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The Development of Low-frequency Piezoelectric Panels for Active Noise Control Applications

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Major professor

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THE DEVELOPMENT OF LOW-FREQUENCY PIEZOELECTRIC PANELS FOR ACTIVE NOISE CONTROL APPLICATIONS

By

Jonathan Iwamasa

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ABSTRACT

THE DEVELOPMENT OF LOW-FREQUENCY PIEZOELECTRIC PANELS FOR ACTIVE NOISE CONTROL APPLICATIONS

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The active modification of sound levels in acoustic spaces is of increasing interest. Active noise control is necessary for low frequency noise reduction, since porous absorbers are ineffective. The objective of this research is to develop a low frequency piezoelectric polymer speaker panel for active noise control.

The acoustic response of prototype speakers was investigated and optimized for low frequency response. Small-angle, multi-layered speakers are more effective in producing low frequency acoustic power. Multi-layer PVDF speaker response differs notably from the single-layer speaker response.

An 11-speaker piezoelectric speaker panel was fabricated, which produced enough low frequency acoustic power to be used in active noise control applications and is capable of producing in excess of 90dB over the range of 40-840Hz given an input white noise signal of 30 volts. Future investigations may find that a speaker panel composed of many smaller-diameter speakers is more effective than the current 11-speaker panel.

In Memory of Robin Joy Theeuwes, 1968-1993

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

LIST OF FIGURES

NOMENCLATURE

A	area
c	speed of sound
d	piezo strain constant
D	diameter
E	Youngs Modulus
f	frequency
F	force
G	frequency response
h or H	height
L	length
P	acoustic pressure
P_o	reference pressure (20μPa)
R	radius
SPL	Sound Pressure Level
t or T	thickness
V	volume of air displaced or voltage
W_a	acoustic sound power
α	angle of incidence
ε	strain
ρ	density of air
σ	stress
θ	speaker angle

INTRODUCTION

The active modification of sound levels in acoustic spaces is of increasing interest to both industry and government. In current automobile industry surveys of customer response to vehicle designs, one of the strongest indicators of customer approval is their perception of the level of noise and vibration experienced while driving. The development of new ways to design for reduced noise levels and control of existing "noise, vibration and harshness" is a primary thrust in new automotive design technology.

Active noise control is necessary for low-frequency noise reduction, since porous absorbers, such as foam, are ineffective. A porous absorber's thickness must be comparable to the wavelength of sound for good sound absorption (Everest, 1989, p.177), therefore porous absorbers are impractical at low frequencies due to the large thicknesses necessary. For example, the wavelengths of 800Hz, 500Hz, and 100Hz are 1.4ft, 2.3ft, and 11.3ft, respectively, and would require these thicknesses to accomplish good sound absorption.

The objective of this research is to determine the feasibility of a low-frequency piezoelectric polymer speaker panel for active noise control. Active noise control by absorption requires large-area coverage by the speakers. This necessitates a panel composed of several individual speakers, and makes conventional speakers impractical due to expense and weight. Polyvinylidene Fluoride (PVDF) piezoelectric

polymer film overcomes these disadvantages. The cost of manufacturing the film is low when manufactured in mass quantities, and it is a thin, light-weight film capable of being easily cut and glued to facilitate speaker fabrication, allowing large-area coverage. The active control of noise requires acoustic generation of equivalent sound powers, and although effective high-frequency piezoelectric speakers exist, no practical low-frequency piezoelectric speakers have been developed.

It has been determined that a low-frequency piezoelectric speaker is feasible through the design and fabrication of prototype speakers, the analysis of the speakers' acoustic response, and the construction of a low-frequency PVDF speaker panel. Before the design and fabrication of PVDF speakers can be discussed, a basic understanding of piezoelectricity and acoustics is necessary. This background is presented in the following section, proceeded by the prototype and panel design section, the experimental measurement section and a final section on acoustic analysis.

PIEZOELECTRICITY

The piezoelectric effect is the property of a material to expand and contract when a voltage is applied across its surface and, conversely, to create a voltage when the sheet is strained. The basic

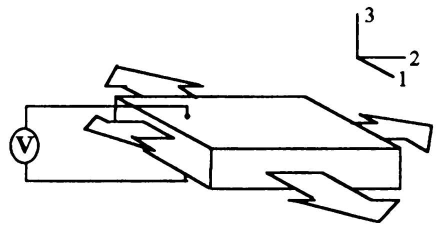

Figure 1: The Piezoelectric Effect - Expansion Due to Applied Voltage

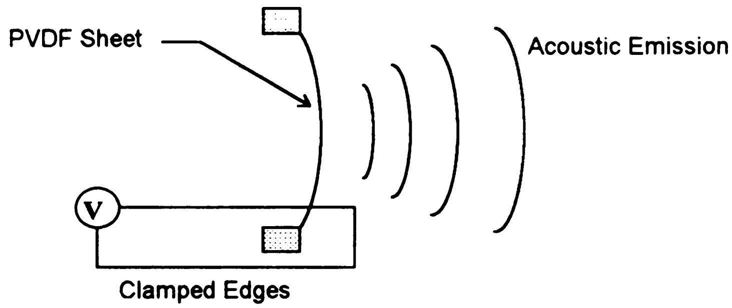

Figure 2: Acoustic Emission

equation describing the strain, ε_1, of a simply clamped sheet is:

$$\varepsilon_1 = d_{31}\left(\frac{V}{t}\right) \tag{1}$$

where ε_1 = strain in the film's stretched direction (or length)
d_{31} = piezo strain constant
V = voltage applied across thickness
t = thickness of film

The subscripts refer to an axis defined by convention, where (3) denotes the thickness direction, and (1) denotes the film's stretched, or length, direction (Figure 1). The 31 subscript on the piezo strain constant denotes expansion in the length direction, (1), when a voltage is applied in the thickness direction, (3). This material expansion can be converted to vibration, producing acoustic power (Figure 2).

