Understanding Piezo Based Sensors for Acoustic Neutrino Detection

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Abstract. The ANTARES collaboration is currently installing a neutrino telescope off the French Mediterranean coast to measure diffuse fluxes and point sources of high energy cosmic neutrinos. The complete detector will consist of 900 photomultipliers on 12 detector lines, using 0.01km$^3$ of sea water as target material[1]. As part of the ANTARES deep-sea research infrastructure, the Erlangen group is planning to modify several ANTARES storeys by fitting them with acoustic receivers to study the feasibility of acoustic neutrino detection in the deep sea.

In this paper, studies of the electromechanical properties of piezoelectric sensors are presented, based on an equivalent circuit diagram for the coupled mechanical and electrical oscillations of a piezoelectric element. A method for obtaining the system parameters as well as derivations of sensor properties like pressure sensitivity and intrinsic noise are treated and results compared to measurements. Finally, a possible application of these results for simulating system response and optimising reconstruction algorithms is discussed.

1. Motivation
To study the possibilities of building and operating an acoustic neutrino detector in the deep sea, our group is planning to equip the ANTARES neutrino telescope with several customised storeys, in which the optical sensor elements will be replaced by ultrasound sensors.

One of the key ingredients necessary for evaluating the performance of an acoustic detector as well as conducting realistic simulation and reconstruction studies is the knowledge of the nature of acoustic background at the detector site. This includes both the spectrum of the constant components as well as the correlation properties of transient noise signals. To gain a thorough understanding of this deep sea noise, an array of several acoustic sensors will be installed with inter-sensor distances of between 1 metre and more than 100 metres to measure correlation lengths over several different length scales [2][3].

For the acoustic sensors, two different designs are being studied, both of which will be used in the ANTARES detector[4]:

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commercial and self-made hydrophones consisting of a piezoelectric sensor element and a
pre-amplifier, which are protected from the sea water by a polyurethane coating, and
so-called acoustic modules, in which piezoelectric elements are coupled to the inside of a
17” pressure-resistant glass sphere normally used to house the photomultiplier tubes.

In each case, the signal response and the noise characteristics of the sensors will depend heavily
on the properties of the piezo element used as an active sensor. As it is therefore necessary to
understand these properties in order to predict and optimise the performance of the sensors, a
simple model has been used to characterise the piezo elements.

2. Modelling piezo sensors with the equivalent circuit diagram

2.1. The electro-mechanical equivalent circuit

In a piezo crystal electrical and mechanical properties are coupled, as a force applied to
the element will result in an electrical field and vice versa. Using the analogy between
forced mechanical and electrical oscillation, it is therefore possible to express the mechanical
properties of an oscillating piezo element by equivalent electrical properties. Table 1 shows the
corresponding pairs and their dependence, where $\alpha$ is the material-dependent electromechanical
coupling constant.

| Force $F$ | Voltage $U = \frac{F}{\alpha}$ | Voltage $U$ |
|-----------|-------------------------------|-------------|
| Elongation $x$ | $Q = \alpha \cdot x$ | Charge $Q$ |
| Stiffness $S$ | $C = \frac{\alpha^2}{S}$ | Capacity $C$ |
| Damping $W$ | $R = \frac{W}{\alpha^2}$ | Resistance $R$ |
| Inertia $m$ | $L = \frac{m}{\alpha}$ | Inductance $L$ |

2.2. Obtaining the electromechanical parameters

By taking the electro-mechanical analogy one step further, it is possible to derive the mechanical
properties by measuring the electrical impedance of this now completely “electrical” circuit.
This was done by applying a gaussian voltage signal to a voltage divider made of the piezo to be
measured and a suitable capacitor (as the piezo’s impedance is mainly capacitative), measuring
the voltage signal over this capacitor and, from the fourier transform of both the sent and
received voltage pulse, calculate the impedance spectrum of the piezo element.

With the equivalent circuit diagram (ECD), the expected impedance curve for each set of
parameters can now be calculated and fitted to the measurement, giving a complete set of equiva-
 lent piezoelectric parameters from a single measurement. As this measurement is possible both
for free and coupled piezo elements, the effect of coupling on the mechanical parameters of the
piezo element can be studied, which is important for the design of acoustic receivers, in which
the piezo will always be surrounded by a coating material and water.

The main effect of coupling is simply an increased damping of the crystal’s oscillation,
manifesting itself in an increased real part in the impedance of the respective parallel branch in
the ECD. If, due to asymmetric clamping, only a certain direction of motion is restricted, this
will manifest itself in different damping of the individual resonance branches, depending on the
spatial direction corresponding to each resonance.
Figure 1. The equivalent circuit diagram (ECD) for a force-free piezo element with an arbitrary number of resonances (left). Voltage divider analogy used for the sensitivity derivation (right).

Figure 2 shows change in the impedance spectrum of a 25x10mm piezo disc resulting from radial and longitudinal obstruction respectively. Radial clamping (red) results in a relatively stronger damping of the first (radial) resonance around 75 kHz, whereas the second (longitudinal) resonance is affected more strongly by longitudinal clamping (blue).

With the parameters fitted, the sensitivity of the piezo element can now be modelled.

