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CONSTRUCTION AND EVALUATION OF A NOISE-SUPPRESSING HYDROPHONE

by

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Various versions of this transducer were constructed and put through a uniaxial vibration test. Upon achieving satisfactory insensitivity to uniaxial vibrations, the transducer was subject to an underwater free-field voltage sensitivity measurement. Results from both tests indicated that the Noise-Suppressing Hydrophone could be effective in the frequency range tested.

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CHAPTER 1

INTRODUCTION

Piezoelectric ceramics, commonly called piezoceramics, have gained wide use since their development over 40 years ago. They make good electromechanical transducers due to their durability, stiffness and resistance to atmospheric conditions such as humidity. One of the most significant benefits of piezoceramic transducers is that they can be manufactured into virtually any size and shape, each excitable into a variety of vibrational modes. Also, piezoceramics are easy to handle and relatively inexpensive.

This work addresses a particular design of a piezoceramic transducer for use as a hydrophone, which is an acoustical receiving device for use underwater. The design, patented as a Noise-Suppressing Hydrophone [1], allows for the transducer to be mounted on a vibrating surface and sense signals received through the fluid media but not sense signals received through the mount as a result of vibration.

Other transducers serving the same function as this invention are in use today, although they eliminate mount noise by mechanical means. The transducers are either separated from the mount using isolation layers which are often quite bulky, or the vibrations are mechanically damped out using heavy masses. The Noise-

Suppressing Hydrophone eliminates the mount noise electrically, and therefore eliminates the need for the extra masses and allows the transducer to be mounted directly onto the vibrating surface.

Although patented, the Noise-Suppressing Hydrophone functioned only in theory prior to this research. The goal of this work was to construct a working model of the invention and test it to see if it functioned as predicted in theory.

Purpose

The purpose of this research was to construct and test the patented Noise-Suppressing Hydrophone which had not been tested previous to this work. The objectives of this thesis were:

- To study the theory of piezoelectric ceramics and basic transducer theory, as well as the theory behind the design of the transducer to be tested;

- To construct working models of the hydrophone;

- To test the ability of the transducer to suppress mount noise and modify the design to maximize its effectiveness;

- To test the transducer's effectiveness as a hydrophone;
- To evaluate the overall effectiveness of the design.

General Outline

Chapter 2 covers piezoceramic transducer theory, which is necessary to understand the design and applications of the transducer to be tested. It also deals with the design of the transducer and the theory of how it should work and discusses the approach used in testing the applications of the transducer. Chapter 3 covers the first phase of testing, while Chapter 4 covers the second phase. Chapter 3 also describes the construction of the various transducers that were tested. Chapter 5 contains the conclusions drawn regarding the effectiveness of the transducers as well as recommendations for further work.

CHAPTER 2

BACKGROUND

Basic Piezoceramic Transducer Theory

Ceramics are manufactured compositions that normally exhibit negligible piezoelectric effect. However, many ceramic compositions can be made piezoelectric by applying an electrical poling treatment. This treatment usually consists of depositing metallized electrodes on two parallel surfaces of the ceramic. A poling voltage is then applied across the two electrodes after the ceramic has been heated to a temperature a little below its Curie temperature or Curie Point. The ceramic is cooled to room temperature and then the poling voltage is removed. The ceramic is now permanently piezoelectric, although aging effects cause the electromechanical properties to change with time. The primary polar direction is that normal to the electroded surfaces and therefore this process allows one to choose the direction of primary poling.

The piezoelectric ceramic is now a transducer. When it is mechanically stressed it will generate a voltage and when a voltage is applied across its electrodes it will change dimensions. The electromechanical interaction of the ceramic can be well approximated by the equations

$$S = s^E_{xy}\, T + d_{xy}\, E, \qquad (2.1)$$

and

$$D = d_{xy}\, T + \varepsilon^T_{xy}\, E, \qquad (2.2)$$

where S is the strain or relative deformation of the ceramic, T is the mechanical stress, E is the electric field strength, and D is the electric displacement. Also s^E_{xy} is the elastic constant of the ceramic measured under the condition of constant E field, i.e., when the electrical terminals are shorted. The symbol ε^T_{xy} is the dielectric constant measured under the condition of constant stress, i.e., in a vacuum, and d_{xy} is the piezoelectric charge or strain coefficient. These coefficents are properties of the individual ceramics and the subscripts marked by x and y are variables which indicate the positioning of the electrodes relative to poling and the type of force applied. In general, the x variable refers to the direction of the poling field and the y variable refers to the direction of the strain.

To further explain how these coefficients apply, consider a rectangular piece of ceramic with three axes denoted 1, 2 and 3 analogous to X, Y and Z (see Figure 1). Place the direction of poling along the 3 axis, and assuming that the electrodes have not been moved after poling, they will be on the faces perpendicular to the 3 axis. Therefore for any force applied or strain experienced along the 3 axis, d_{33} would apply. For a strain along the 2 axis, d_{32} would apply and likewise for a strain or force along the 1 axis, d_{31} would be applicable. Other subscript combinations are possible if the electrodes are moved or relative poling direction changed, but for this work these were the only coefficients applicable.

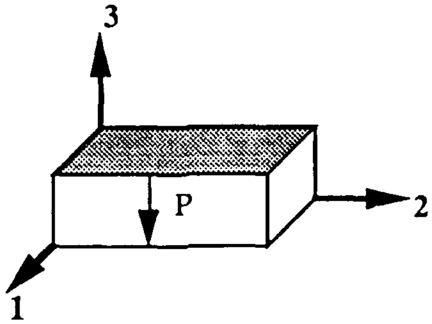


Figure 1. Standard piezoceramic axes. P indicates direction of poling and shaded surface indicates electroding.

Other coefficients commonly used with piezoceramics are the piezoelectric voltage coefficients g_{33}, g_{32} and g_{31}, which are directly proportional to d_{33}, d_{32} and d_{31}. The actual relationship is given by

$$d_{xy} = K_3 \varepsilon_o g_{xy} , \qquad (2.3)$$

where K_3 is the relative dielectric constant in the 3 direction, and ε_o is the dielectric constant of free space. The product of the two yields the absolute dielectric constant, which is the only difference between the g_{xy} and d_{xy} coefficients. The g coefficient is used to determine the voltage output of the ceramic.

Stress in any direction on the piezoceramic will develop an output voltage between the two electrodes. Note also that a compressive stress will produce a voltage opposite of that of a tensile stress (see Figure 2), and that the output voltage is a linear function of input stress.

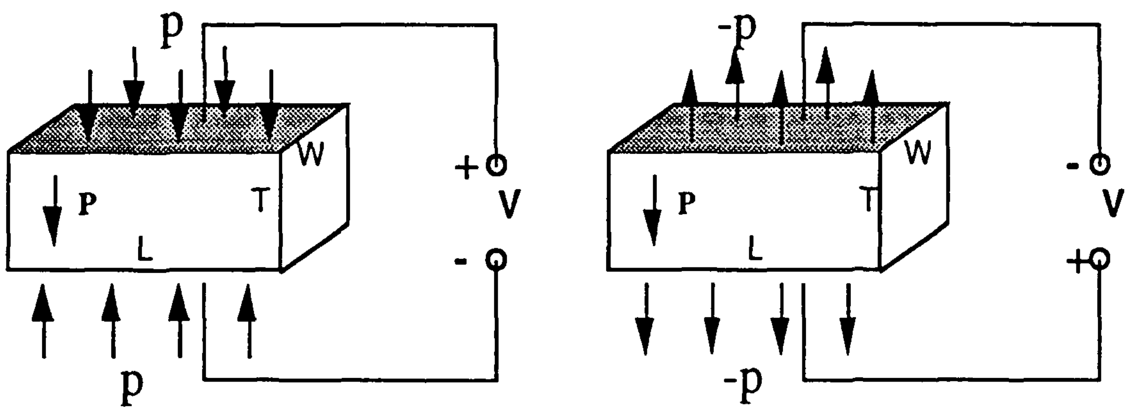


Figure 2. Electrical response of piezoceramic to compressive (left) and tensile (right) stresses. P indicates poling axis, p indicates pressure. L, W and T indicate Length, Width, and Thickness respectively.

For the case in Figure 2, the low frequency voltage V is given by

$$V = pTg_{33}, \qquad (2.4)$$

where p is the resulting pressure on the face of the ceramic, and T is the thickness of the ceramic. The coefficient g_{33} is used because the stress is exerted in the 3 direction of the ceramic. The piezoceramic is also sensitive to stresses applied along the 1 and 2 axes, and the expressions for the voltages are the same except that g_{13} and g_{23} are used instead of g_{33} (see Figure 3).

Measurements of the various coefficients indicate that

$$g_{33} \approx -2g_{32} = -2g_{31}. \tag{2.5}$$

Therefore, the voltage resulting from a stress along the 3 axis of the piezoceramic is approximately twice the magnitude of the voltage resulting from an equal stress exerted along either the 1 or 2 axes. The fact that the ceramic is most sensitive in the 3 direction should be intuitive because the 3 direction is the direction of poling. Note, however, that in addition to this magnitude difference, the voltage resulting from a compressive stress along the 1 or 2 axis is opposite in phase from the voltage resulting from a compressive stress along the 3 axis.

Also implicit in the above equation is the fact that the piezoceramic is isotropic along the 1 and 2 axes. In other words there is no difference in the properties along the 1 or 2 axes, since both axes are perpendicular to the poling axis. Therefore

$$g_{31} = g_{32}, \tag{2.6}$$

and

$$d_{31} = d_{32}. \tag{2.7}$$

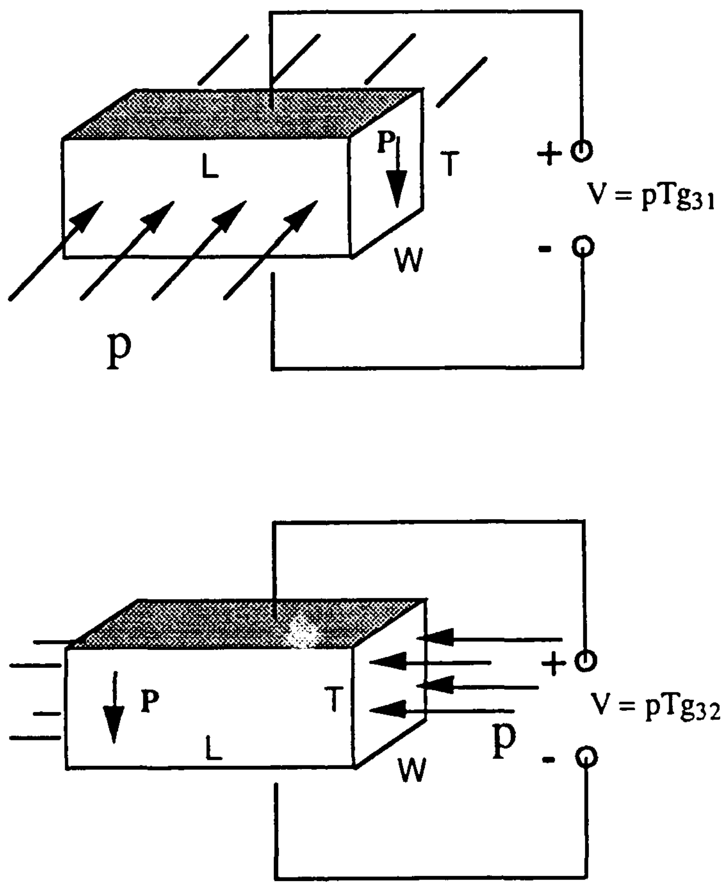


Figure 3. Electrical response of piezoceramic to stresses in the 1 (top) and 2 (bottom) directions.

Consequently, g_{31} and d_{31} will be used to refer to either the 1 or 2 directions.

Piezoceramics can function well as one dimensional vibration sensors, such as accelerometers or vibrometers, and are usually used in the poling direction since they are most sensitive in this direction. However, if a piezoceramic is used as a pressure detecting transducer at low frequencies, then the pressure wave, whose wavelength is long compared to the size of the piezoceramic, essentially squeezes it equally in all three directions. There is another g coefficient that is used to describe the output voltage in this application, called g_H (the subscript H stands for hydrostatic and implies that the sensor is small compared to the acoustic wavelength). The expression for output voltage in this case is the same as in the axial excitation case except that g_H is used instead of an axial g_{xy}. Since the pressure wave, whether in air or water, squeezes the ceramic equally on all sides, g_H is simply the sum of the g parameters in each direction, or

$$g_H = g_{33} + 2g_{31}, \tag{2.8}$$

where $2g_{31}$ is now used to indicate the sum of g_{32} and g_{31}. Equation (2.5) can be written as

$$g_{31} \approx -\frac{1}{2} g_{33} \tag{2.9}$$

and inserted into (2.8) to conclude that

$$g_H \approx 0. \qquad (2.10)$$

Although the g_H for a piezoceramic is not exactly zero, it is a very small number. The point is that the outputs of the 1 and 2 directions essentially work against the output of the 3 direction and therefore the piezoceramic makes a very poor hydrostatic pressure sensing transducer.

The information in this section was compiled from a variety of sources, including the Piezoelectric Ceramics Application Book [2] and the Introduction to Theory and Design of Sonar Transducers [3], (see also [4]). These sources may be consulted for more in-depth information on this topic.