Greater force can be generated with multi-layer PVDF designs. To illustrate this, two piezoelectric configurations are examined. In the

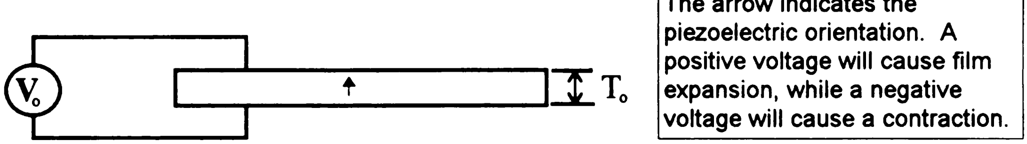

Figure 3: Single-layer PVDF Configuration

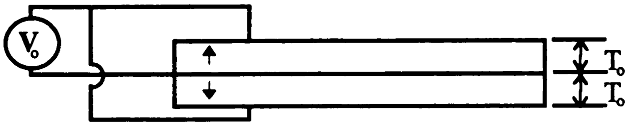

Figure 4: Multi-layer PVDF Configuration

first, a voltage, V_O, is applied across a single sheet of thickness T_O (Figure 3). The strain is then,

$$\varepsilon_1 = d_{31}\frac{V_0}{T_0} \tag{2}$$

with a corresponding force of,

$$F_0 = \sigma A = \left(E\,\varepsilon_1\right)A = \frac{E\,d_{31}\,V_0\,A}{T_0} \tag{3}$$

where A is the cross-sectional area of the expanding edge. The orientation of the film is such that a positive voltage will cause film expansion, while a negative voltage will cause contraction. In the multi-layered system, the sheets of PVDF are glued together with opposite piezoelectric orientation (Figure 4). The two-sheet interface is grounded, and a voltage of V_O is applied across both sheets. The strain in this case is the same amount of strain as the single-sheet system:

$$\varepsilon_1 = d_{31}\frac{V_0}{T_0} \tag{4}$$

the cross-sectional area, however, is doubled due to the increased thickness. The force generated in the two-layer system, then, is twice as much as the single-layer configuration.

ACOUSTICS

Large volume displacements of air are necessary for low-frequency generation. The sound power level of a monopole, or point, sound source

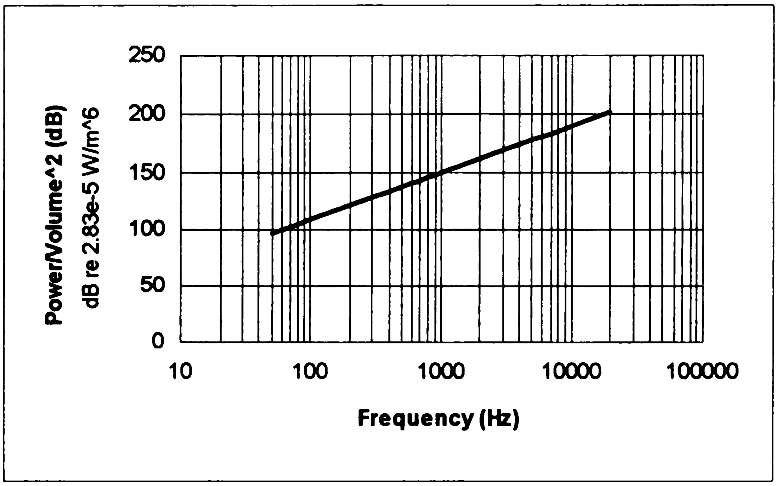

Figure 5: Power per Volume Squared vs. Frequency for a Monopole Source

may be calculated from the net volumetric displacement of air of the given sound source. As the frequency of sound decreases, the volume of air displaced must increase in a squared-sense to keep the sound power level constant. The ratio of sound power to volumetric displacement squared varies linearly with frequency (Figure 5) (Crocker and Price, 1975, pp. 18-19).

The sound power can also be expressed as a function of the volume of air displaced and frequency of sound as,

$$W_a = \frac{2\pi\rho}{c} V^2 f^4 \tag{5}$$

where W_a = acoustic sound power
ρ = density of air
c = speed of sound
V = volume of air displaced
f = frequency

Sound Pressure Levels (SPL) are used to quantify the sound power. Sound power is measured as a surface integrated value of the sound pressure, and can be found as,

$$W_a = \iint P(x,y)\, dx\, dy \tag{6}$$

Sound pressure is commonly measured on a logarithmic scale in decibels. The equation for Sound Pressure Level (SPL) is,

$$SPL = 10 \log \left(\frac{P^2}{P_o^2} \right) \tag{7}$$

where the reference pressure, P_O = 20μPa, is the ASA standard for the smallest audible pressure.

PROTOTYPE AND PANEL DESIGN

The preliminary prototype design consisted of a 7cm x 15cm rectangular section of PVDF mounted along its edges to a 3.0 inch diameter cylindrical enclosure. Acoustic measurements were below measurable levels at frequencies less than 1000Hz, and the speaker profile was too large to accommodate a thin speaker panel. A new prototype design was developed with these considerations in mind.

