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Wide-Bandwidth Lithotripsy Hydrophone

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Background

Students at Swarthmore College, a private four-year college near Philadelphia with Quaker roots, have the opportunity to participate in advanced research since Swarthmore professors have strong research interests but no graduate students. Acoustics is an attractive field because of its inherent accessibility to undergraduates, and biomedical acoustics further attracts Engineering majors with interests in medicine or biomechanics. Development of practical devices helps students learn the importance of engineering design and integrates the electrical and mechanical concepts the students are learning in their coursework. For this reason, student participation in research is considered an important component of the educational process at Swarthmore.

In the medical procedure known as extracorporeal lithotripsy,[1] a high-amplitude acoustic shock wave is created by a device known as a lithotripter (from the Latin roots for "stone" and "break into fragments") and focused onto a patient's kidney stone, which is thereby pulverized. The procedure is considered much less traumatic than abdominal surgery, and cheaper, since it can be performed on an outpatient basis. The precise mechanism by which the converging acoustic shock wave breaks the stone is still a matter of active research in acoustics. However, stone breakage is thought to be governed by either the internal reflection of the compressional portion of the acoustic pulse (which becomes a tension wave) from the posterior of the stone, or the action of microscopic gas bubbles collapsing onto the stone surface in response to the rarefactional portion of the acoustic pulse.[2] Both mechanisms may operate simultaneously or in combination, but each is dependent upon the temporal and spatial characteristics of the lithotripter pulse.

Lithotripters of various designs produce acoustic shock waves using different techniques. Often an initial shock wave is created by an underwater explosion driven by a high-voltage spark discharge.[3] The spark-gap electrodes are located at one focus of a hemi-ellipsoidal metal bowl so that the spherically-expanding shock wave reflects from the bowl walls and converges at the opposite focus (Fig. 1). This second focus is placed (via ultrasound imaging or fluoroscopy) so as to coincide with the patient's kidney stone. Acoustic pulses can also be created via an electromagnetic device that is analogous to a loudspeaker, or via a piezoelectric crystal (or crystal array), but in these cases the waves produced are nearly sinusoidal and not shock waves.[3] By focusing them with an acoustic lens or by placing the crystals on a spherical backing surface, the converging waves steepen and form shock waves en route to the stone. The "shape" of the lithotripter pulse varies from one lithotripter to another but shares the common characteristics of a rapid rise time (from ambient pressure to nearly 1000 atmospheres in several nanoseconds) followed by a slower return to ambient pressure (in about one microsecond) and a longer negative tail (200 atmospheres of tension lasting up to ten microseconds). It is clear that such extreme conditions place severe demands upon a hydrophone, or underwater microphone, designed to measure the focal lithotripter waveforms.

Existing Hydrophone Designs

Polyvinylidene fluoride, or PVDF, is a piezoelectric polymer that can be cast or spun into thin sheets for use as transducer material in ultrasonic hydrophones.[4] Its carbon backbone has pairs of hydrogen atoms and fluorine atoms attached at alternating positions. When a high-voltage electric field is imposed, the