Voided Ceramics

In an effort to make piezoceramics more sensitive to hydrostatic pressure waves, different approaches have been taken. One of the more common methods of accomplishing this has been to keep the 1 and 2 directions unstressed by putting an air cushion around the transverse faces of the ceramic, but not on the poled surfaces. This will not affect the uniaxial (3) response of the transducer, but will keep the transverse (1 and 2) modes from reducing the output voltage of the transducer. In other words this method stops the pressure wave from squeezing the ceramic in all three directions, and just allows the pressure to be applied in the direction of poling where the ceramic is most sensitive. This makes the piezoceramic as effective hydrostatically as it is uniaxially, but in order to achieve this air cushion, a hermetic seal is required around the transverse faces which adds considerable bulk to the transducer. Furthermore, it is difficult or even impossible to realize this air cushion when operating in an extremely high ambient pressure environment such as the deep ocean depths.

Another approach has been to make composite ceramic devices, i.e., to use a material more compliant than the ceramic to interconnect smaller piezoceramics in the transverse plane. Therefore, when the ceramic is squeezed in the 1 or 2 direction, the compliant material, which is not piezoelectric, will get squeezed more than the piezoceramic in those directions and hence the stress will be greatly reduced in those directions. The stress will be largely unchanged in the 3 direction since no compliant material is placed across that axis, so the hydrostatic response of the ceramic composite will be greater. This general class of ceramic design is called the 3-1 composite.

The approach taken by Dr. Manfred Kahn at the Naval Research Laboratory in Washington, D.C. is a mass reducing one. Introducing macrovoids or "air gaps" (see Figure 4) inside the piezoceramic actually reduces the g_{31} coefficient. Dr. Kahn experimented with

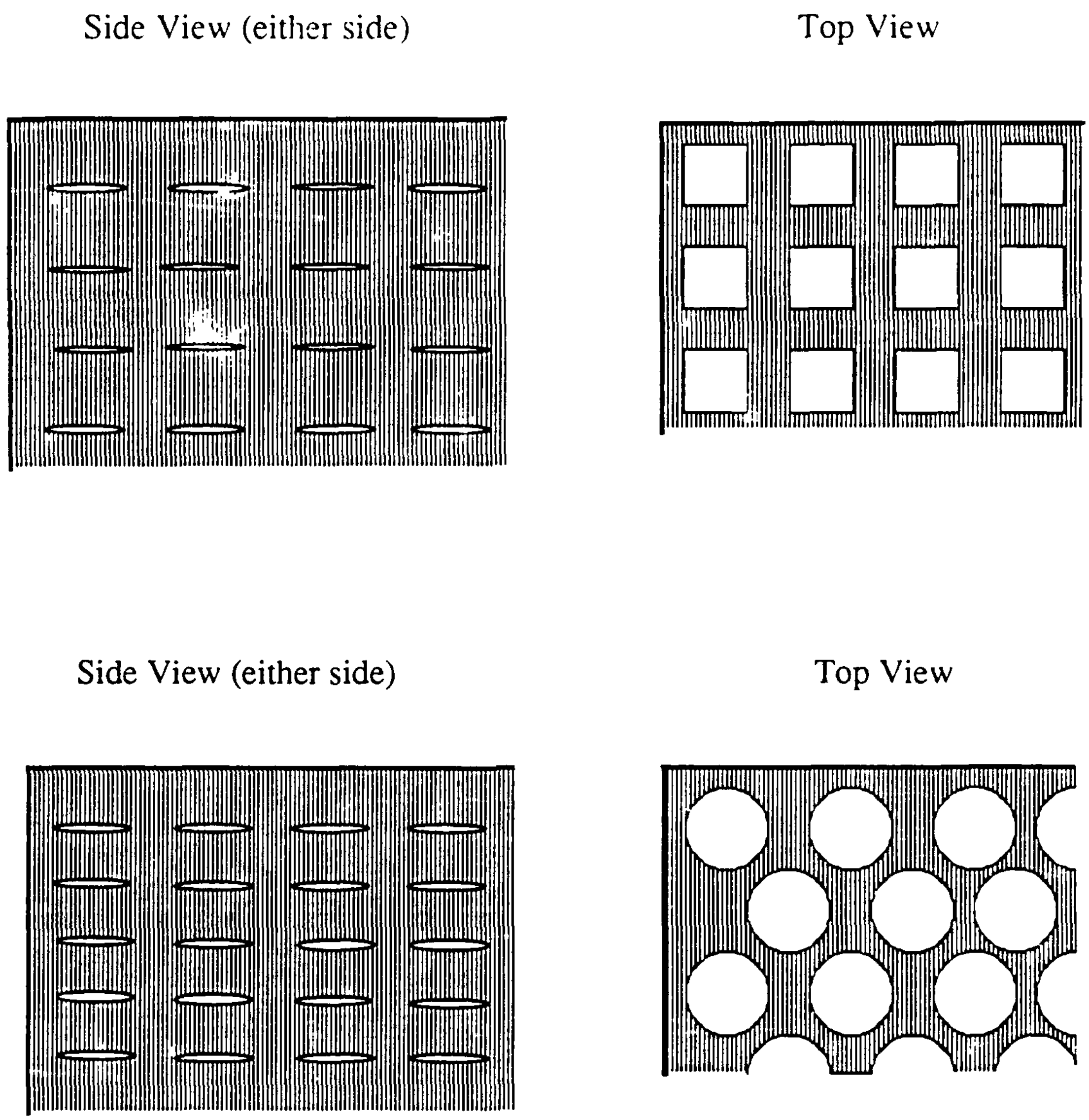


Figure 4. Sections of ceramic showing rectangular (top) and circular (bottom) macrovoids.

different sizes, shapes and orders of macrovoids to find those that significantly reduced g_{31} without affecting g_{33} [5], [6].

The manufacturing of ceramics is done through the use of tape technology. This method consists of stacking up layers of ceramic tape. The stack is then heated to a high temperature or "fired", whereupon all the organic (non ceramic) parts of the tape evaporate out. What remains after firing is a solid piece of ceramic.

To create internal voids in the ceramic, a template is used deposit ink patterns onto the ceramic tape. The ink is primarily carbon with a little bit of ethyl cellulose. The templates have the shape of the voids cut into them and would look like the top views of Figure 4. Pieces of tape with these ink patterns are then stacked up and fired, and during firing the inked parts also evaporate out and leave voids where the ink had been.

Since these voids lower the g_{31} significantly without changing the g_{33}, the resultant ceramic is much more sensitive to hydrostatic pressure. The uniaxial (3) direction is the main contributor to the output with very little cancellation from the transverse (1 and 2) directions.

To get a feel for how these voids actually affect the hydrostatic response, consider a solid piezoceramic block. The ceramic is essentially just a capacitor. When the electrodes or plates of a capacitor are moved closer together, the charge developed yields an increase in voltage. When the plates are moved apart from the equilibrium position, the polarity of the voltage is reversed. In the piezoceramic, pressure in the 3 direction will force the electrodes closer together and produce a voltage increase. Pressure in either the 1 or 2 direction will move the electrodes farther apart and produce a voltage decrease. However, the pressure along either transverse axis does not move the electrodes as far from the center as the same amount of pressure in the 3 direction moved them, because pressure in the 1 or 2 direction will also cause displacement along the other transverse axis. However, applying the same pressure along both transverse axes will move the electrodes far enough apart so that the voltage decrease is essentially equal to the voltage increase caused by the pressure in the axial direction. Therefore, applying equal pressure in all three directions will essentially keep the electrodes in the same place and thereby result in negligible output voltage.

Now consider a voided piezoceramic. The voids make the ceramic more compliant in the 3 direction. Pressure in the 3 direction causes the electrodes to move even closer together than they did in the solid ceramic and produces a higher increase in voltage. However, the design of the voids is such that they don't allow a significant increase of compliance in the 1 or 2 directions. Therefore, the pressure in the transverse directions cannot counteract the effects of the pressure in the axial direction on the electrodes, and an overall output voltage is experienced [7].

The Noise-Suppressing Hydrophone

The Noise-Suppressing Hydrophone is a patented device invented by Dr. Manfred Kahn of the U.S. Naval Research Laboratory in Washington D.C. Prior to this research, the device had never been built or tested and the patent was granted to Dr. Kahn solely on the basis that the device was theoretically sound. The following section describes the theory behind this device (for a more detailed description, see United States Patent number 4,928,264 [1]).

Dr. Kahn's invention is designed to be mounted on a vibrating surface. Its function is to listen to underwater sound signals from distant sources with minimal interference from the vibrations of the mount. In other words, it is to function as a poor accelerometer, but a good hydrophone.

Recall that a solid piezoceramic is a good accelerometer and a poor pressure sensor. The voided piezoceramic is a good pressure sensor, but also a good accelerometer. To achieve good pressure sensitivity and poor axial vibration sensitivity, Dr. Kahn employs both a solid and a voided piece of ceramic. Two piezoceramics of the same dimensions, one solid and one voided, are coupled together such that one is right on top of the other (see Figure 5). They now will experience the same axial disturbances in the 3 direction and, for low frequencies, the same pressure disturbances. The output of one of the two piezoceramics is inverted and added to the output of the other. The solid ceramic senses the vibrations from the mount, but is relatively insensitive to pressure waves. The voided ceramic senses both the mount vibrations and the pressure waves. When the voltage signals from both transducers are added, the output of the solid ceramic cancels out the mount noise signal from the output of the voided ceramic because it is inverted, but it does not cancel out the pressure wave signal. Therefore the sum of the two signals results in mostly the pressure wave signal without the contamination from the vibration of the mount.

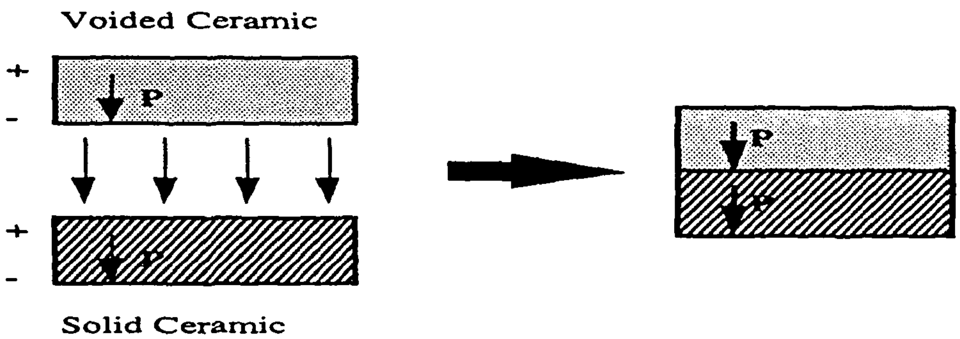


Figure 5. Mechanical coupling between the two ceramics (poling axis is 3 axis).

Figure 6 shows a more complete embodiment of the invention with the electronics components and connections involved. It should be noted that transducers have been used for this application prior to this invention, but the mount vibrations were mechanically damped out using heavy masses or isolation layers were positioned between the transducers and the the vibrating mount [1]. Dr. Kahn's invention is the first to minimize mount noise by electrical means, which eliminates the need for these masses or isolation layers.

Following the construction of the transducers, which will be described in the following chapter, they were tested in two phases. First, the transducers were subjected to an axial vibration in air to test the response to mount vibration. After that the transducers were positioned in an anechoic water tank to test their hydrostatic receiving response. These two phases of testing will be addressed in the following two chapters respectively.

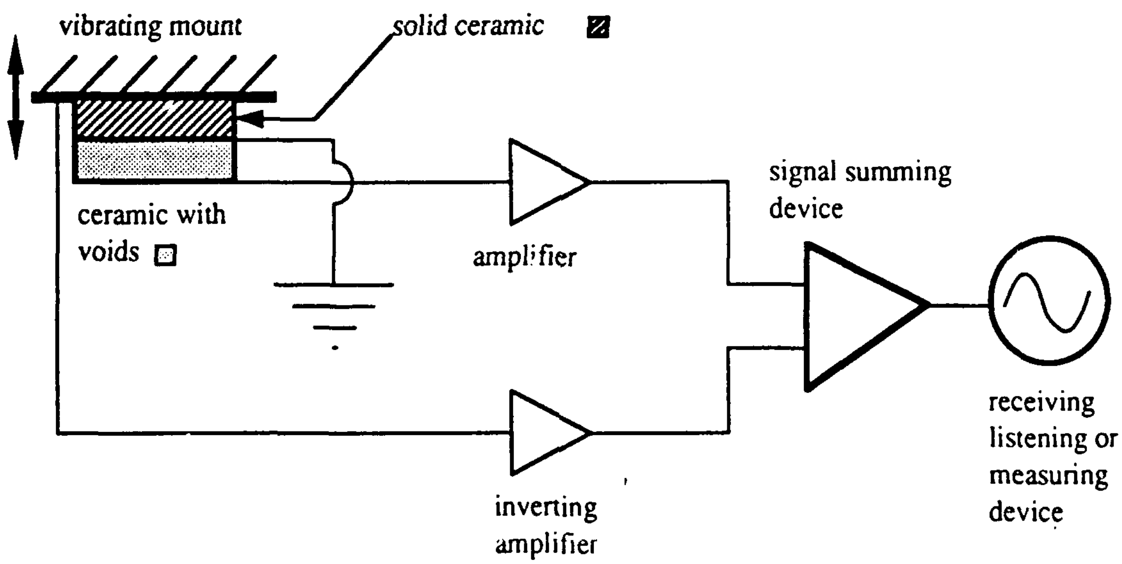


Figure 6. Diagram of Kahn's Noise-Suppressing Hydrophone.

CHAPTER 3

TRANSDUCER CONSTRUCTION AND VIBRATION TESTING

The testing of the Noise-Suppressing Hydrophone was done in two phases. The first phase was a vibration test in air. The second phase was an open circuit voltage sensitivity measurement, which was done underwater. This chapter covers the entire first phase of testing.