A cone shape was chosen as the prototype PVDF design because it is easily fabricated, has a potentially flat profile, and has a symmetry that does not restrict PVDF expansion when mounted. The individual speakers must have a thin profile, because the final speaker panel should be thin to conserve space. A cone-shaped speaker with a 3.0 inch diameter and a 30-degree angle meets this criterion and is only 1.5 inch in height (Figure 6). The diameter of 3.0 inch was chosen based on the stiffness of the PVDF film; if the cone diameter is too large, the structure is not self-supporting.

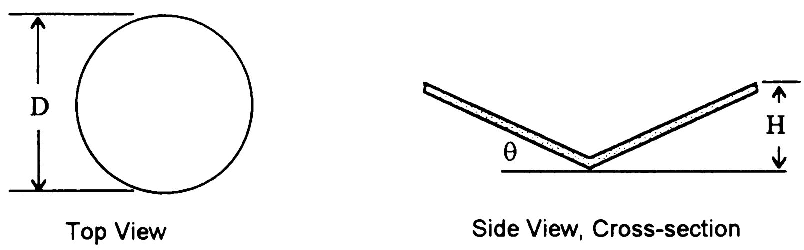

Figure 6: PVDF Speaker Cone

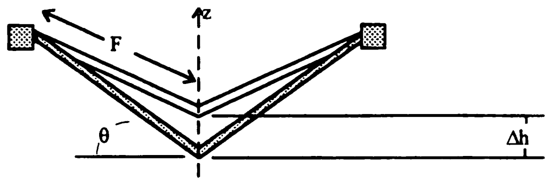

Figure 7: Static Displacement of PVDF Cone

Low frequency sound pressure will be mainly composed of air displaced by the first vibrational mode of the cone. Higher modes will generate less pressure because of the decrease in net displaced air caused by simultaneous positive and negative cone motion. The static displacement of this cone shape is shown in Figure 7. By examining the cone displacement, we can determine the speaker parameters to investigate to optimize the acoustic output.

The speaker angle is a parameter of interest in optimizing the acoustic output. The greatest volume of air displacement, and thus the largest acoustic output, will be generated when Δh is maximized (Figure 7). The piezoelectric force, however, may not be sufficient to produce the full strain that would occur in a simply clamped geometry. Therefore, it is important to understand how Δh and the piezoelectric force change with speaker angle.

The maximization of Δh as a function of θ is dependent on the geometry's strain. By examining the radial cross-section of the cone, it can be seen that while the speaker cone of length, L, expands to $L+\varepsilon L$, both H and θ change (Figure 8). The radius, R, is fixed due to the clamped circumference and the symmetry boundary along the centerline (Figure 7). Δh can be found by reducing the Pythagorean Equation, as

follows (Figure 8):

$$(H+\Delta h)^2 + R^2 = (L+\varepsilon L)^2 \tag{8}$$

$$\Delta h = [(L+\varepsilon L)^2 - R^2]^{1/2} - H \tag{9}$$

To maximize Δh as a function of θ, Δh is normalized by the constant R, and the derivative taken:

$$\frac{\Delta h}{R} = \left[\left(\frac{L}{R}\right)^2 (1+\varepsilon)^2 - \left(\frac{R}{R}\right)^2\right]^{1/2} - \frac{H}{R} \tag{10}$$

$$\frac{\Delta h}{R} = \left[(\sec^2\theta)(1+\varepsilon)^2 - 1\right]^{1/2} - \tan\theta \tag{11}$$

$$\frac{d\left(\frac{\Delta h}{R}\right)}{d\theta} = \frac{1}{2}\left[(\sec^2\theta)(1+\varepsilon)^2 - 1\right]^{-1/2}\left[2\sec\theta(\sec\theta * \tan\theta)(1+\varepsilon)^2\right] - \sec^2\theta \tag{12}$$

The maximum/minimum solution of Δh occurs when the derivative is zero, therefore Equation (12) is set equal to zero and simplified.

$$\frac{d\left(\frac{\Delta h}{R}\right)}{d\theta} = 0 = \left[(\sec^2\theta)(1+\varepsilon)^2 - 1\right]^{-1/2}\left[(\sec^2\theta * \tan\theta)(1+\varepsilon)^2\right] - \sec^2\theta \tag{13}$$

$$\frac{(\sec^2\theta * \tan\theta)(1+\varepsilon)^2}{\left[(\sec^2\theta)(1+\varepsilon)^2 - 1\right]^{1/2}} = \sec^2\theta \tag{14}$$

