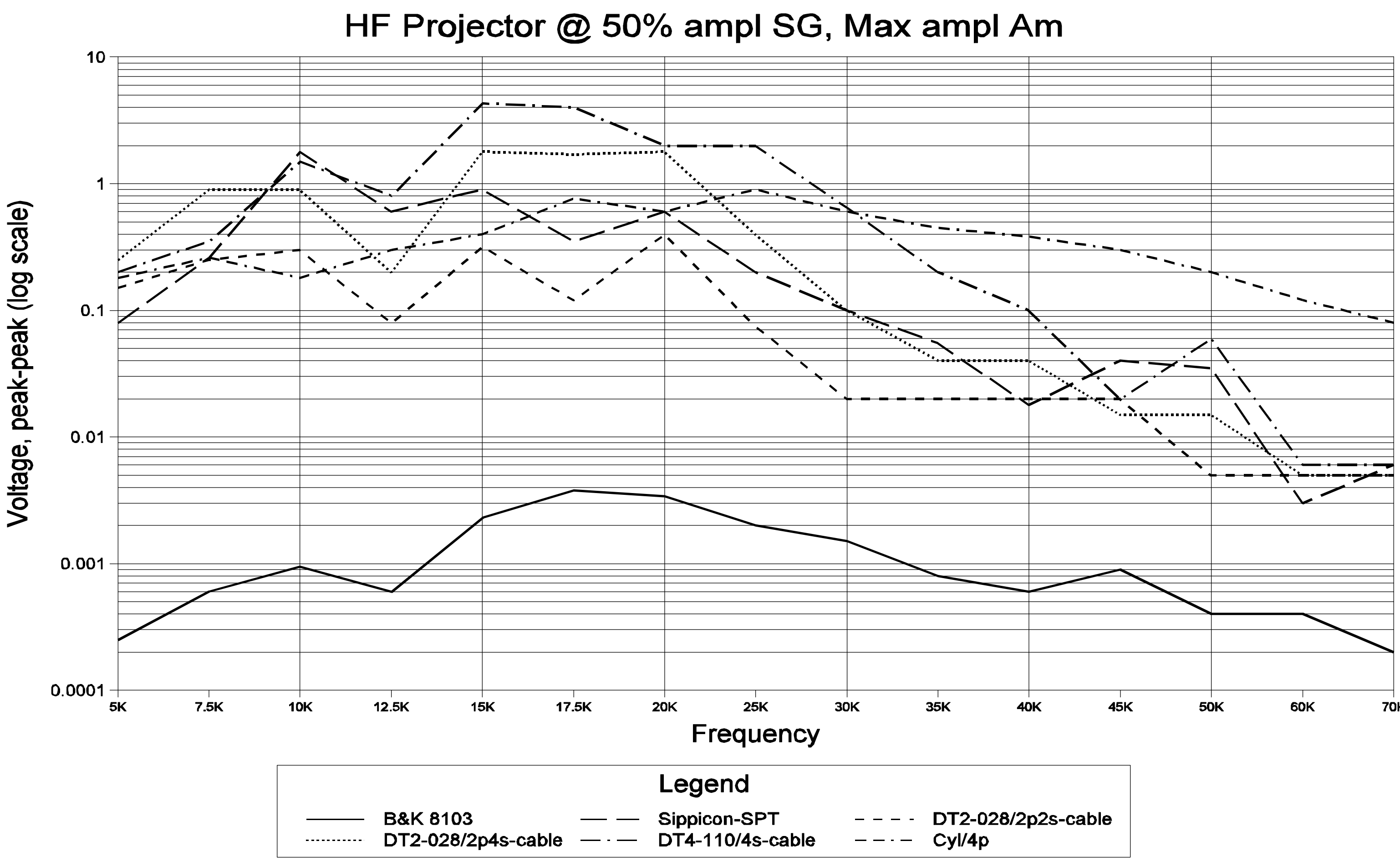
All versions of the design were tested at the same time against the B&K reference hydrophone. On the following pages, the data has been broken up by design and plotted per linearity. As a summary, a set of composite plots showing relative voltage sensitivities is presented for comparison. This plot also includes a commonly-used commercial hydrophone manufactured by Sippican for comparison.

Note that the fabrication and the testing for these designs was performed on a rather hurried basis, with the intent of generating a comparative set of data only. The plotted linearities and derived sensitivities have already been shown to be greatly improved with careful construction.

Hydrophone Test Results



Hydrophone Test Results



Appendix C. Transducer Characteristics and Cost Comparisons

In the table following, a summary of calculated and experimental data for the 5 versions is presented. The 'Experimental Sensitivity' column represents the sum of the derived sensitivity (with respect to the B&K reference hydrophone) and the experimentally-derived gain of the preamp. The 'Linearity' column is taken directly from the spreadsheet response column.

Legend Name [nickname]	Description	Cap.	M_o, Calc. Sensi-tivity	Exp. Sensi-tivity	Lin-earity	Cost (4/94)	Fab. Length
DT2-028/2p2s-cable [2p2s]	70x15mm, 28um thick films, 2 paralleled per set, 2 sets in series wrapped onto 1/2" cable	4nF	-218dB	-206dB	+6, -20dB	$16 (4 films)	1.5"
DT2-028/2p4s-tin [2p4s-tin]	As above -- excepts 4 sets in series, with tin flashing between films and cable (to reduce compliance)	2nF	-212dB	-210dB	+8, -11dB	$32 (8 films)	3"
DT2-028/2p4s-cable [2p4s-cab]	As above, without the tin.	2nF	-212dB	-202dB	+8, -24dB	$32 (8 films)	3"
DT4-110/4s-cable [110/4s]	165x22mm, 110um thick films; 4 in series wrapped on 1/2" cable.	0.9nF	-200dB	-196dB	+8, -29dB	$20 (4 films)	3.5"
Cyl/4p [Cyl4p]	4 copolymer cylinders in parallel	72pF	-195dB	-191dB	+18, -22dB	$140 (4 cylinders or 1 4" cylinder)	5"

Appendix D. References

Amp Sensors Piezo Film Sensors Technical Manual Valley Forge, PA (order #65751).
-- Also request the bulletins/technotes on hydrophones that they have available.

Bobber, Robert J. Underwater Electroacoustic Measurements Naval Research Lab, Washington DC 1970.

Powers, James M. Long Range Hydrophones Naval Underwater Systems Center, New London, CT.

Powers, James M. Piezoelectric Polymer -- An Emerging Hydrophone Technology Naval Underwater Systems Center, New London, CT.