Before any tests could be conducted or data taken, the transducer had to be constructed. Following construction, the transducer was subjected to vibration testing. Following these tests, the design was often modified slightly to improve its function under axial vibration, or even to eliminate a potential problem. A new transducer was then constructed, tested and then perhaps remodified.

First Version of the Transducer

The type of piezoceramic used to construct the transducers was PZT-5 which was manufactured by Dr. Manfred Kahn at the Naval Research Laboratory in Washington, D.C. and sent to us in solid and voided pairs. The piezoceramic pieces were rectangular in shape and measured 1.27 cm by 0.95 cm by 0.23 cm. However, since the supply of these ceramics was very limited, pairs of PZT-4 ceramic disks were used for the early tests because there was a plentiful supply of these available. These disks had a diameter of one inch and a thickness of one-quarter inch, and had fired-on silver electrodes. All of these disks were plain solid piezoceramics which were used only for the vibration testing to refine the experimental procedure and evaluate the measurement apparatus. These disks could not be used for the underwater tests due to their insensitivity to hydrostatic pressure.

Construction

The original construction of the transducer included an aluminum shaker mount designed so that the pair of disks could be glued to it and then screwed on to a shaker which would subject them to a controlled axial vibration. The mount was shaped like a hexagonal nut and measured one inch wide across the points, with a threaded hole in the bottom so it could be attached to the shaker using a threaded stud. Also used were two circular grooved nickel electrodes with a diameter of one inch designed specifically for use with the piezoceramic disks, some very thin silver wire, and some Devcon® 5-minute Epoxy. Again recall that both disks were *solid* piezoceramic.

To start with, the top surface of the shaker mount, both surfaces of the electrodes, and all the surfaces of the piezoceramic disks were cleaned using a fiberglass transducer brush to remove stubborn dirt and tarnish. Then they were further cleaned chemically, using the three-step process explained below. The first step is to clean each surface with toluene. This is done by wetting a sterile cotton swab with clean toluene and cleaning each surface with the swab. The second step is to clean each surface with alcohol (either 2-propanol, methanol, or ethyl alcohol) using the same procedure as with the toluene. The final step is to repeat the cleaning process using acetone. The acetone will evaporate off leaving a clean surface. A clean cotton swab was used every time a new cleanser was needed to avoid getting dirt into the clean solution, and rubber gloves were usually used to keep finger oils off the clean surfaces.

Following the cleaning process, a small amount of the epoxy was mixed on a clean surface, using a clean wooden applicator. Once mixed, the epoxy was spread on both sides of one of the electrodes, and then that electrode was promptly sandwiched by the two piezoceramic disks such that the transducer contacted the positive side of one disk and the negative side of the other disk (see Figure 7). The transducers and electrodes were then aligned and placed in a clamp or under some weight at room temperature for about five minutes until the glue hardened. If too much epoxy was used in this bonding process, it was removed with a little acetone while the assembly was held in the clamp. After the epoxy hardened, more epoxy was mixed and spread in the same fashion on the other electrode. That electrode was then sandwiched between the top

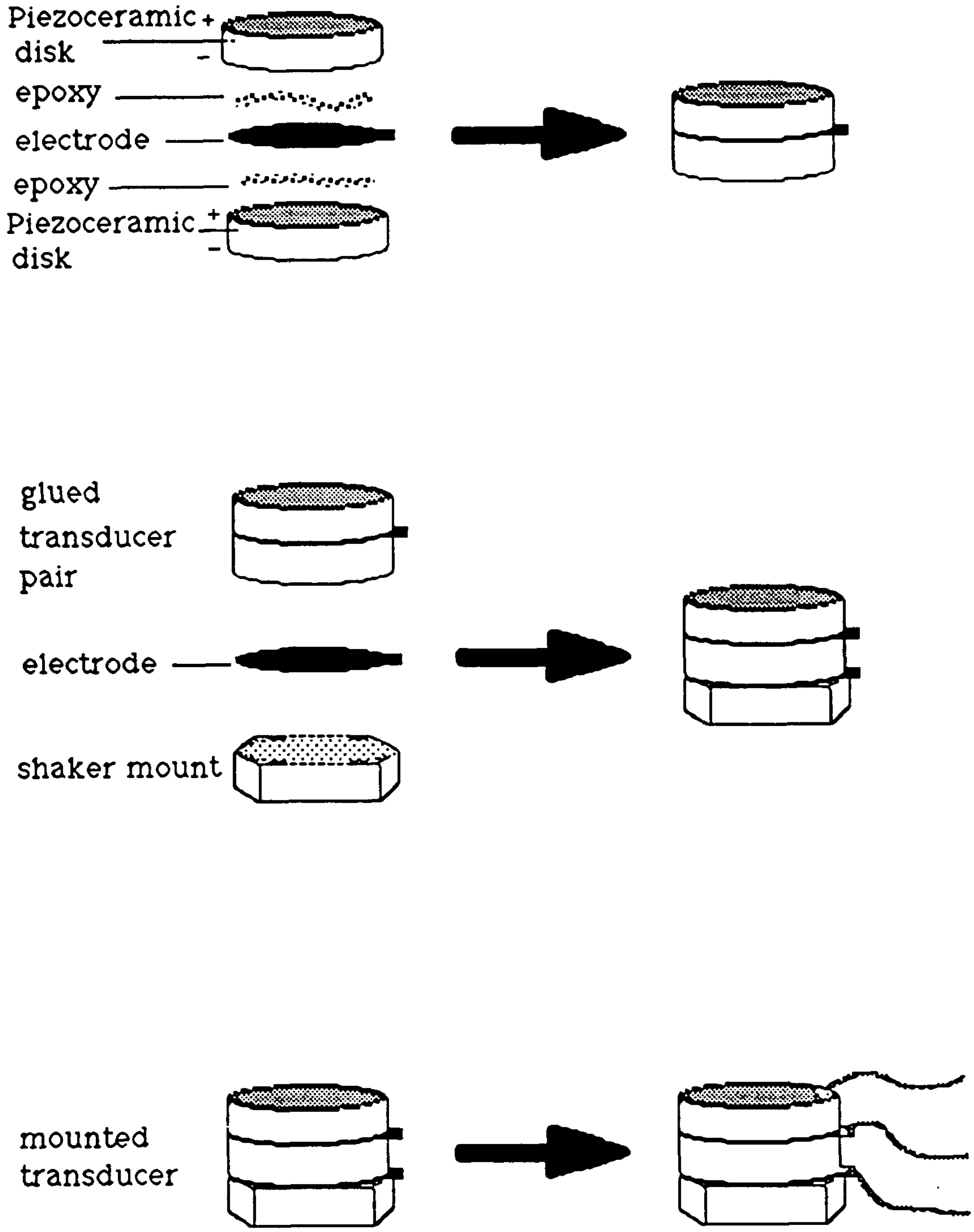


Figure 7. Transducer assembly using two solid piezoceramic disks

surface of the shaker mount and the bottom surface of the recently bonded transducer pair (see Figure 7). The parts were again aligned, clamped and the excess glue removed if necessary. After another 5 minutes, the transducer was removed from the clamp. Wire was then soldered carefully to the top electroded surface of the assembly as well as to both electrodes using low temperature solder, creating a total of three wire leads from the transducer pair (see Figure 7). This completed the construction process, and the transducer was then ready for the vibration test.

Vibration Testing Apparatus

Uniaxial vibration of the piezoceramics was achieved using a Wilcoxon Shaker (Model F3 Wrap-Around Driver with Z602W Impedance Head). The shaker was fastened to a workbench using a homemade clamping unit, and the piezoceramic pair was fastened to the shaker using a threaded stud which was screwed all the way into the shaker mount, and then screwed down onto the shaker. The threading in the shaker mount was the same as the thread of the shaker, and the threaded stud was cut so it was just a little shorter than the combined length of the holes in both the shaker and shaker mount, so that the surfaces of the shaker and mount would be flush against each other when tightened.

The shaker was driven by a McIntosh MC-30 audio amplifier and a signal generator (JDR Instruments Audio Oscillator Model DOS

600) which generates sinusoids at various frequencies and features a built in frequency counter. Each piezoceramic was connected to its own amplifier (two Ithaco modular amplifiers model 257A were used). The output of one of those amplifiers was sent directly into an inverter (a homemade inverting amplifier with a gain of unity, see Figure 8) and into a signal summing box (another homemade apparatus). The output of the other amplifier was sent directly to the summing box. The output from the summing box was connected to a Fluke 8000A Digital Multimeter which was used as a voltmeter to measure the final sum of the two signals (see Figure 9(a)). A BK Precision 20 MHz oscilloscope (model 2120) was frequently used to look at the output signals, either individually or in combination. When the phase difference between the two output signals was to be recorded, it was measured using an Ono Sokki CF 350 portable dual channel FFT analyzer (see Figure 9(b)). All the equipment was thoroughly tested to insure that it was functioning properly.

Alternatively, the signal from one piezoceramic piece could be inverted by positioning the piece so that its direction of polarization is in the opposite direction compared to that of the other. This causes the output signal of each transducer to be opposite in sign from one another and eliminates the need for the inverting amplifier. However, using the inverting amplifier proved to be more desirable since some 60 Hz noise would be inverted and subtracted from the net output, yielding a cleaner signal.

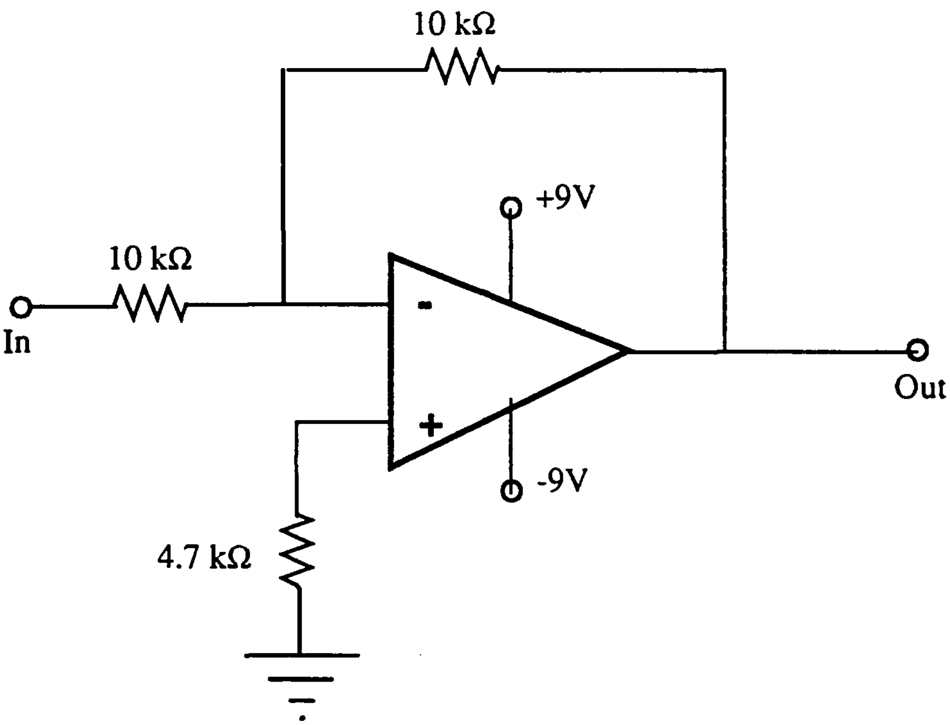


Figure 8. Circuit diagram for the inverter (an inverting amplifier with a gain of unity) used to invert the phase of one of the signals. The op-amp used was a PMI OP16

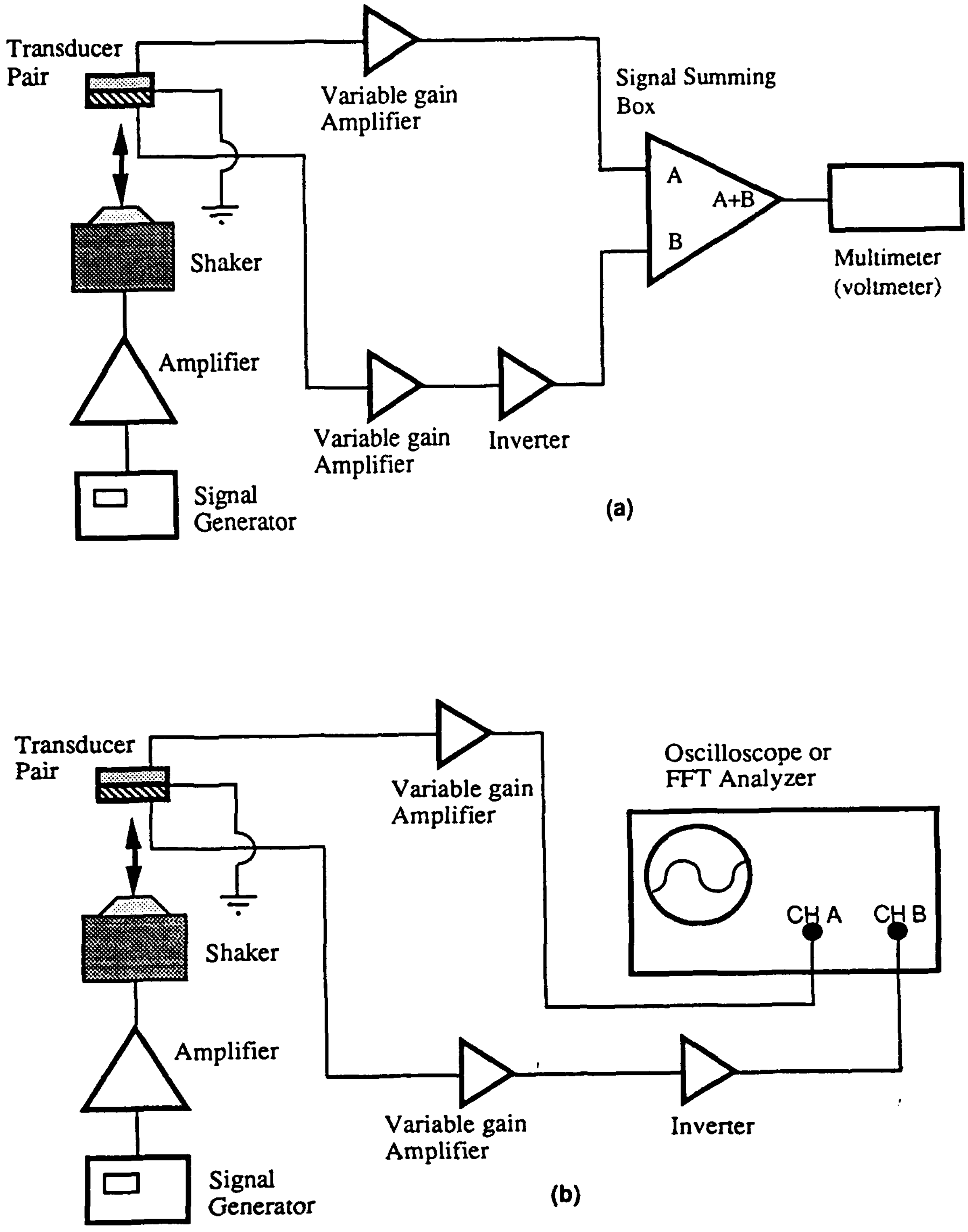


Figure 9. Setups used for uniaxial vibration testing (a) using a voltmeter and (b) using an oscilloscope or FFT analyzer.