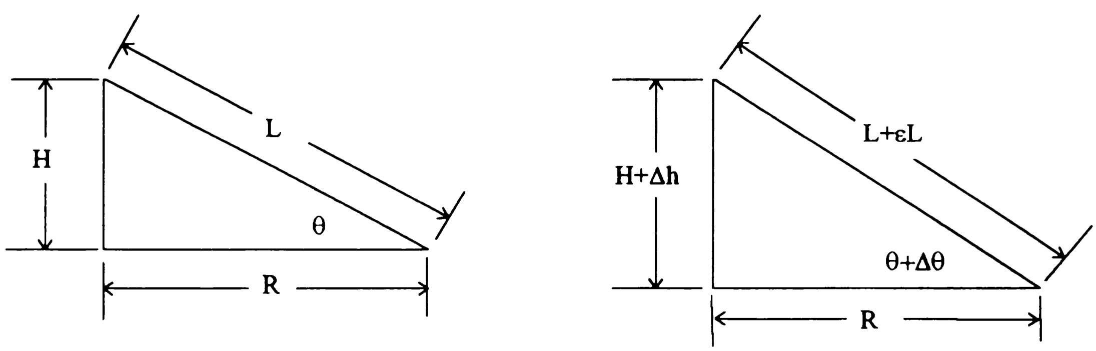

Figure 8: Static Displacement Geometry of the Speaker's Radial Cross Section

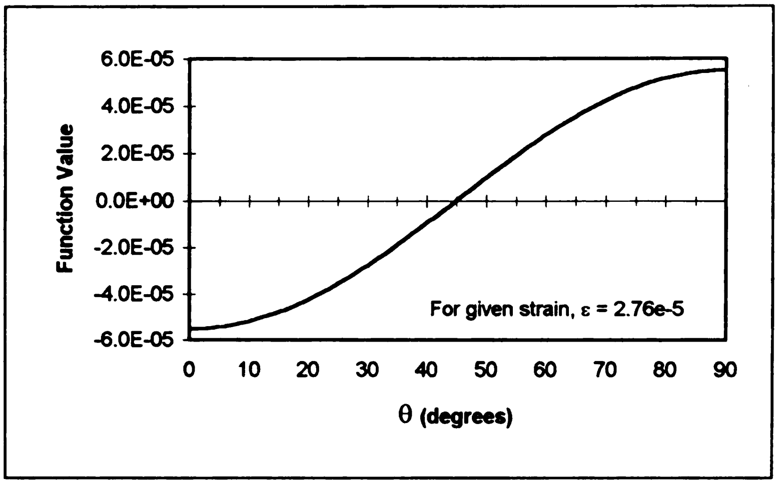

Figure 9: Graphical Solution of Equation (17), the Maximization/Minimization of Δh

$$\tan\theta(1+\varepsilon)^2 = \left[(\sec^2\theta)(1+\varepsilon)^2 - 1\right]^{1/2} \quad (15)$$

$$\tan^2\theta(1+\varepsilon)^4 = (\sec^2\theta)(1+\varepsilon)^2 - 1 \quad (16)$$

$$(1+\varepsilon)^4\sin^2\theta + \cos^2\theta - (1+\varepsilon)^2 = 0 \quad (17)$$

The maximum Δh, then, is dependent on the strain. Equation (17) is solved graphically for ε = 2.76e-5 in Figure 9, and is shown to be a minimum by plotting Δh vs. θ in Figure 10. The minimum is similarly found for various strains, and plotted as a function of strain in Figure 11.

Δh is minimized at a speaker angle of 45 degrees for the piezoelectric strains generated by the prototype speakers. Choosing a nominal value of 30 volts for safety purposes, the maximum strain produced (assuming a simply clamped geometry) is:

$$\varepsilon = \frac{d_{31}V}{t} = \frac{\left(23\text{e}-12\ \frac{\text{m/m}}{\text{V/m}}\right)(30\,\text{V})}{25\text{e}-6\text{m}} = 2.76\text{e}-5 \quad (18)$$

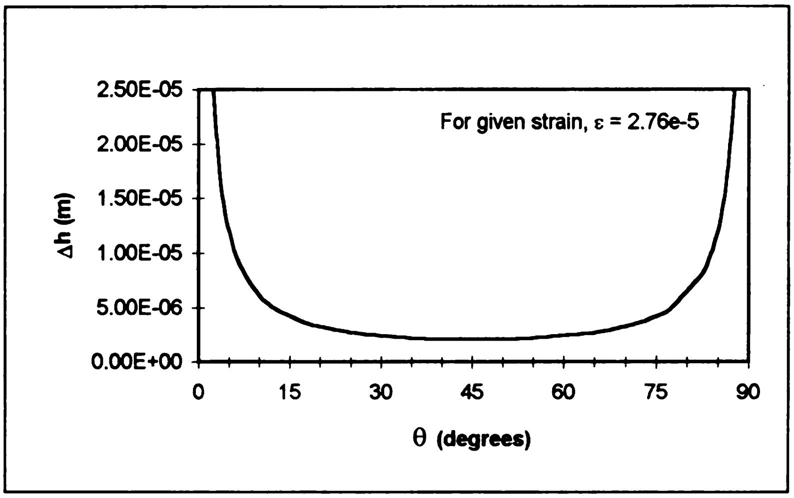

Figure 10: Δh vs. Speaker Angle Given ε = 2.76e-5

Referencing the graph of Δh_{min} vs. ε (Figure 11), it is seen that Δh_{min} occurs at 45 degrees, even when the voltage is increased to 300 volts (ε = 2.76e-4).