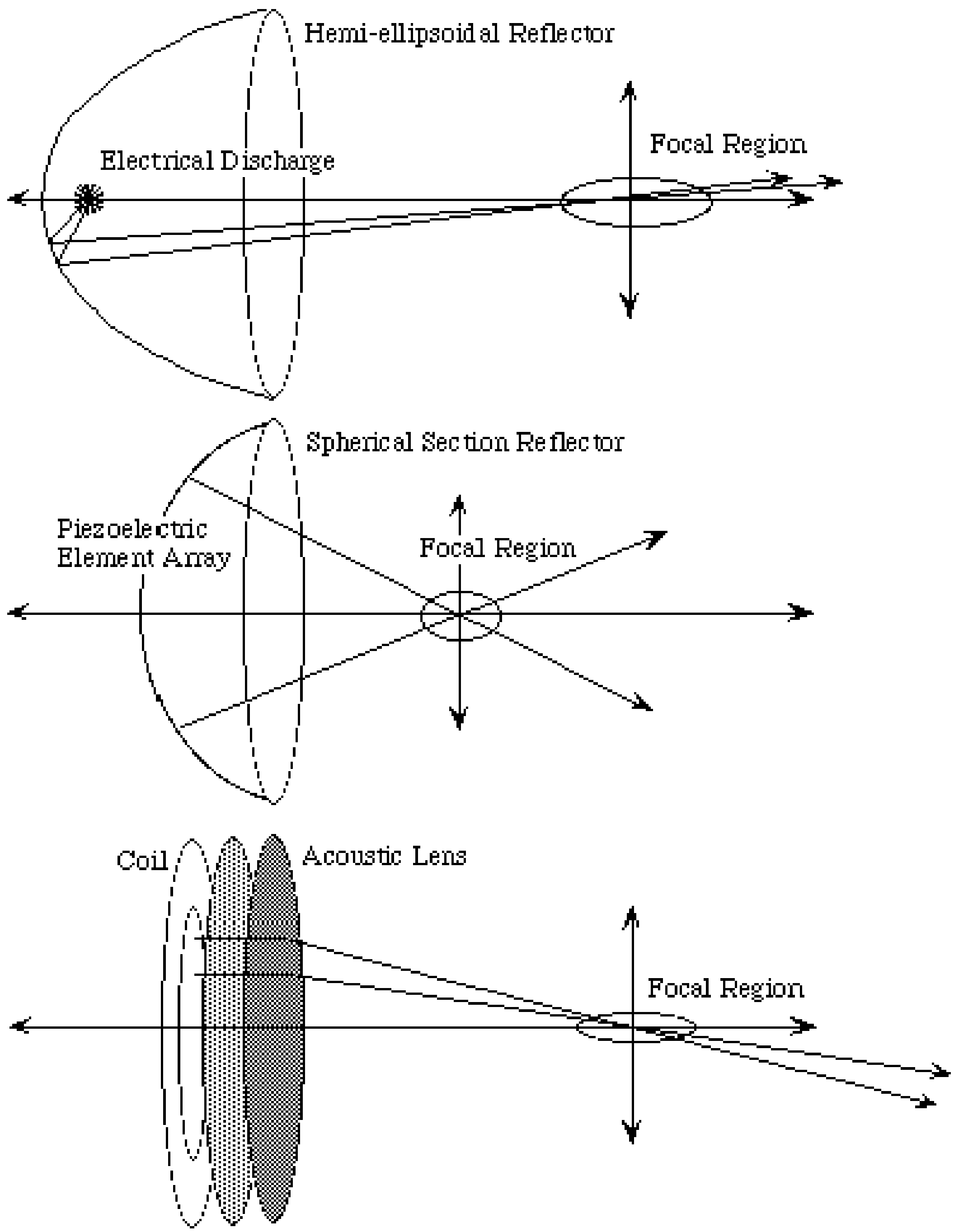

Figure 1: Lithotripter Designs (after Coleman and Saunders, 1989)

hydrogen and fluorine atoms rotate around the carbon backbone to align with the field, a condition known as "poled." When the field is removed, some residual polarization remains (especially if the poling is performed at elevated temperature and the PVDF then cooled). A mechanical stress, such as a change in pressure, causes a voltage to develop across the thickness of the PVDF sheet that can be measured directly by a high-impedance oscilloscope. The frequency response of the material is limited on the upper end by the half-wavelength resonance frequency of standing waves in the PVDF and on the lower end by the inherent capacitance of the electrode pattern.[5]