Observations and Results

When using the vibrational testing apparatus to observe the output of the first transducer, a couple of problems were noted immediately. First, there was a lot of noise present in the output signals of the transducers. Second, the output signal of the inner or bottom transducer was much larger than that of the outer or top transducer. This was due to the fact that the inner transducer was mass loaded by the outer one, and the problem was overcome simply by boosting the gain on the variable amplifier of the outer transducer until both signals were equal in amplitude. The noise problem was reduced by using coaxial cable between the piezoceramics and the modular amplifiers, and keeping the cables as short as possible (usually about a foot). The coaxial cable was still attached to the couple of inches of very thin wire that constituted the output leads of the piezoceramic pair. To inhibit noise pickup by those thin wires, a grounded wire cage was placed over top of the shaker and transducer and the thin wires were positioned inside of this cage. This noticeably reduced the noise pickup.

No quantitative data were taken for the first version of the transducer, yet after qualitative observation it was apparent that it would not yield good cancellation because of a constant phase difference that existed between the two ceramics at low frequencies (2 kHz and below). The output from the top or outer ceramic lagged that of the bottom or inner ceramic by a phase angle of about 20 degrees. Because of this, the best reduction possible by adding the two signals was only about 6 dB.

Second Version of the Transducer

In an effort to reduce the phase difference between the two ceramics, the design was modified slightly. A very thin brass electrode was used between the two ceramics instead of the nickel electrode used in the last version, to see if that change would reduce the phase between the outputs of the piezoceramics. No quantitative data were taken for this version of the design either, but the improvements in the phase lag were negligible if any. The reduction from adding the two signals was still not sufficient to be effective.

Third Version of the Transducer

Construction

Due to the lack of success of the first two versions of the coupled piezoceramics, the construction of the transducer was further modified to try and improve the results. First of all, Dr. Kahn's paired pieces of PZT-5 were used instead of the PZT-4 ceramic disks. This was because it was suspected that the fired-on silver electrodes of the original disks were contributing to the phase difference between the two ceramics. Dr. Kahn's PZT-5 samples had extremely thin gold sputtered electrodes as well as polished electroded surfaces which hopefully would improve mechanical coupling of the piezoceramics. Also, the electrode between the two ceramics was eliminated. This was accomplished by beveling one edge of each rectangular piece on the face where the other piece would be attached. The beveled edges were placed opposite each other (as shown in Figure 10) and then the two piezoceramic pieces were glued together. The electroded surfaces of the ceramics now contacted each other directly and wires were attached to those inner electrodes along the grooves created by the bevels using a conductive epoxy (Acme E-Solder® 3021). This epoxy was also used to attach the wire to the top surface of the top piezoceramic piece. Instead of the 5-minute Epoxy, contact cement (Krazy Glue®,a cyanoacrylate) was used to glue the two ceramics together since bonding is achieved with an extremely thin layer of this cement. The thin brass electrode was still used between the inner transducer and the shaker mount (see Figure 10), and 5-minute Epoxy was still used to glue the transducer and electrode to the shaker mount (which was the same mount used with the ceramic disks).

This new version of the transducer showed considerable improvement over the previous ones in terms of mechanical coupling and phase. Since reasonable cancellation was now possible at the lower frequencies, quantitative data were recorded.

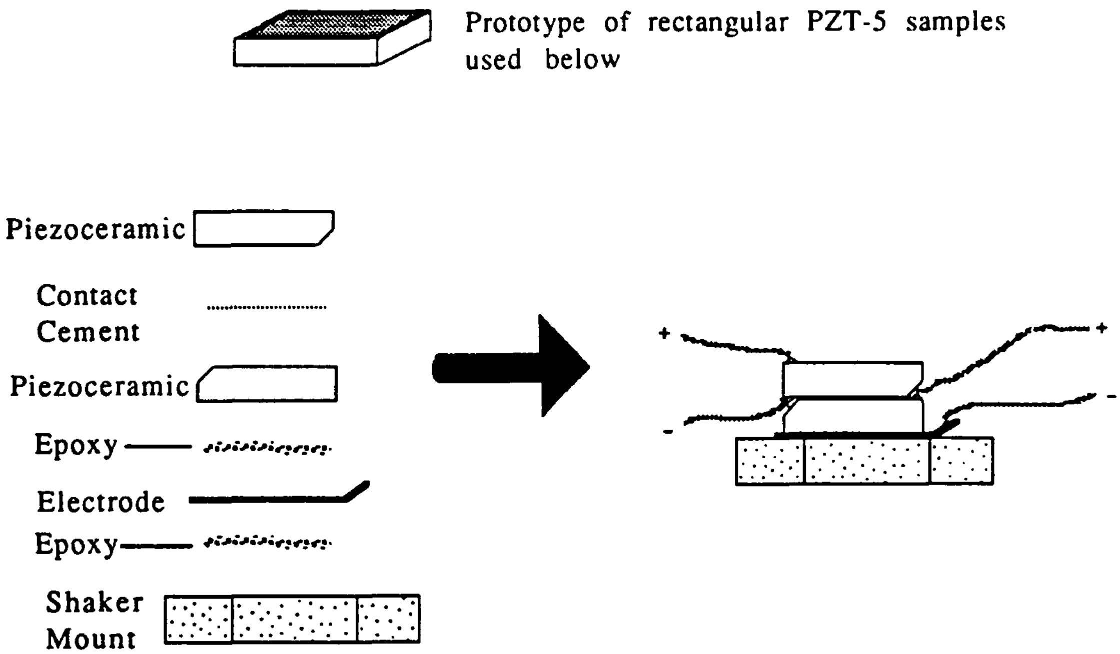


Figure 10. Transducer assembly using two rectangular pieces of PZT-5.

Testing Procedure

Since the data taking was a completely manual process, it was rather involved and time consuming. The process is explained below. Following the construction of the transducer, which usually involved letting it sit overnight so that the conductive epoxy of the leads could harden, the transducer was firmly screwed onto the shaker using the threaded stud. The leads from each piezoceramic were then attached to their respective amplifiers and then to the oscilloscope (see Figure 9(a)). A signal was then sent from the signal generator to the shaker, and the output of each piezoceramic was observed on the oscilloscope. Adjustments were made for noisy signals (usually by either repositioning the small wires or surrounding the entire transducer with the grounded cage), and then using a frequency around 3 to 5 kHz, the amplitudes on the Ithaco amplifiers were adjusted to make the signals from each of the piezoceramic pieces as close as possible in amplitude. The oscilloscope allows one to add both of its input channels and observe the sum while manually sweeping across the range of frequencies to be tested. This provides a qualitative preview of the data to be recorded.

The frequency range used for the testing was 2 kHz to 20 kHz. This range was selected rather arbitrarily; however it was necessary to use the same frequency range in the underwater tests conducted in the anechoic tank. The tank size is such that it is not feasible or accurate to record signals much below 5 kHz. This range also allows the activation of a filter included in the Ithaco amplifiers that rolls off at frequencies below 1 kHz, thus filtering out a lot of unwanted low frequency noise.

After observing the signals on the oscilloscope and adjusting the amplifiers to yield the best possible cancellation of the two outputs, the two signals were connected through the signal summing box into the multimeter (as shown in Figure 9(b)) which was set up to record voltage. Then, starting at one end of the frequency range (usually the lower end) the driving frequency was manually increased at the signal generator and its value was observed on the built in frequency counter. At each integer frequency, i.e., 5.0 kHz, 6.0 kHz, etc, the combined output voltages of the piezoceramic pair were recorded. Also, the output of each individual piezoceramic piece was recorded by disconnecting the other one from the summing box. Then, at the same driving frequency, the leads were disconnected from the signal summing box and connected to the FFT analyzer (as in Figure 9(a)) which could measure the difference in phase between the two channels. This phase difference was recorded, the leads were connected back to the signal summing box, the driving frequency was changed to the next increment, and the entire process was repeated (in increments of 1 kHz, ±0.02 kHz) throughout the testing range. Note that the signal generator used is only capable of generating sine tones, so that the signals driving the shaker and the transducer are always sinusoids.

Afterwards, the data were converted to an attenuation level in dB using the equation

$$\text{attenuation level} = 10 \log (V_t / V_s)^2 \qquad (3.1)$$

where V_t is the output voltage of one piezoceramic piece and V_s is the sum of the two voltages. This attenuation level was calculated for each piezoceramic piece since the output voltages were usually different.

Data and Results

To establish some criterion of what level of attenuation was expected, a scale will be described hereafter. An attenuation of 20 dB or more is the ideal. Between 14 to 20 dB was considered good attenuation. Between 10 and 14 dB was considered fair and 10 dB was still acceptable. However, an attenuation of less than 10 dB was considered poor.

The third version of the transducer was the first time that a voided piezoceramic was used in the testing process. When the transducer was built the voided piezoceramic was arbitrarily placed on the bottom so that it was mass loaded by the solid piezoceramic. After the amplitudes were matched at a low frequency, the transducer performed quite well, and subtracting the two signals yielded attenuation levels of well over ten decibels. However, as the frequency was increased, there was a large increase in output from one piezoceramic that was not matched by the output of the other one, as well as a change in phase between the two signals that occurred around 8.5 kHz. These characteristics resulted in very poor cancellation between the two signals (see Figure 11).

These amplitude and phase changes then continued to occur as the frequency sweep continued upwards to the top of the frequency

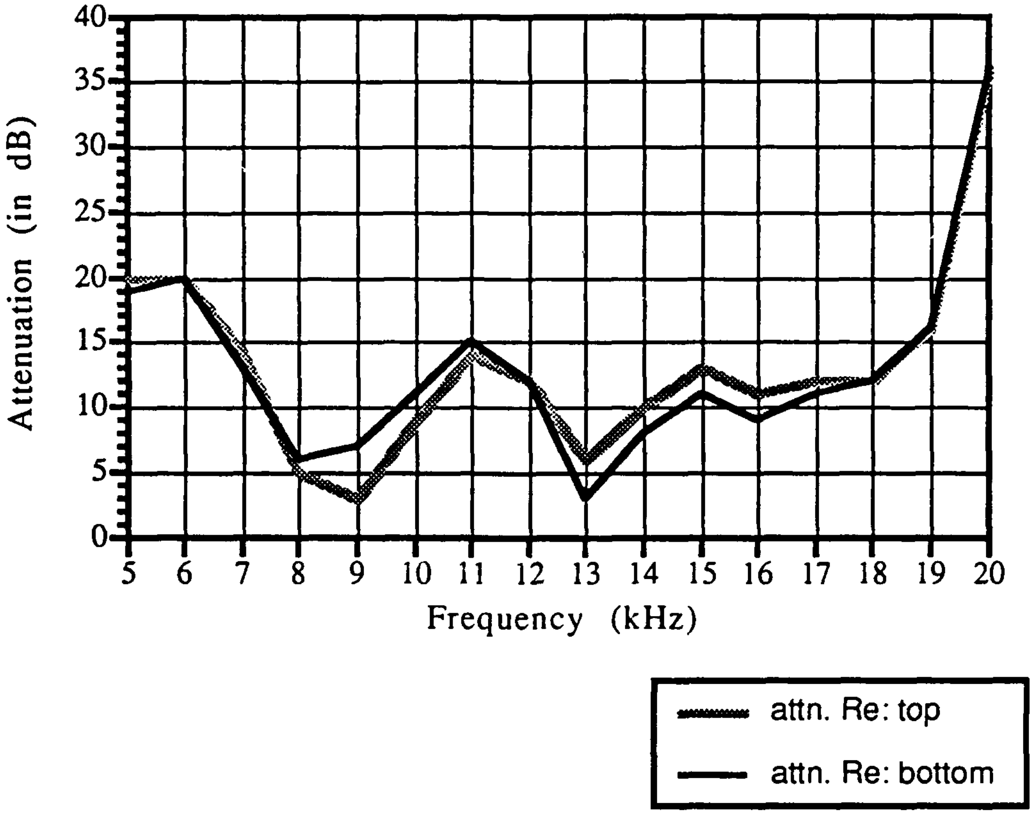


Figure 11. Attenuation vs. frequency of the transducer held together with contact cement. Voided piece on bottom.

range. Closer observation revealed that the voltage output of the bottom (voided) piezoceramic piece was relatively constant over the frequency range and that the radical changes in amplitude were coming from the top (solid) piece. Another transducer was built, this time with the solid piece on the bottom and the voided piece on top, to see if it would make any difference. Testing this piece yielded similar results, with good cancellation until around 8 kHz and then inconsistent results above that frequency (see Figure 12). Also, the amplitude and phase changes were still exhibited in the top piece even though it was now a voided piezoceramic. The bottom (now solid) piece seemed to produce a steady uniform output over the entire frequency range.