The optimum speaker angle is a compromise between maximizing the calculated Δh, and generating enough force to cause this displacement. Δh is at a minimum when the speaker angle is 45 degrees, and increases as the speaker angle approaches both 0 and 90 degrees. Since

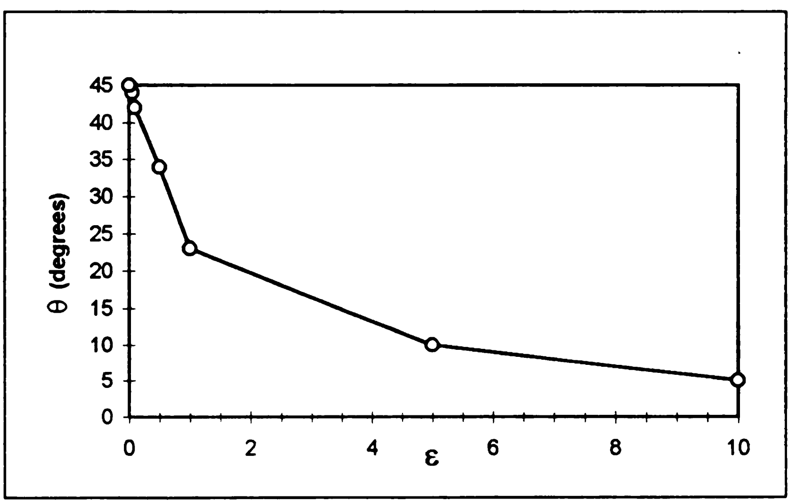

Figure 11: Speaker Angle for Minimum Δh vs. Strain

small-angle speakers will be more conducive to a thin speaker panel design, we will only consider speakers with an angle less than 45 degrees. In this situation, Δh is inversely proportional to θ. The z-direction component of the force, F, equals F $\sin(\theta)$ and thus, is proportional to θ. Therefore, if the speaker angle is small, the force may not be great enough to generate the full displacement.

The number of PVDF layers is also a parameter of interest in optimizing the acoustic output. As stated previously, multi-layer PVDF designs can increase the amount of force generated. The acoustic output may be increased with a multi-layer design, then, for small-angle speakers where the small force generated limits the acoustic output.

The prototype speaker design in this research consists of a PVDF cone mounted along the outer circumference to an enclosure (Figure 12). The sealed speaker enclosure consists of a 3-inch diameter polyvinyl pipe 8'' tall, and is designed with a beveled angle to prevent initial strains on the PVDF film and provide a uniform speaker geometry. Light gage wires are used to prevent applied stress to the film, while barrier strips are utilized to allow transfer from light gage wires to heavy gage wire for electrical connections.

Electrical connections to PVDF film must insure low-contact resistance in acoustic actuator designs to prevent electrical breakdown

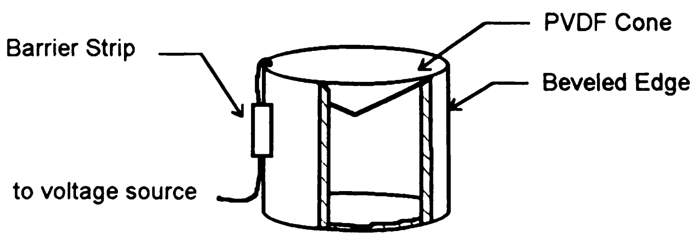

Figure 12: Prototype Design, Partial Section View

due to the large voltages required to operate the actuators. PVDF film is typically supplied with surface electrodes covering both sides of the film. The surface electrodes allow voltages to be applied across the entire area of the film. Wires soldered to copper foil with conductive adhesive was used to connect electrical leads to the aluminum-electrodes on the surface of the film used in this research. Electrical breakdown occurred at high electric fields for a $2cm^2$ of copper foil. By increasing the area of the copper foil, the contact resistance can be reduced. The electrical connection using copper foil with conductive adhesive, however, degrades over time due to decreased contact (acoustic output decreased over a period of one month); therefore clamping the copper foil is suggested to insure a consistent contact resistance over time.

Arcing across the edges of the film at high voltages must be prevented by increasing the dielectric constant between the top and bottom surface electrodes. The dielectric constant defines the maximum voltage per distance that can be applied in a given medium without arcing. Arcing occurred at approximately 100 volts for 25μm film, resulting in lower acoustic output, or even no acoustic output, due to the electrical short created by the arcing between the two sides of the film. Initially, glue covering the edges proved efficient at preventing arcing up to approximately 300 volts. Additionally, removing the PVDF surface electrodes along the edges prevents a voltage potential in this area, thus preventing arcing. The surface electrodes near the edges may be removed with dilute NaOH (Scott, Bloomfield, 1981, p. 80). Ferric Chloride ($FeCl_3$) has also been used as an etchant for nickel-aluminum electrodes (C.-K. Lee, 1990, p. 438).

Multi-layer speakers were fabricated using spray epoxy to bind the PVDF layers together. It is important to use as little epoxy as possible to prevent damping of the cone structure, and the associated loss in acoustic power. A two-compound epoxy was initially used, but could not be applied sufficiently thin to prevent a large damping of the acoustic output; spray epoxy was found to be suitable for applying very thin coats.

The speaker panel system consisted of an 18" x 30" x 4" speaker case with a hinged, sealable back and a panel inset with 11 individual speakers (Figure 13). The speaker case was made from high-grade particle board to prevent energy-dissipative resonances within the boards. The speaker case was made larger than necessary, so the speaker could be filled in and the optimum volume determined. Air-impassable foam was used to seal the hinged back with the speaker case. The speaker panel was designed with 11 uniformly-spaced, beveled holes, and the individual speakers were wired in parallel to prevent a single short from effecting the entire system. Phono connector jacks were installed to allow direct connection to a drive source, such as a stereo amplifier, and a transformer within the speaker case was used to increase the supplied voltage signal to usable piezoelectric levels.