Lithotripsy hydrophones are of two principal types: membrane and needle (Fig. 2). A needle hydrophone has a small PVDF element on its tip and has the advantage of robustness and small size. Due to acoustic resonances within the solid portion of the needle, however, this type of hydrophone typically has a frequency response dominated by large peaks, making it unsuitable for use in describing accurately a lithotripter pulse's shape. Membrane hydrophones employ a thin sheet of PVDF stretched across a (typically circular) rigid frame, with an electrode pattern that defines an active poled area at its center. The electrodes consist of gold lines sputtered on opposite sides of the PVDF sheet. In a "coplanar" design, the lines terminate in small aligned circles located opposite each other across the thickness of the sheet. In a "bilaminar" design, two sheets of PVDF are bonded together with the positive electrode in the center and a large ground electrode on the outside exposed surfaces. The bilaminar design helps shield the positive electrode from the r.f. signal launched by the spark discharge of the lithotripter, but creates a double-thickness membrane with a correspondingly lower half-wavelength resonance frequency. Bilaminar hydrophones can cost upwards of $5000 each, if purchased with NIST-traceable calibration.[6]

When a membrane hydrophone is placed at the focus of a spark-gap lithotripter, the membrane can be destroyed by as few as one or two acoustic shockwaves. The damage is mostly due to pitting of the membrane surface by collapsing bubbles, the same mechanism responsible for some of the fragmentation of kidney stones. Adjacent pits can coalesce to form a tear in the PVDF, which can bisect the sputtered electrode and sever the connection. Likewise, bubbles collapsing on the electrode material can remove it from the PVDF surface in the manner of an ultrasonic cleaning bath. Even if the membrane survives a shock wave, the waveform recorded may contain artifacts such as small spikes caused by flutter reflections in the hydrophone cable. In an attempt to overcome these difficulties, a hydrophone is being developed with on-board conditioning electronics and unique electrode design.

<u>Proposed Lithotripsy Hydrophone</u>

Since it is difficult to prevent bubbles from collapsing violently on the surface of PVDF membranes, we have developed a hydrophone with disposable membranes, each of which has the same calibration value so that recalibration is unnecessary.[7] The elements are of coplanar design, but each line of sputtered gold is covered by a thin (500 angstrom) non-conductive layer of sputtered silicon sulfide. The non-conductive layer inhibits leakage of charge into the liquid surrounding the hydrophone and provides some additional toughness to resist violent bubble collapse. To further increase the resistance to tearing, the membrane material is not pure PVDF homopolymer, but rather a co-polymer of PVDF and an additional, tougher plastic polymer. Though the use of a co-polymer reduces the piezoactivity of the hydrophone membrane, the lithotripter signal is large enough for the tradeoff between toughness and sensitivity loss to be attractive.[8]

To achieve constant sensitivity from one membrane to the next, the method of poling used is non-standard. Unlike the spot poling method described above, in so-called "hysteresis poling" the sputtered electrodes themselves provide the intense electric field via application of high voltage, and the field polarity is reversed once per second for 12 hours at room temperature. The polarity reversals serve to recruit the maximum number of alignments possible of the PVDF molecules, providing nearly identical sensitivity if the quality control of the co-polymer mix is high or the same sheet is used for many membranes.[9] The electrode pattern itself also promotes consistency: instead of overlapping filled circles that would require careful registration, a cross-hair pattern consisting of two constant-thickness lines (0.25 mm) crossing at right angles is used (Fig. 3). The overlap region is therefore a square whose area changes only as the sine of the angle between the cross-hairs, a relatively weak dependence for small deviations from perpendicularity.