A few other transducers were constructed and tested in this fashion; however the results were similar for all of them. It was strongly suspected that there was some sort of resonance occurring between 8 and 9 kHz which was perhaps causing poor mechanical coupling between the two pieces. The individual resonances of the piezoceramics were tested (using a Hewlett Packard HP4192A Impedance Analyzer), but the resonances of each individual ceramic were well above 100 kHz. When coupled, the resonances of the pair were brought down to around 55 to 65 kHz and were still much too high to influence the results at the low frequencies being tested.

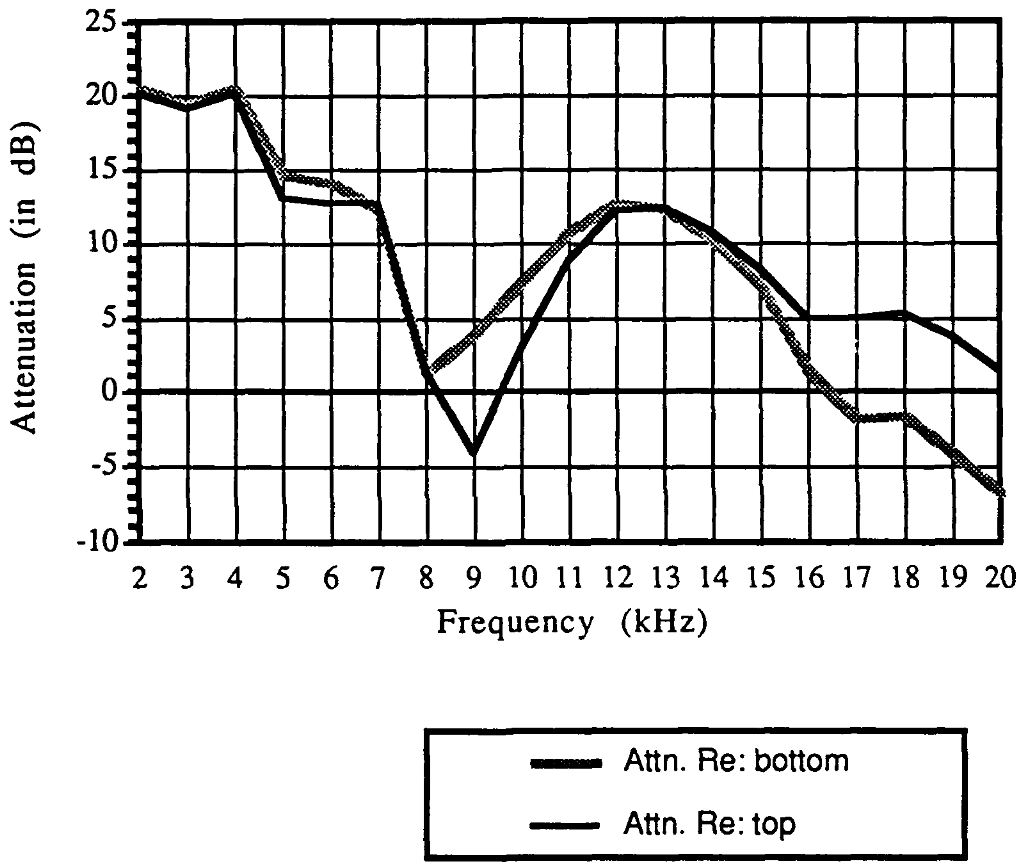


Figure 12. Attenuation vs. frequency of another variation of the transducer held with contact cement. Voided piece on top.

Fourth Version of the Transducer

One possibility for the cause of resonance was that there was some resonance due to the glue being used. Not much was known about the properties of the Krazy Glue® used, so another transducer was constructed using a different type of glue.

Construction

The next version of this transducer was built just like the last one (keeping the voided piece on top), except that a Shell 828 epoxy (Shell Chemical Company EPON® Resin 828) was used between the transducers instead of the Krazy Glue®. The glue consists of the Resin 828 and an EPON® Curing Agent V-40 packaged in separate bottles. The resin was mixed with the curing agent 100% resin to 75% curing agent by weight. The piezoceramics were glued together and then put in an oven and baked overnight at 140 degrees Fahrenheit.

Data and Results

When this transducer was first tested, ten days after the shell 828 was cured, the results were not at all impressive. There was a significant phase difference between the two signals from the piezoceramics at even the low frequencies, and it got worse at the higher frequencies tested. Therefore it was thought that perhaps the contact cement created the best bond between the two piezoceramics, and the focus shifted back to improving on the contact cement version of the transducer.

However, a couple of months later (about three months after the glue had been cured) this transducer was tested again, just to once again verify its lack of effectiveness. This time the transducer showed considerably better results, although it still exhibited resonances above 8 kHz (see Figure 13).

Although much better than the data taken right after the transducer was constructed, this transducer was still no improvement over the one held together with the contact cement. In fact, it was even worse above the lowest resonance (around 8.5 kHz) because at some frequencies a negative attenuation was recorded with reference to the bottom transducer. The only significant information that could be gathered from this data was that the first resonance still occurred at approximately the same frequency as it did with the last version of the transducer, and therefore implied that the resonance had been caused by something other than the glue.

Other Versions of the Transducer

Various modifications were made to try and isolate the cause of the resonances. The fact that any resonance was occurring at all was

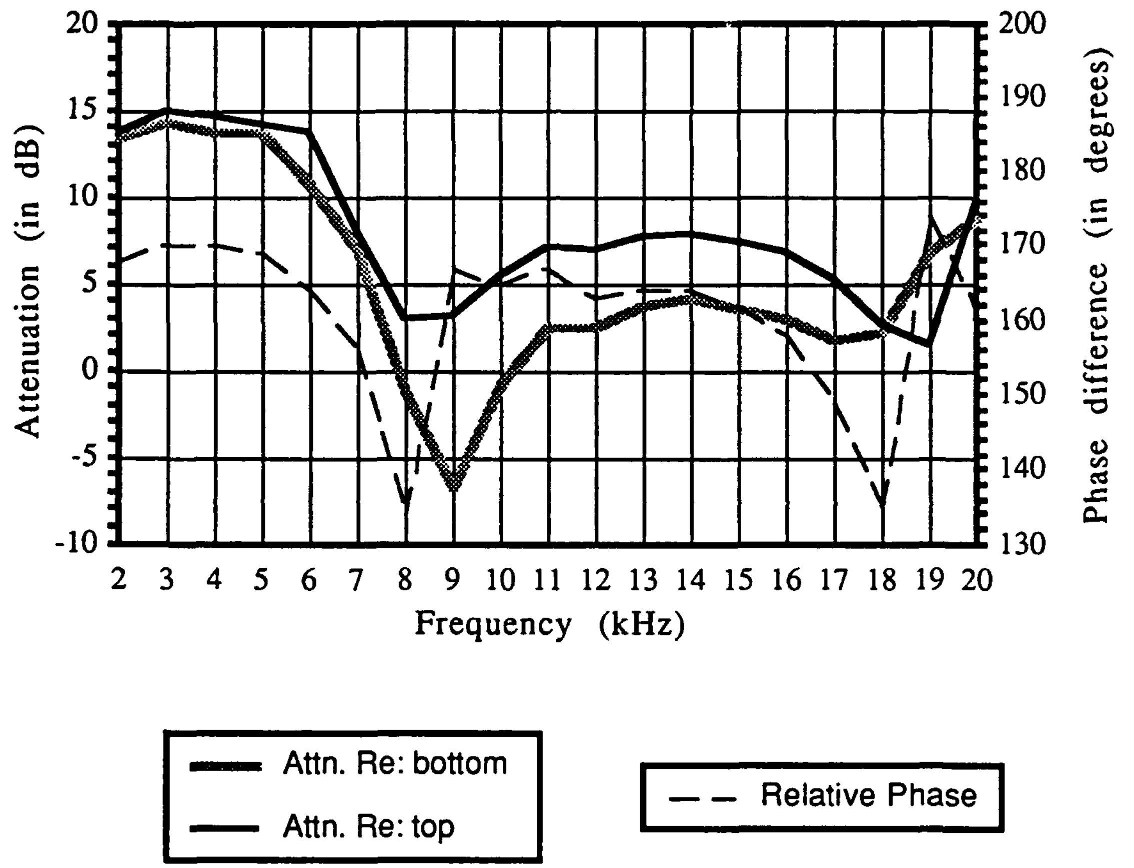


Figure 13. Attenuation vs. frequency of transducer bonded with Shell 828 epoxy. Voided piece on top.

somewhat unexpected, since the transducer and its piezoceramic components are small compared to any of the wavelengths of the testing frequencies. One theory was that the resonance was actually in the shaker mount (perhaps a bending mode in a free-free bar fixed at its center), so another mount was constructed. The new mount was smaller in diameter and much thicker, so that if the resonance was due to the mount it would now be much higher in frequency and maybe not even be seen in the testing frequency range. A transducer held together with contact cement was constructed using this new mount, and it was put through the vibration test. The troublesome frequency did not change, however, and the results were basically the same as with the original mount.

Since neither the mount nor any of the equipment seemed to be the cause of the resonances, it was suspected that the problem was occurring inside the actual transducer pair. From observations of the signals on the oscilloscope, the resonances seemed always to be associated with the top piezoceramic whether solid or voided. The lowest resonance seemed to occur at the same frequency regardless of the glue used. Applying a force to the top surface of the transducer did not improve the coupling or affect the resonance. Adding a mass on the top surface of the transducer did not eliminate the resonance either, but sometimes created problems at lower frequencies also. Adding the mass on the short edge of the transducer had a significantly greater effect on changing the frequencies of the resonances. This suggested lateral modes of vibration in the piezoceramic.

The transducer was also analyzed one piezoceramic at a time. That is, the solid ceramic was glued on the mount by itself with 5-minute epoxy. It was then put through the vibration test and showed no resonances. A voided piezoceramic was also glued onto the mount by itself, this time using contact cement. This piece showed resonances between 8 and 9 kHz and higher. This implied that the resonances were a result of either the glue or perhaps the glue in combination with some property of the ceramic.

There was still no solid evidence as to what the cause of the resonance was. It was apparent that the resonance would need to be studied in depth and a modal analysis of the piezoceramic was required in order to understand why the resonance was occurring.

Fifth Version of the Transducer

It was noted in the single-piezoceramic analyses that the 5-minute Epoxy seemed to offer some degree of stability to the piezoceramic. Since that epoxy had never been used between the rectangular piezoceramics, a transducer was constructed using 5-minute Epoxy instead of contact cement to bond the piezoceramics together (the voided piece was still kept on top).

The result was a transducer that was much improved over the frequency range. The resonance was still present between 8 and 9 kHz, as were the higher frequency resonances, but the coupling between the piezoceramic pieces was much better (see Figure 14). As a result, the resonances were not as devastating to the cancellation process. The minimum attenuation achieved was 10 dB at 19 kHz, while it was as large as 28 dB at other frequencies.

Since the average attenuation of this version of the transducer is over 15 decibels, and there is no frequency where the attenuation is less than 10 decibels, the transducer is the only one that performed effectively over the entire frequency range. Therefore, it can be concluded that the transducer is able to perform its function as a relatively insensitive accelerometer.

Error and Discussion

The data shown in this chapter are samples of a considerable amount of data gathered over a long period of time. The quantitative consistency of the data could vary quite a lot, but qualitatively they were quite consistent. Looking at results from multiple testing of the same transducer, the data were often very inconsistent at frequencies above the lowest resonance. Below that resonance, there was a lot more stability.