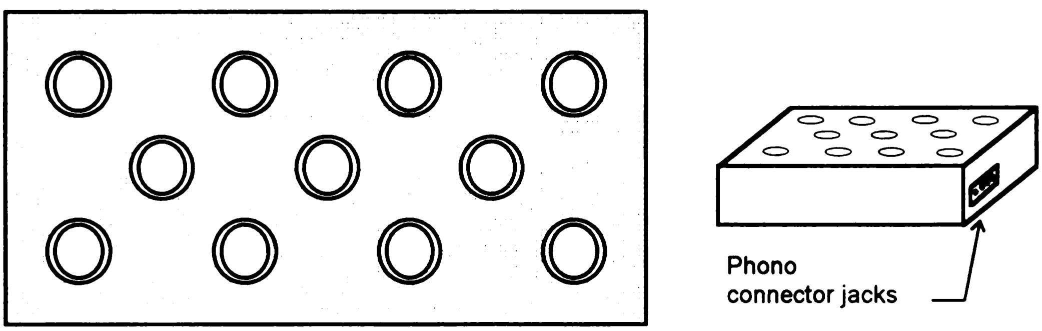

Figure 13: Speaker Panel Design

EXPERIMENTAL MEASUREMENT

A system to measure the sound pressure level characteristics was devised utilizing a PC, a digital frequency analyzer, amplifier, transformer, an acoustic microphone probe and the PVDF speakers (Figure 14). The frequency analyzer supplied the acoustic measurement capabilities and the drive voltage. The drive voltage was supplied at both discrete frequencies and over specified frequency ranges to an amplifier. The amplifier increased the signal power to usable levels, while the transformer increased the voltage to drive the piezoelectric speakers. The frequency analyzer was then used to measure the acoustic pressure distribution and the frequency response of the system's acoustic pressure to drive voltage, and this data was transferred to the PC for further analysis. All measurements were obtained at 15cm from speaker to microphone probe.

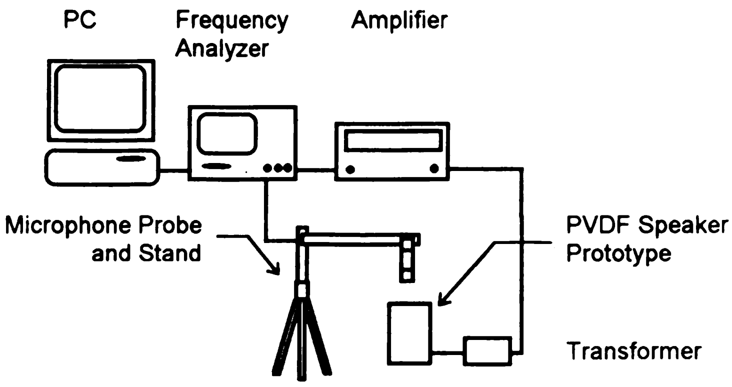

Figure 14: Experimental Set-up

ACOUSTIC ANALYSIS

PROTOTYPE SOUND CHARACTERISTICS

The prototype is non-directional at low frequencies, allowing characterization of the sound power by sound pressure level measurements at one point. The SPL was measured at 100Hz, 500Hz, and 1000Hz for α between 0 and 90 degrees. The directional characteristics of a 5-degree, 3-layer speaker showed a maximum difference of only 3.5dB throughout a 90-degree angle of incidence (Figure 15).

The sound pressure per volt frequency response for 1-layer prototypes had a repeatable curve shape as the speaker angle varied and showed an increase in response for a 15-degree speaker over larger-angle speakers. Actual spectral data are shown for four different 1-layer speakers in Figure 16. This data shows that the low frequency acoustic

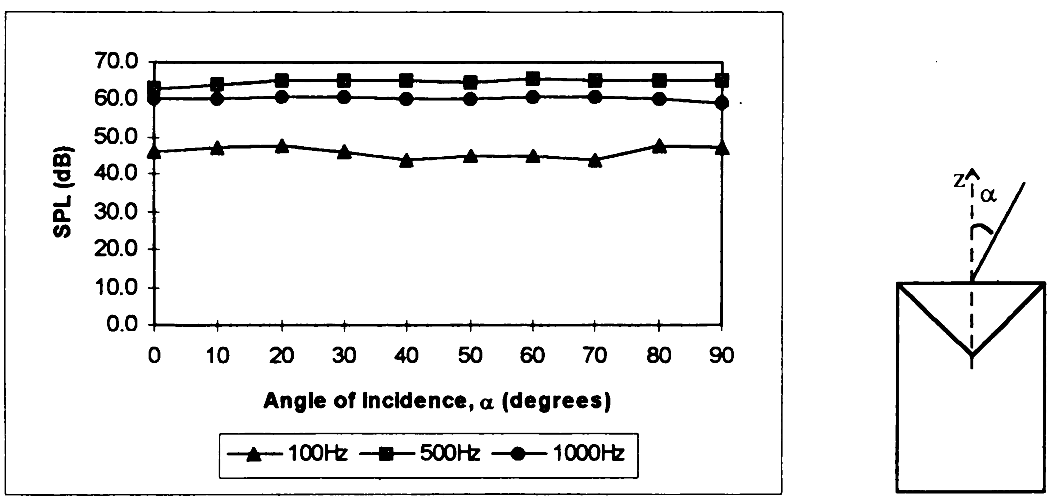

Figure 15: Sound Pressure vs. Incident Angle of 5-degree, 3-layer Speaker at 100Hz, 500Hz, and 1000Hz