To maximize the frequency response of the hydrophone, a wide-bandwidth (350 MHz) operational amplifier is included in a small hollow chamber in the rim of the hydrophone. The surface-mount amplifier provides a high-impedance input (500 kohm) to the PVDF co-polymer and a low-impedance output (50 ohm) to drive a 50-ohm coaxial cable terminated into the 50 ohm input of a fast digital oscilloscope. The termination assures no detectable reflections within the cable. The small size of the poled region minimizes the inherent capacitance of the membrane, lowering the low-frequency cutoff. Currently the circuit design

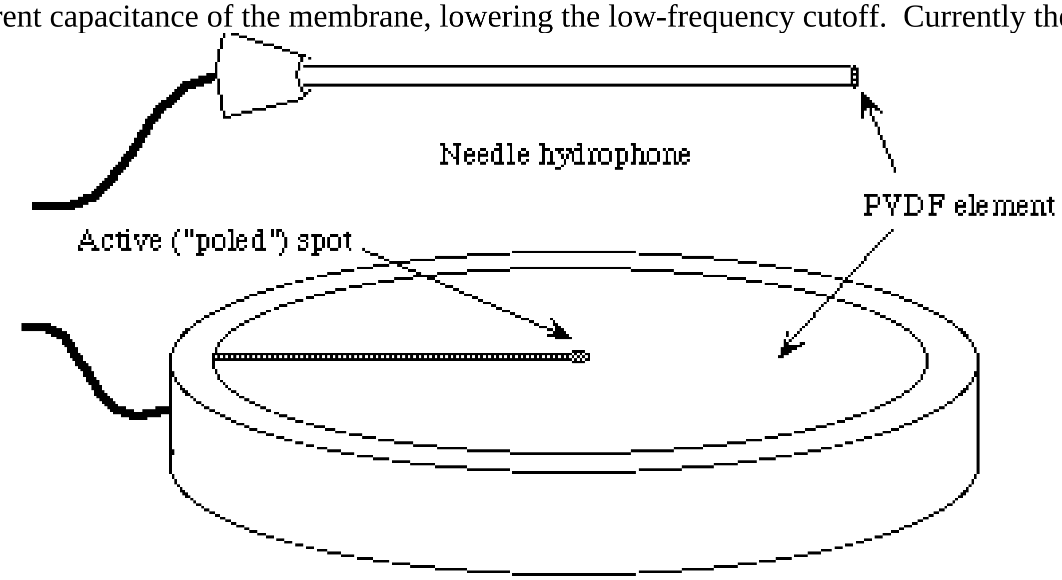

Figure 2: Hydrophone Designs

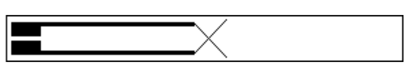

Figure 3: Proposed Electrode Design

uses external power supply voltages supplied by separate wires, but on-board batteries could also be included to avoid ground loops.

The final element of our lithotripsy hydrophone design is perhaps the most important. The electromagnetic spark discharge can create an r.f. pulse in any non-shielded conductor nearby, which will act like an antenna. The cross-hair electrode pattern acts as a conductor loop through which an electromagnetic flux occurs. Induced voltage spikes of hundreds of volts can result that cause the amplifier to saturate and not recover until after the acoustic signal has propagated from the explosion point to the hydrophone. To avoid this problem, the hollow containing the amplifier is shielded with conductive silver paint, and a diode clipping circuit stands between the PVDF co-polymer and the amplifier input. The fast computer switching diodes turn on quickly enough to direct current to ground and protect the amplifier. Connections between the sputtered gold electrodes and the diode clamp portion of the circuit are made with conductive rubber pads that squeeze between them when a new element is clamped into the hydrophone frame.

While membrane hydrophones typically cost several thousands of dollars, our design can be implemented for several hundred dollars. With volume pricing, individual membranes could cost as little as $20 each and withstand hundreds of shock waves before failure. Such inexpensive measurements allow the possibility of full mapping of a lithotripter field under various conditions, such as when spark-gap electrodes become worn. Further innovations, such as a secondary circuit that would notify the user that a membrane has failed, are being developed by Engineering students at Swarthmore. We hope that our design will allow researchers and medical practitioners greater freedom in probing the complex temporal and spatial characteristics of lithotripters and other ultrasonic biomedical devices.

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1

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