There were many factors that could cause variation in these results. One was the climate conditions in the laboratory, which could affect the properties of the glue, the length of the threaded stud, and

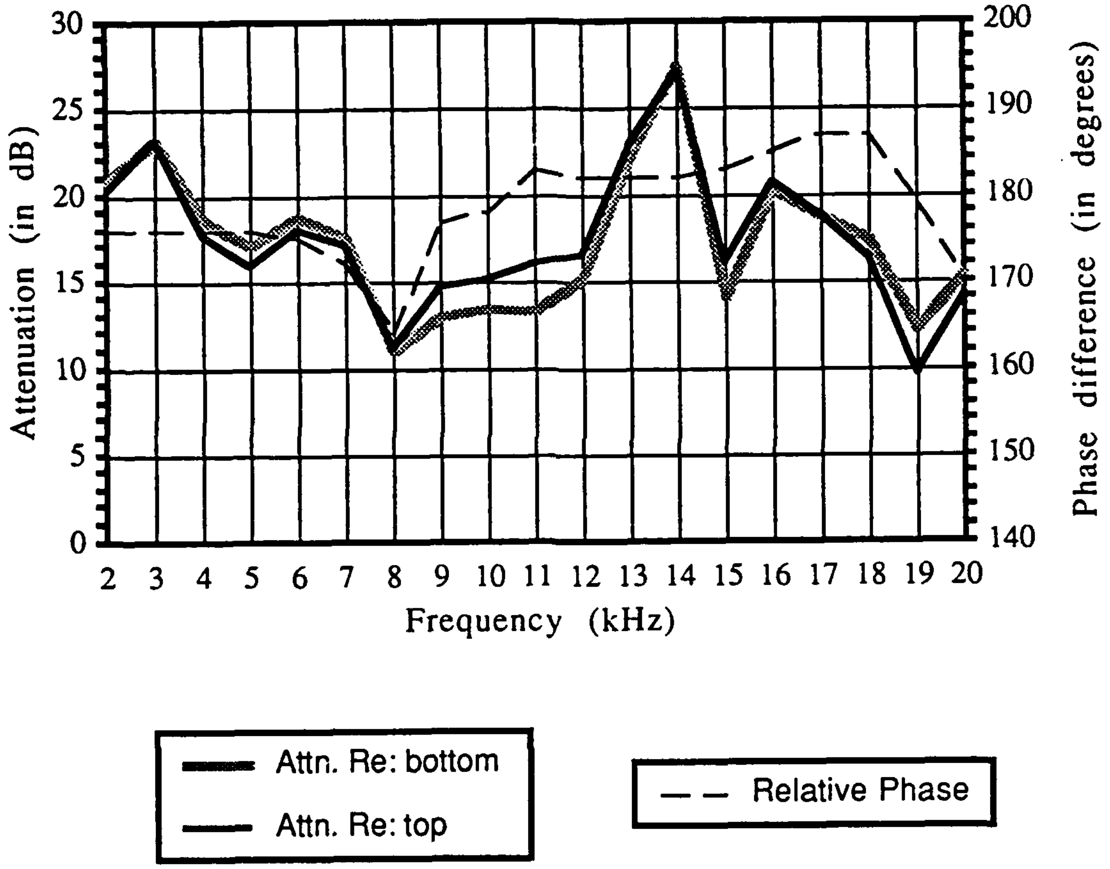


Figure 14. Attenuation vs. frequency of transducer bonded with Devcon® 5-minute Epoxy. Voided piece on top.

other key properties of the transducer and apparatus. Also, certain parts of the experiment could not be kept consistent. For example, the amplitude of the signal driving the shaker was never the same, and could not be gauged with the apparatus available. Still, if the mechanical coupling between the transducers is good, this should not make much of a difference, even if significant distortion is present. Another factor that could not be gauged, but could make a significant difference from transducer to transducer is the exact amount of glue used in the bonding process.

One factor that could have affected the consistency of the results and the cancellation process is the amplification of the piezoceramic output signals. Although the same type of amplifier was used for both of the piezoceramics, the one amplifying the signal from the top piezoceramic receives a much weaker signal and is required to amplify that signal 30 to 40 dB more than the other amplifier. This could cause distortion in one amplifier which could subsequently affect both the attenuation and the consistency of the data.

The frequency counter on the signal generator was known to be rather imprecise, which can allow for some inconsistency and error along the frequency axis. For the most part, however, the data are pretty consistent in indicating whether the attenuation is significant or not and whether the transducer is effective or not.

A key factor in achieving good coupling of the piezoceramic pieces was to make sure that the electroded surfaces of the pieces were polished. The pieces sent to us by Dr. Kahn were not always polished, and the thicknesses of the sputtered-on gold electrodes were not always constant. To create more consistency between the individual pieces of ceramic, the electrodes were sanded off the surfaces of each piece using 400 grade sandpaper, and then the surfaces were polished using 500 grade sandpaper and then either aluminum paste or 1000 grade sandpaper. The pieces were cleaned with acetone and then sputtered on gold was re-deposited on the polished surfaces.

The polishing and sputtering was done at the Materials Research Laboratory (MRL) at The Pennsylvania State University. The surfaces were sputtered for exactly a minute and 20 seconds using the machine at MRL which corresponds to depositing a layer of gold around 400 angstroms thick. The gold surfaces must be as thin as possible, but thick enough to read less than 10 Ω on an ohmmeter with its probes positioned about a quarter inch apart.

CHAPTER 4

FREE-FIELD VOLTAGE SENSITIVITY MEASUREMENT

This chapter covers the second phase of testing, which was to measure the free-field voltage sensitivity of the transducer when used as a hydrophone. The free-field voltage sensitivity, M_O, of a transducer is the voltage generated by the transducer as a result of an incident plane wave of unit pressure coming into contact with it. The free-field voltage sensitivity is also called the open circuit voltage sensitivity, since the voltage is measured across the open circuit terminals of the transducer. Free-field voltage sensitivity is expressed in units of dB (re 1V/μPa).

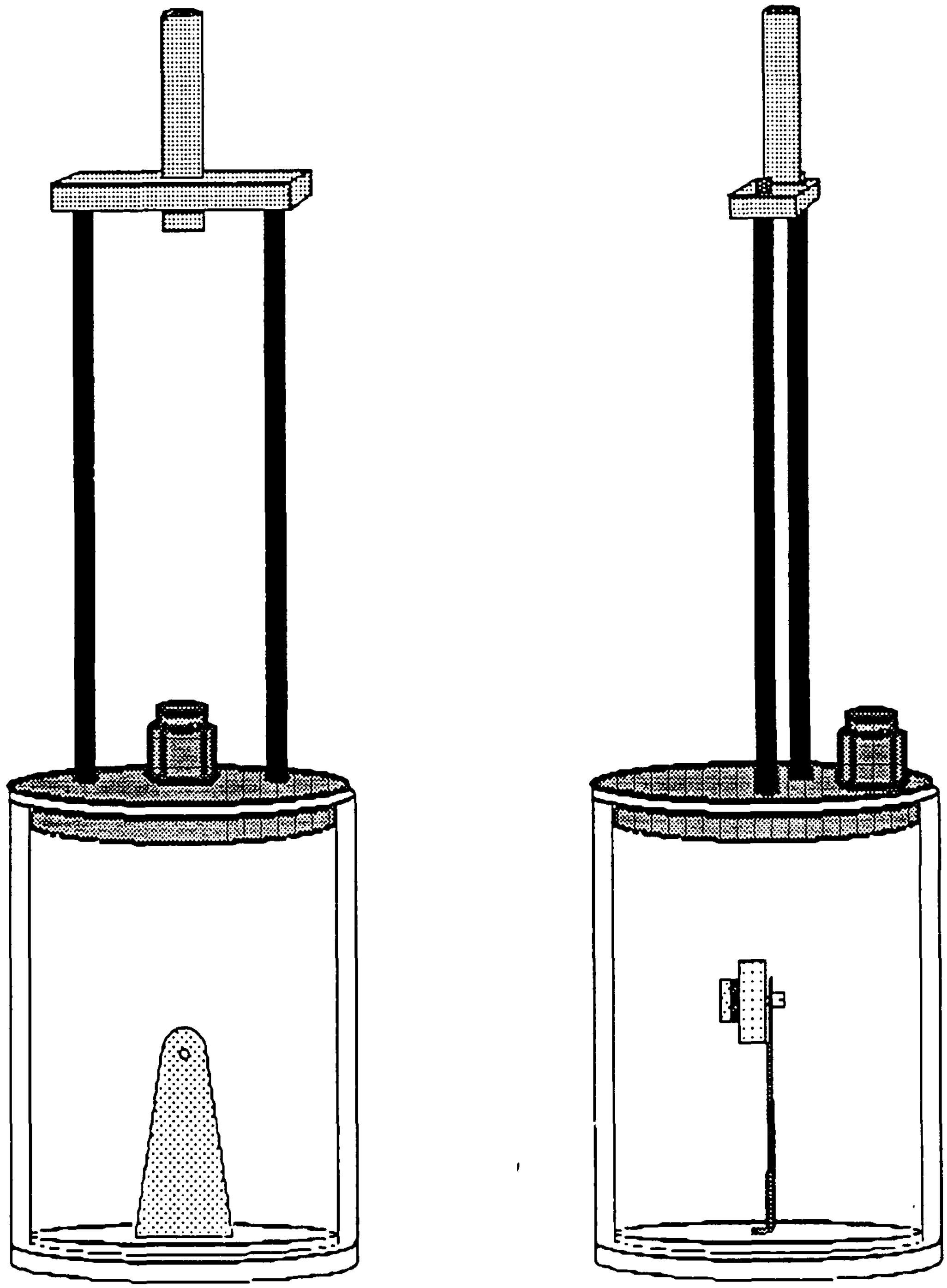
Therefore, to conduct this evaluation of the transducer, it had to be placed in a simulated free-field and be subjected to incident plane waves across the testing frequency range while its output voltage was measured. Since the transducer was designed as a hydrophone, this test was conducted underwater in the anechoic tank at the Applied Research Laboratory.

Measuring Apparatus

The transducer could obviously not be placed directly into the water or its electrical terminals would short out. Castor oil has approximately the same acoustic impedance as water and does not conduct electricity. Therefore, a castor oil chamber was used to protect the transducer from the water. The walls of the chamber are made of a transparent plastic which also has approximately the same acoustic impedance as water. Therefore, when the oil chamber is filled with castor oil and placed underwater, the whole container is acoustically transparent. Hence a pressure wave will pass right through the walls of the chamber and the oil as if it were water and a transducer sitting inside the chamber is subjected to the wave just as if the transducer were sitting directly in the water.

The oil chamber was essentially a piece of clear plastic tubing six inches long with an outer diameter of three and a half inches and walls an eighth of an inch thick. The two ends were sealed with two lucite lids which fit snugly into the open ends of the tubing, and were sealed using large hose clamps (see Figure 15).

Attached to the bottom "lid" was a metal mounting bracket to which the transducer mount used in the last experiments could be directly attached. The transducer was mounted with a nylon screw which left the transducer positioned more or less in the center of the



(a) (b)

Figure 15. Front view (a) and side view (b) of oil chamber used to protect the transducer from the water. The mounting bracket without the transducer can be seen in the front view. The side view shows the transducer mounted inside with the incident wave travelling left to right.

chamber and facing the cylindrical wall. The top "lid" had a brace attached to it which was used to connect the oil chamber to the mechanical arm that would lower and hold the chamber in the water. This top also had a bulkhead connector to which a special 8-pin shielded cable could be attached. The connecting pins ran through this lid and into the oil chamber, where the electrical leads from the transducer could be soldered. The cable made a watertight seal by screwing tightly into the bulkhead connector.

The anechoic water tank at the Applied Research Laboratory has water filled dimensions of 17.5 feet wide by 26 feet long by 18 feet deep. The top of the tank has two large steel beams which run the length of the tank and support a telescoping tube positioner and a separate hydrophone support cart used for mounting and positioning transducers inside of the tank. Standard tests are set up so that the separation distance between source and receiver is 3.16 meters which, assuming far-field conditions exist, corresponds to a 10 dB spherical spreading loss.

The boundaries of the tank are lined with acoustic absorbing material to help simulate a free-field underwater environment; however there are still significant reflections at these boundaries. A pulsed sound technique is used to eliminate the effects of the boundary reflections; however even with this technique, the finite size of the tank and the associated electronic instrumentation still impose a low frequency limit of 5 kHz.

The setup and apparatus used for measurement was that used by the Transducer Group at the Applied Research Lab and is shown in Figure 16. The apparatus was all controlled by an HP-9000 (model 320) computer. An HP-33330B frequency synthesizer was used to generate sinusoids for the source, and an HP-3570A network analyzer was used to receive and measure the output and input signals. A Dranetz digital tone burst timing generator was used to gate the continuous signal to a pulse (whose length can be specified) and also gates the times at which the output signal from the receiver was measured. An HP-59307A VHF switch was used to switch the signal to the network analyzer back and forth from the source to the receiver. Also, an HP-59306A relay was used as an attenuator, and an Instruments Incorporated power amplifier and voltage and current sensor were used to power and monitor the source transducer. The source transducer was a USRD Type F33, which is also a piezoceramic transducer.

The two variable amplifiers (Ithaco model 257A), inverter, and summing box used in the vibration tests were also used between the test transducer and the network analyzer. Also, two wide band preamplifiers with a fixed gain of 12 dB (see Figure 17) were used to boost the signals of the piezoceramics in the oil chamber and negate the capacitance effects of the cable. A Lambda® regulated power supply was used to power the preamps.