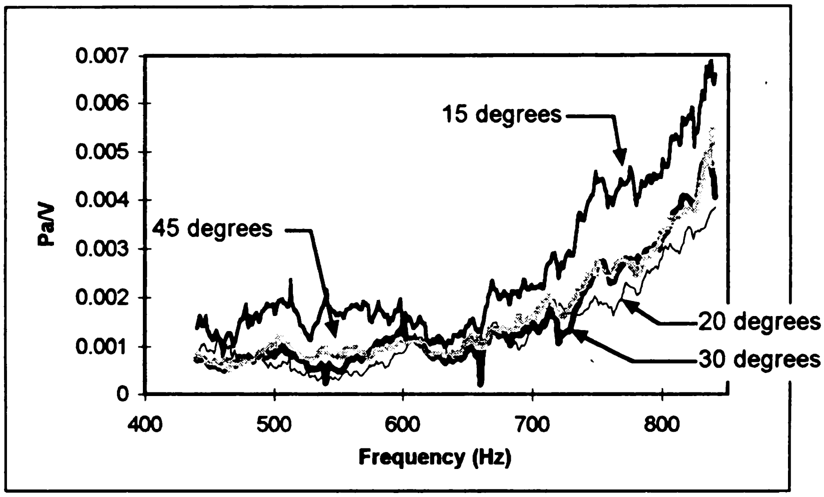

Figure 16: Frequency Response for 15-, 20-, 30-, and 45-degree Speakers with 1-layer

response is approximately the same for speaker cones with an angle greater than 20 degrees, and increases at angles smaller than 20 degrees. This increase in acoustic response is expected, but a decrease in response at smaller cone angles is also expected; this data does not indicate if, and when, the acoustic response begins to decrease with angle.

A 5-degree, 1-layer speaker, however, develops structural harmonics which reduce the acoustic output. A 5-degree, 1-layer speaker was not stiff enough to provide a uniform cone shape, given the 3.0 inch speaker diameter. Instead, the cone shape had a waviness characterized by taut radial sections bounding relaxed film areas. This created structural harmonics that diminished the energy and acoustic response. Additionally, this non-uniform geometry was unstable and produced an inconsistent frequency response.

Multi-layered PVDF speakers are able to remove the harmonics that occur due to geometry non-uniformity. A 5-degree speaker was investigated with 2, 3, 4 and 6 layers. Speaker cones of more than 6 layers were determined to be cost ineffective and not investigated. The 2-layer speaker had greater acoustic output, but harmonics were still present. For 3 layers and greater, the harmonics were not detected.

This multi-layer speaker data was used to select a 3-layer, 5-degree speaker as the speaker panel prototype. The 3-layer, 5-degree speaker produced more acoustic output than any of the single-layer prototypes (Figure 17). The multi-layer frequency response is notably different from the single-layer frequency response trend. Instead of a smooth curve, drops in the frequency response appear at approximately 525Hz, 700Hz and 825Hz. The first mode of the speaker enclosure is approximately 1,100Hz, and therefore, these peaks in frequency response are not due to the enclosure resonances. The change in the frequency response trend may instead be due to the characteristics of a multi-layer PVDF system or the consistency of the spray epoxy used to glue the layers of PVDF together. The multi-layer speaker data collected, however, did not contain enough detail and are not sufficient to present here.

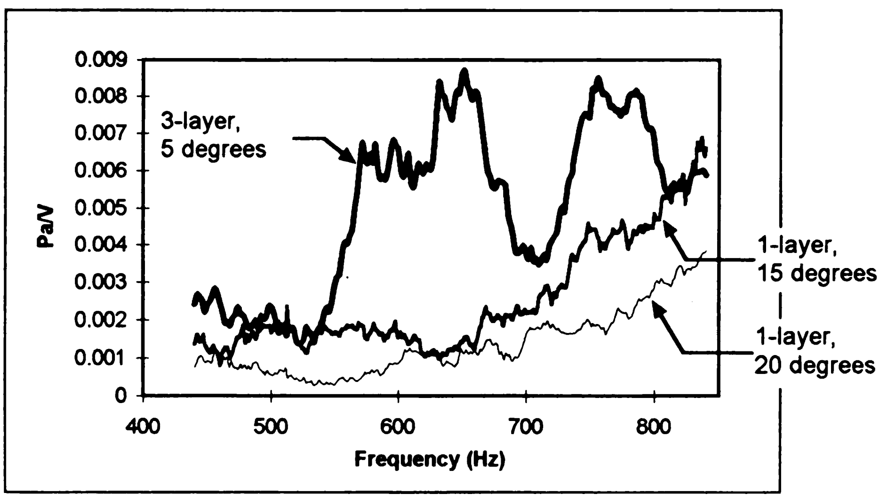

Figure 17: Frequency Response for 5-, 15-, and 20-degree Speakers

PANEL SOUND CHARACTERISTICS

The speaker panel produced a higher acoustic output with a general frequency response shape comparable with that of the single speaker frequency response (Figure 18). The increase in the magnitude of the speaker panel frequency can be characterized over three different regions. From 150Hz to 325Hz the response is increased by approximately fourteen times the single speaker response, while the response is increased by 6.5 and 3.5 times the individual speaker response over the ranges of 325-550Hz and 550-840Hz, respectively. The general shape of the panel frequency response is comparable to the one speaker response with variations most notable by the shift in the low frequency response drops at 525, 700, and 825Hz to drops at 485, 675, and 775Hz.