3. Sensitivity of piezoelectric sensors

3.1. Derivation

The receiving sensitivity of a piezoelectric sensor is determined by the voltage at its electrodes as a result of applied force. While this ratio is constant for an idealised piezo transducer, the sensitivity spectrum of a true piezo element is modified by the presence of the electromechanical resonances. As shown in figure 1 (right), the piezo acts as a frequency-dependent voltage divider, made up of the mechanical LRC branches and the electrical capacity $C_p$, on the ”ideal” voltage signal $U_0$, resulting in a frequency dependence of the voltage on the electrodes. Thus,

$$ U_a = \frac{Z_p}{Z_p + Z_{LRC}} $$

for one resonance branch. The sensitivity is maximised at the piezo’s anti-resonance, where the voltage signal can be amplified by more than an order of magnitude, depending on the damping of the corresponding mode. Allowing for different coupling of the individual mechanical resonances, this can be generalised to an arbitrary number of resonances. For frequencies well below the resonances, the sensitivity approaches its static value.
3.2. Comparison with Measurement

To verify the validity of these sensitivity predictions, a comparison was made with a measurement on a 25x10mm disc piezo attached to the wall of a water tank. The impedance spectrum was obtained in situ from the coupled element, yielding the expected sensitivity shown in Figure 3 together with the result from a direct calibration done with a transducer hydrophone in the tank. The result shows both good agreement between prediction and measurement and with the low-frequency value of -192dB re 1V/μPa stated by the manufacturer, which corresponds to $2.5 \times 10^{-4} \frac{V}{Pa}$.

![Figure 3. Comparison of measured (data points) and calculated (solid line) sensitivity for a 25x10mm piezo disc. Taken from [5].](image)

4. Signal Response

From the (frequency dependent) sensitivity of a sensor system, the response to any applied pressure signal can be predicted, facilitating the development of efficient data analysis and reconstruction software for an acoustic detector system.

4.1. Basic Principles

In the time domain, the signal response $R(t)$ measured by a sensor system is equal to the raw signal $S(t)$ convoluted with the system’s impulse response $I(t)$,

$$ R(t) = \int_{-\infty}^{+\infty} S(\tau) \cdot I(t - \tau) d\tau, \quad (2) $$

which by Fourier transform translates into a simple product in the frequency domain:

$$ \tilde{R}(\omega) = \tilde{S}(\omega) \cdot \tilde{I}(\omega) \quad (3) $$

Thus, the response to an arbitrary signal can be obtained directly by multiplying the Fourier transform of the signal with the (measured or predicted) complex sensitivity spectrum of the sensor and subsequently re-transforming the result into the time domain.
4.2. Application to a Complex System

This method was applied to predict the signal response of a commercial hydrophone from High Tech, Inc., which will be used for the ANTARES acoustics. First, the absolute value of the hydrophone’s sensitivity for each frequency was obtained in the water tank using a calibrated transducer. This sensitivity spectrum was then fitted with a simplified model with three resonances giving a full complex transfer function for the sensor system (Figure 4). From this the system’s impulse response was obtained. Figure 5 shows an application to a neutrino-like bipolar pressure signal, comparing the signal predicted by the three-resonance model with the signal actually measured by the hydrophone in the water tank. The very good agreement confirms the possibility of modelling a complex system like the hydrophone with a piezo element and a pre-amplifier - both of a priori unknown characteristics - by means of a simple piezo receiver with a moderate number of resonant branches.

**Figure 4.** Result of fitting a 3-resonance model to the measured sensitivity of a commercial hydrophone (black line = measurement, red line = fit). The amplifier’s additional high-frequency cut-off is not included in the model.

**Figure 5.** Comparison of simulated (red) and measured (black) response to a neutrino-like bipolar pressure signal in a commercial hydrophone.

5. System Noise

To an even greater extent than a sensor’s sensitivity, which can in principle be arbitrarily increased by internal or external amplification, a sensor’s detection capabilities are limited by its intrinsic noise. This noise has two distinct components:

- Intrinsic noise of the piezo element resulting from thermal movement which induces voltage signals on the electrodes. In the context of the ECD, this is equivalent to the thermal Nyquist-Johnson noise from the real part of the piezo’s impedance:

  \[ e_n^2 = 4kT \cdot Re (Z_{piezo}) , \]  

  (4)

  where \( e_n^2 \) is the power spectral density of the voltage noise. As \( Z_{piezo} \) depends on frequency, so does \( e_n^2 \).
the noise from the amplifier, both from active components (operational amplifier, transistors) and from passive components (resistors). In a multi-stage architecture, anything but the first amplifier stage can be neglected as long as the initial gain is high enough.

Again, predictions can be made from a single measurement of the piezo element’s impedance curve and the specifications of the components used for the pre-amplifier, which are in good agreement with measurements on the fully integrated hydrophone (see figure 6).

Figure 6. Comparison of measured system noise with estimation for the separate components: black=piezo self noise from real part of piezo impedance, blue=amplifier noise, red=measurement in laboratory, including acoustic noise at low frequencies.

6. Conclusions
The possibility of a unified description of the electrical and mechanical properties of piezoelectric elements with an equivalent circuit diagram has been demonstrated together with predictions for sensitivity, signal shape and system noise derived from this model, all of which are in good agreement with measurements. An uncomplicated method of obtaining the necessary parameters for the ECD has been presented, which can be applied to any kind of piezoelectric sensor, both prior to and after integration into a sensor device. In addition, an example of the application of the ECD’s sensitivity model to a commercial hydrophone has been given.

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