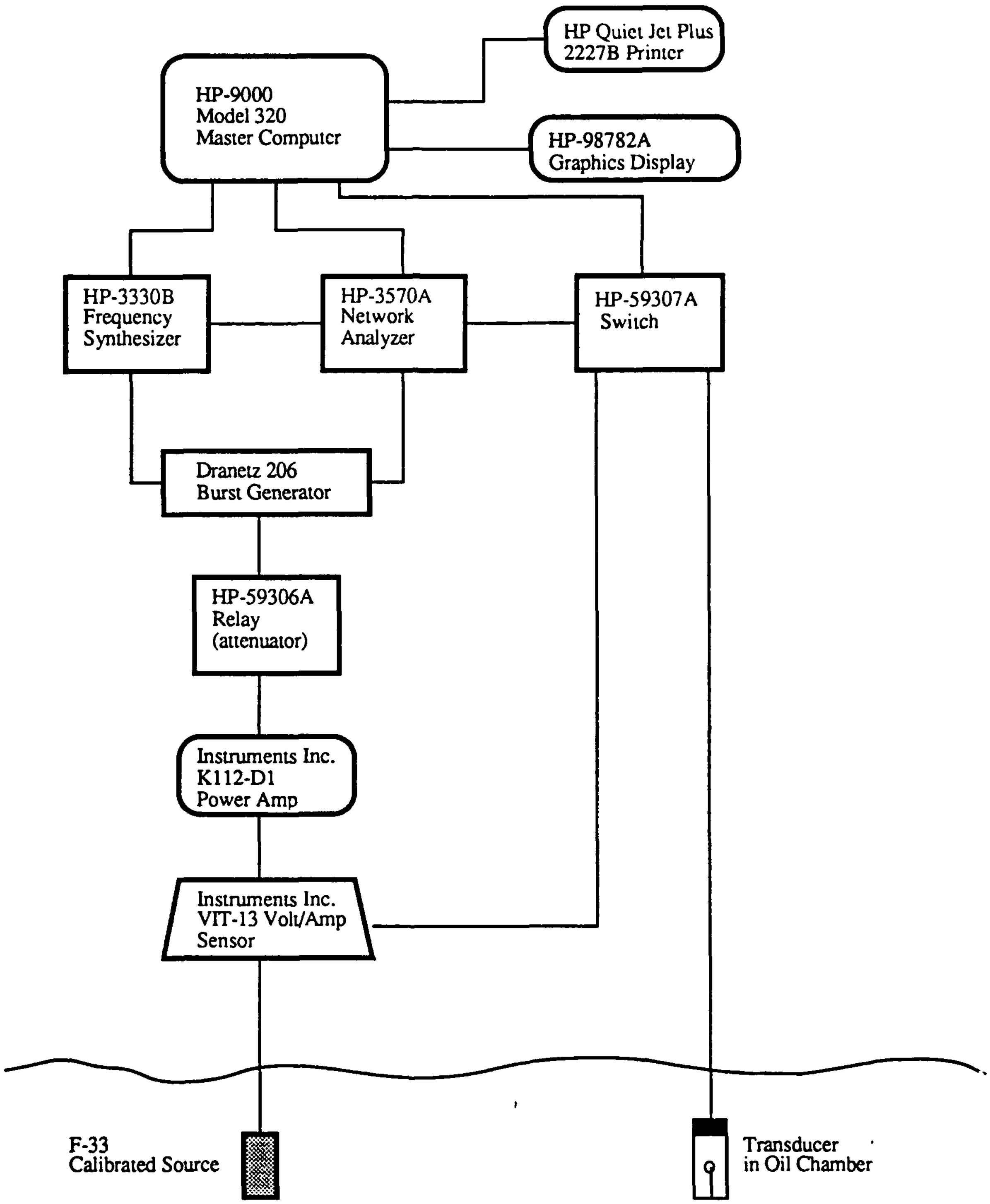


Figure 16. Diagram of system at the Applied Research Laboratory used for underwater measurements.

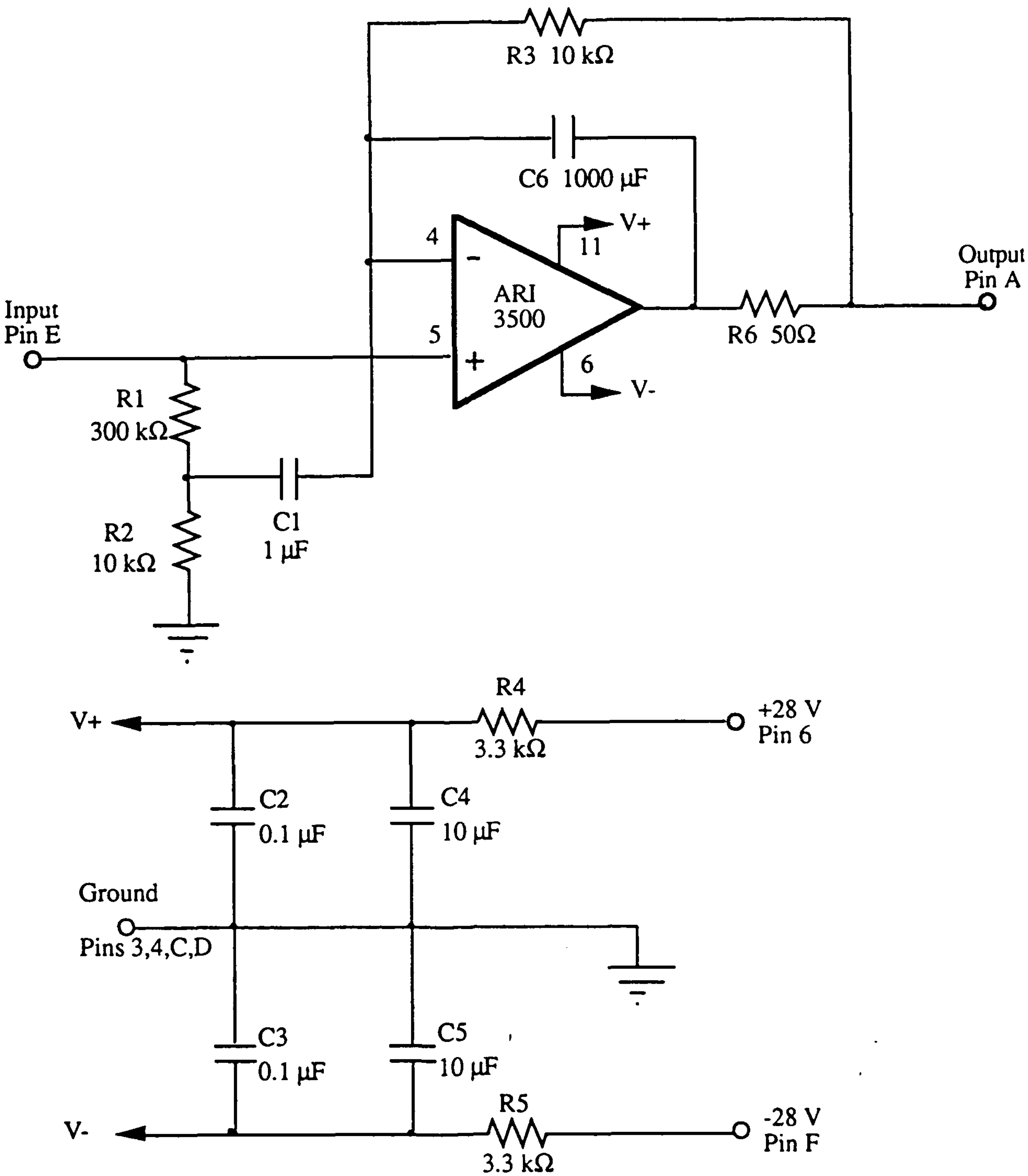


Figure 17. Circuit Diagram of preamplifiers. All capacitors have a maximum rating of 50 volts.

Pre-Testing Preparation

After the vibration testing of a transducer was complete, the wire leads from the transducer were cut from the coaxial cable. The leads were between three and five inches in length after they were cut. The transducer and mount were unscrewed from the shaker and fastened tightly onto the mounting bracket on the base of the oil chamber with a nylon screw. The leads from each piezoceramic were soldered to one of the preamplifiers, which were small enough to fit in the oil chamber with the transducer. The output terminals of the preamps were then connected to pins in the socket in the top cover of the oil chamber using thin wire and solder. The V_{cc} power terminals of the amplifiers were also connected to pins in the socket. Careful note had to be made as to what each pin was connected to, since each pin corresponded to a different wire in the cable. The wires were all color coded, which made it easy to electrically access anything in the oil chamber after the chamber was sealed and underwater, provided all the connections were noted during the mounting process.

When all the connections between the transducer, amplifiers, and socket pins were tested to satisfaction and accurately recorded, the preamplifiers were fastened to the top of the chamber using a waxed thread. This was done to keep the preamps away from the transducer so they would not block the sound wave from the transducer or create any unwanted reflections. After the preamplifiers were securely fastened, the chamber was filled with castor oil which was degassed (subjected to a vacuum to eliminate air bubbles) and the top lid of the chamber was pressed on and tightened. Any additional air in the oil chamber was forced out through a couple of small air escape holes in the lid, and the transducer was then ready to be submerged in the water.

Testing Procedure

When the transducer was ready to be tested, the shielded cable was screwed into the threaded socket on the oil chamber. A rubber gasket around the end of the cable insured that no water would get in and short out the connections. Before either the test transducer or the source were submerged in water, the surfaces of the oil chamber and F33 source transducer were thoroughly cleaned by scrubbing them with a cleaning solvent. This was to prevent air bubbles from clinging to them and interfering with the test. After the oil chamber and source transducer were cleaned to satisfaction, they were lowered into the water to a depth of 87.37 inches (measured from the surface of the water to the approximate center of the transducers). Recall that the separation distance was 3.16 meters.

On the other end of the cable coming from the oil chamber housing the test transducer were eight separate wires corresponding to the eight pins in the chamber. These were connected appropriately as described below. The shield was connected to the chassis (ground), the wires to the preamps were connected to the power supply, and the outputs from the amplifiers were connected to the network analyzer through the HP-59307A switch. The rest of the connections were all made as shown previously in Figure 16.

Next the source and receiver transducers were aligned so that they were facing each other in the direction of highest response. This was done by generating a 50 kHz tone to excite the source and slightly rotating the test transducer while observing its response. Usually the hydrophone is rotated to the point where it is most sensitive, that being its angle of maximum response. However, these transducers proved not to be very directional and did not have a pronounced favorable response direction, so the transducer was positioned at normal incidence to the source.

After the transducers were positioned and aligned, the testing process could begin. The frequency range used for these tests was 5 kHz to 20 kHz. Pure tone pulses starting at 5 kHz and going up to 20 kHz (in increments of 0.2 kHz) were transmitted by the source transducer. The length of each pulse transmitted by the source was 2.0 milliseconds (ms). The time between the pulses was about 60 ms, long enough for the interference associated with boundary reflections to die down to the background noise level. The apparatus starts measuring the output of the test transducer 3.2 ms after the start of the original pulse sent from the source. This time allows for the pulse to travel the direct path between source and receiver and also for the receiver to reach steady-state conditions (approximately in the middle of the pulse). The measurement lasts for about 0.5 ms, since it has to be stopped before the reflections arrive at the receiver.

The F33 source was the standard source, meaning it was pre-calibrated. Therefore, the acoustic field at one meter away from the source was known for each frequency. Since the separation distance between source and receiver was set up so that the spreading loss is 10 dB, the acoustic field was also known at the receiver (when no interference is present). The free-field voltage sensitivity in dB was calculated by the computer using the equation

$$M_o = V_r - G_p - S_s - V_t + 10. \qquad (4.1)$$

V_r is the output voltage level of the receiver resulting from the pressure wave, G_p is the gain of the preamplifiers (a constant 12 dB for this experiment), S_s is the sound pressure level in the water one meter away from the source when one volt is applied to the input terminals of the source, and V_t is the actual voltage level applied to the source. All of these values, whether voltages or sound pressure levels, are in decibels. Note that V_r and M_o are invariably negative numbers, while all the others are positive. The measuring system will only measure the output of the receiver if it is under one volt rms. The computer is constantly analyzing the output of the receiver to make sure that its output is less than one volt. If the output voltage gets too close to one volt, the computer attenuates the voltage sent to the source using the HP-59306A as an attenuator.

When computing the dB value for V_r, the computer uses one volt as a reference value, therefore making V_r, and consequently M_o, negative values. A typical value for S_s for the F33 source is 127.41 dB (re 1μPa/volt at 1 meter) at 10 kHz with a slope of +12 dB per octave.

Data

At first, the free-field voltage response was measured for each transducer without adding the respective gains of the Ithaco amplifiers. This was done to compare the sensitivity of the macrovoided piezoceramic piece to that of the solid piece. The lead from each piezoceramic piece was therefore connected directly to the switch, and the M_o was computed for each piece (see Figure 18). Then, just to test the effectiveness of the transdu er without the individual gains set on the piezoceramic, one of the signals was connected to the inverter, and then both signals were sent to the summing box so that the difference of the two signals was measured by the analyzer. The computer could then calculate and plot the free-field voltage sensitivity of the transducer (see Figure 18).