The speaker panel system design is successful and can generate usable low frequency acoustic power. The sound pressure level spectrum for a 30 volt input white noise signal of frequency span 40-840Hz is shown in Figure 19. The total band SPL from 40-840Hz is 91.8dB. The SPL is greater than 50dB for all frequencies above 150Hz, and the SPL is

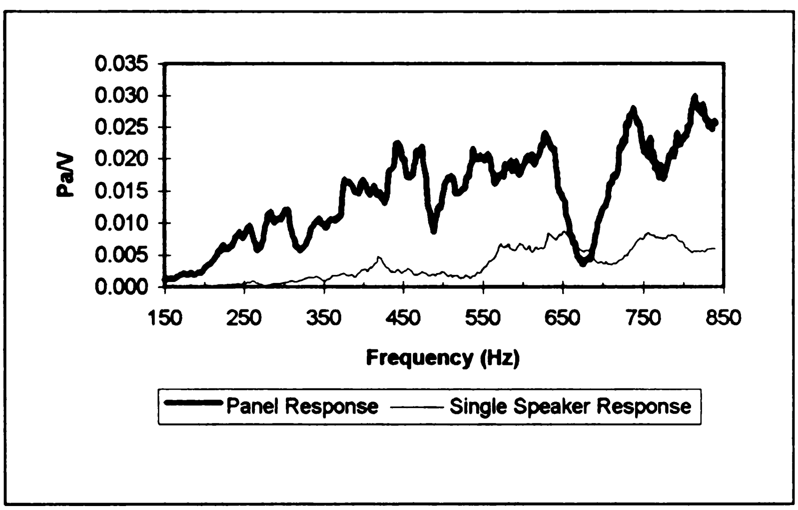

Figure 18: 5-degree Single Speaker and 11-speaker Panel Frequency Response

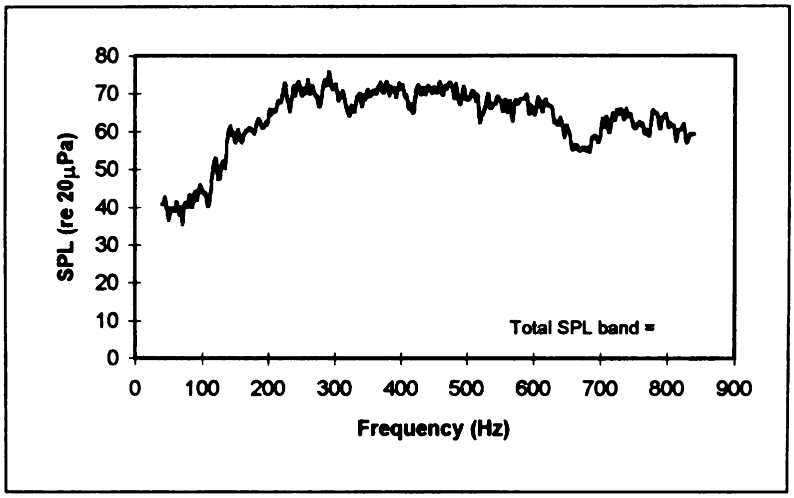

Figure 19: Speaker Panel System SPL Response Spectrum for 30 Volt White Noise Input Signal

approximately 40dB or greater between 40Hz and 150Hz. These levels are sufficiently high to further investigate the PVDF speaker panel for use in an active noise control system.

CONCLUSIONS

The first stage of developing an acoustic PVDF active noise control system has been successful. The speaker panel of eleven 3-layer 5-degree PVDF cones mounted on a speaker box of dimensions 18" x 30" x 4" produced in excess of 90dB from 40-840Hz given an input white noise signal of 30 volts. This speaker's enclosure was overly large to allow for later optimization of the speaker enclosure volume. The design presented here requires only an amplifier connected in series with a step transformer to drive the PVDF speakers. This speaker design and the acoustic response show that it is feasible to create a PVDF speaker panel with enough sound power for actual implementation of an active noise control system.

Small-angle, multi-layered speakers are more effective in producing low-frequency acoustic power than large-angle, single-layered speakers. The 3.0 inch diameter speakers investigated showed increased acoustic response for a 15-degree speaker over the similar acoustic responses of the 20-, 30- and 45-degree speakers. While these speakers were stiff enough to provide a uniform geometry, a 5-degree speaker required at least 3 layers of PVDF to produce a stable speaker that did not produce acoustic harmonics. The 3-layer, 5-degree speaker produced more low-frequency acoustic power than all of the 1-layer speakers investigated.

Multi-layer PVDF speaker response differs notably from the single-layer speaker response. The general shape of the 3-layer, 5-degree speaker had drops in frequency response at approximately 525, 700 and 825Hz, while all 1-layer speaker responses were characterized by a smooth shape from 440-840Hz. Additionally, a greater number of layers increased the acoustic power, but also changed the shape of the frequency response. The change in frequency response as a function of the number of PVDF layers requires future investigation.

A speaker panel composed of many smaller-diameter speakers may be more effective than the current 11-speaker panel. By reducing the speaker diameter, the effective stiffness of the cone is increased and it may be possible to use single-layer speakers at angles as small as 5-degrees without structural harmonics developing. This will reduce manufacturing efforts associated with multi-layer constructions.

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