Notice that at the lower frequencies, the voided piezoceramic is 10 to 20 dB more sensitive than the solid piezoceramic. However, at the higher frequencies this difference decreases due to an apparent rise in sensitivity of the solid piezoceramic. Therefore the sensitivity of the transducer is good up to around 14 kHz, above where it

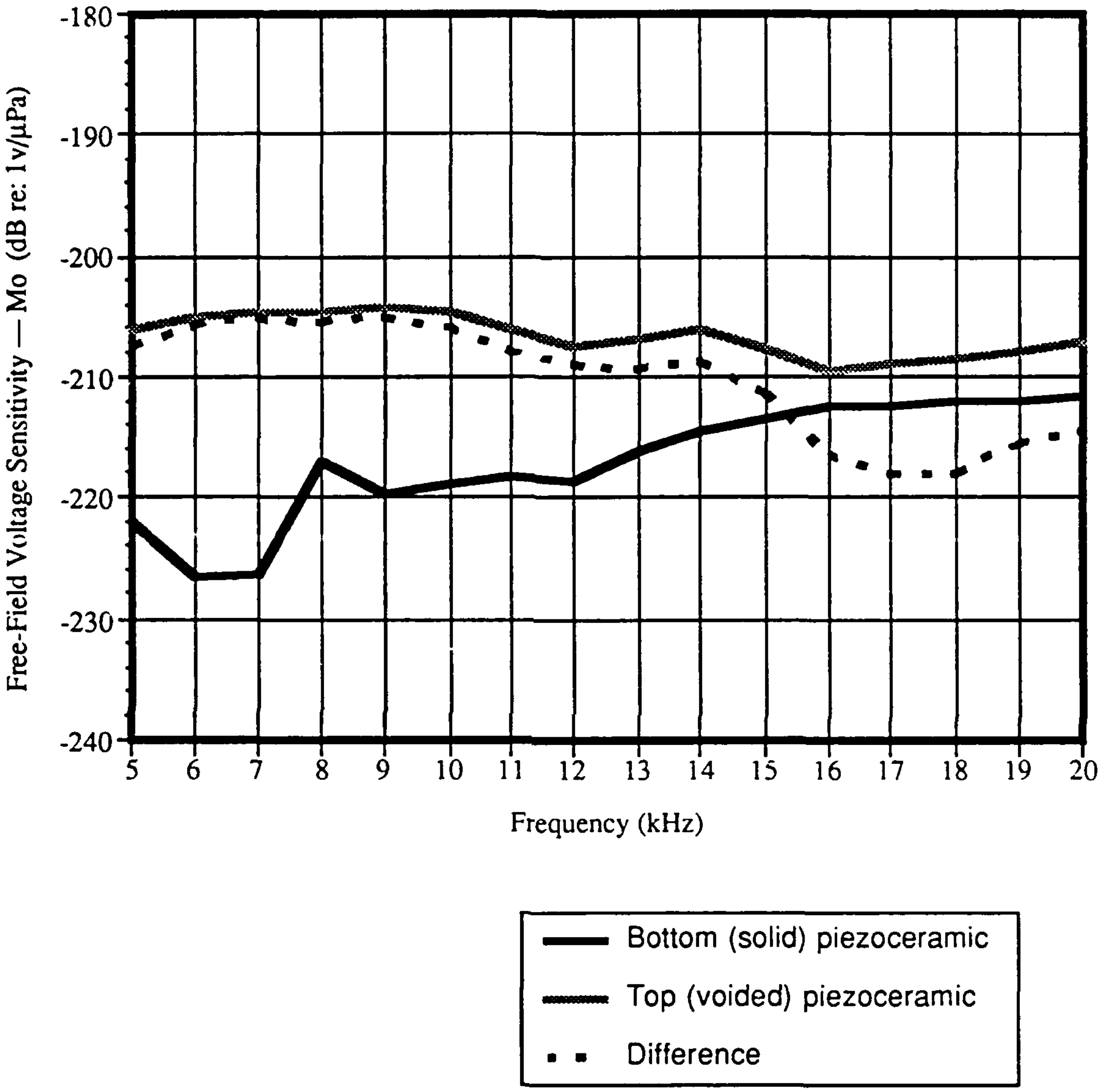


Figure 18. Unamplified free-field voltage sensitivity vs. frequency of each piezoceramic component (bonded with 5-minute Epoxy) and of the transducer.

sharply loses sensitivity due to cancellation from the solid piezoceramic.

This rise in sensitivity of the solid piezoceramic piece is unnatural and unexplained. Yet it was present in every transducer that was measured, regardless of the glue that held it together. A single solid piece was tested, and it showed no increase in sensitivity (see Figure 19). Therefore, this phenomenon is the result of the piezoceramic being physically coupled to the voided piezoceramic.

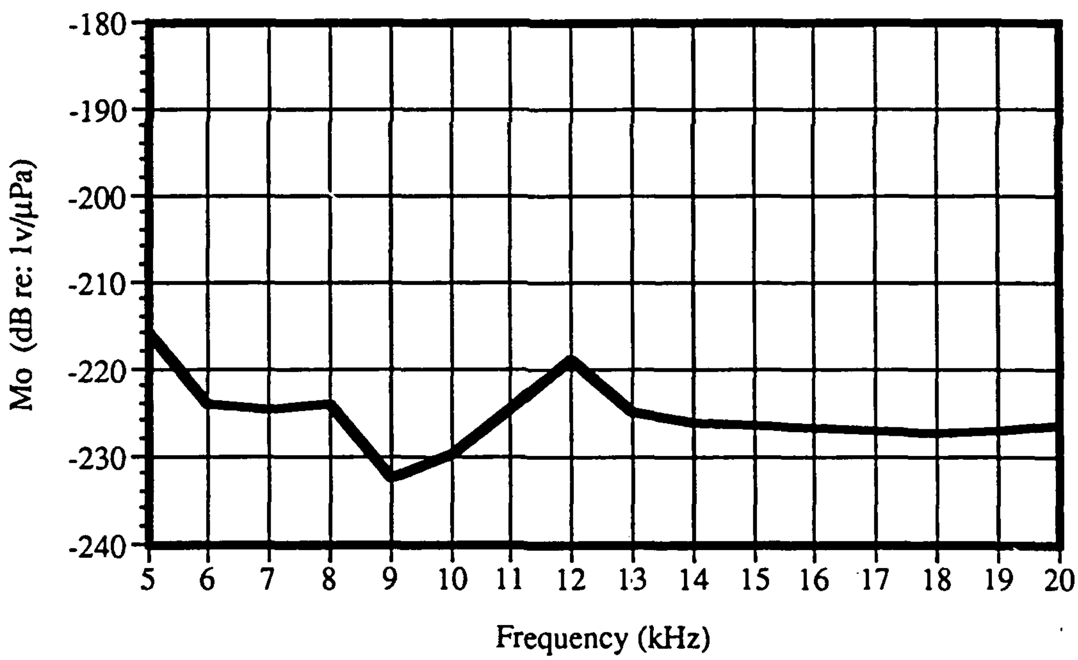


Figure 19. Free-field voltage sensitivity vs. frequency of a single solid piezoceramic piece.

However, recall that the gains required for vibration cancellation had not been accounted for in the last test. Recall that due to the fact that the solid piezoceramic was mass loaded by the voided one, the solid piece required much less gain than the voided piece. Therefore, it was believed that when the respective gains were applied to each piezoceramic, the voided piece would become even more sensitive and the transducer would be effective over the entire frequency range.

To add in the gains, the same test was run on the same transducer; however the output leads from the cable were connected to the Ithaco amplifiers, which were set to the exact same gain required for optimum vibration cancellation. For the transducer held together with 5-minute Epoxy, a differential gain of 27 dB was applied to the output of the voided piece, relative to that applied to the solid piece. The sensitivity of each transducer was measured, and then the difference of the two signals was measured (by connecting the inverter and summing box after the amplifiers and before the switch). The result was a difference in sensitivity of 30 dB or more between the two piezoceramics, and the transducer functioned very well over the entire frequency range (see Figure 20).

The system used to take these measurements is an extremely precise measuring system, which is used for much of the transducer calibration work done at the Applied Research Laboratory. The results are known to be accurate to within ±0.5 dB.

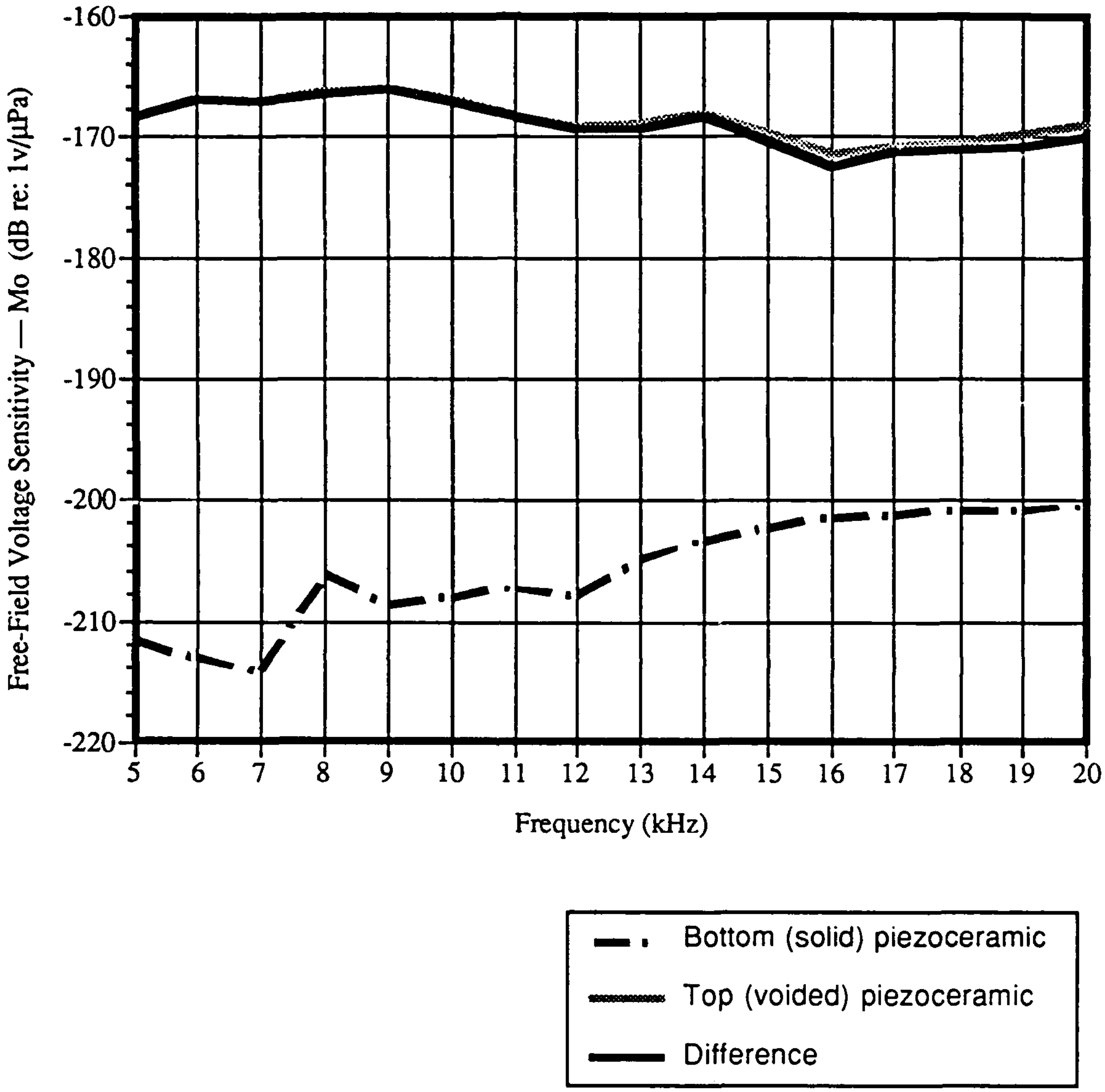


Figure 20. Free-field voltage sensitivity of transducer bonded with 5-minute Epoxy. Differential amounts of amplification, as determined from the vibration tests, are applied to the outputs of the two piezoceramic pieces.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The data gathered during the vibration testing indicated that the Noise-Suppressing Hydrophone did a reasonable job of suppressing mount noise over the tested frequency range if Devcon® 5-minute Epoxy was used to bond the component piezoceramics. The results from the free-field voltage sensitivity tests indicated that the transducer functioned well as a hydrophone over the tested frequency range, and that the pressure waves were sensed by the voided (top) piezoceramic with negligible interference from the solid (bottom) piezoceramic.

Both tests indicated that the transducer would work well at frequencies lower than those at which it was tested (2 to 5 kHz). High frequencies attenuate very quickly in water and it is the low frequencies only that travel a significant distance. Therefore, when used as a passive listener, the Noise-Suppressing Hydrophone would primarily be used at low frequencies. If the signal from the transducer were sent through a low pass filter with a cutoff frequency of around 6 kHz, then either the contact cement or 5-minute epoxy would work well as a bonding agent. If the transducer is to be used at higher frequencies, then the 5-minute Epoxy should be used for bonding.

The key to the Noise-Suppressing Hydrophone working well is to achieve good mechanical coupling between the two piezoceramics, which subsequently produces good attenuation of the mount noise. Further research to create better coupling between the piezoceramics would improve the effectiveness and consistency of the transducer over frequency. Performing a modal analysis of the transducer to find the cause of the resonances at the higher frequencies could lead to the elimination of those resonances and result in a better transducer.

Another approach would be to try different methods of bonding the two piezoceramics together. Of particular interest is to create a fusion bonding involving the sputtered-on gold electrodes of the piezoceramics. Gold fuses with indium at around 140°C, and with indium-gallium at an even lower temperature. By sputtering or evaporating a very thin layer of indium (or indium-gallium) onto one of the bonding surfaces of the piezoceramic and then, with the piezoceramics in place, heating the pair of piezoceramics to the eutectic temperature of the two metals, the metals will fuse together by forming a eutectic of the 2 metals. This bonding could be an improvement over the organic bond created with glue; however this bonding process can be very involved and time consuming.

Even better than fusion bonding would be to actually manufacture a ceramic piece which contains voids in the top half but is solid in the bottom half. A layer of conductive material such as platinum which would serve as an electrode between the two sections. This ceramic could be manufactured using the tape technology mentioned in Chapter 2. Layers of non-inked ceramic tape would be stacked up to create the solid part of the ceramic. On top of that would be placed a layer of conductive metal to serve as an electrode. Next would be stacked alternate layers of ceramic tape and tape with the ink patterns. The entire stack would be fired at one time to yield a single ceramic with a voided and a solid section and an electrode in between. This eliminates the problems which can arise by using epoxy joints, such as the relative phase shift between the two signals from each section of the transducer.

It should be noted that although the voided piezoceramic piece proved to be more sensitive to hydrostatic pressure than the solid piece, a big part of the transducer's success at higher frequencies was due to the fact that the voided piece required around 30 db more gain than the solid piece from the vibration point of view because it was not mass loaded. Therefore, the transducer could actually work using two voided pieces or piezoceramic, or maybe even two solid pieces.

Finally, it should be mentioned that before any final conclusions can be made about the Noise-Suppressing Hydrophone, it must be subjected to a final test in which a free-field voltage sensitivity is measured while it is subject to an underwater axial vibration at the same frequency. This will require a major revision of the experimental apparatus. Overall, the Noise-Suppressing Hydrophone has proven good functioning potential and should be further developed and put into use.

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