2pEAA3. Noise minimization in micromachined piezoelectric microphones

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Piezoelectric MEMS microphones have been built for more than 30 years and they offer some advantages over other technologies such as improved linearity, simple construction, no need for a bias voltage or charge, and the ability to withstand high temperatures. Despite these advantages, a relatively high noise floor has always limited their utilization. Traditionally, the noise of these sensors has been minimized by viewing the pre-amplifier or amplifier as a black box with fixed gain and noise. This leads the designer to minimize noise by maximizing microphone sensitivity. By viewing the microphone-amplifier system together, we develop a different method of optimization, leading to lower noise. Further, by including the back cavity compliance of the package in the optimization, we can determine absolute limits on the minimum achievable noise floor with very few assumptions. To date, we have built piezoelectric MEMS microphones utilizing aluminum nitride with a 32 dBA noise floor. We can compute a minimum achievable noise floor of 24 dBA for the same sensing structure with a 2 mm$^3$ back cavity volume.

Published by the Acoustical Society of America through the American Institute of Physics
INTRODUCTION

Piezoelectric MEMS microphones have been researched since the early 1980’s because they offer a unique set of advantages [1]. Unlike capacitive MEMS microphones, piezoelectric MEMS microphones do not require a bias voltage, they do not require the fabrication of a thin air gap, and they have a large enough capacitance to work with off-the-shelf circuitry. Unlike electret microphones, piezoelectric MEMS microphones can withstand the temperatures of solder reflow and high temperature MEMS processes. Further, the piezoelectric transduction mechanism is inherently more linear than capacitive transduction leading to microphones with a larger dynamic range. To date, the primary drawback of piezoelectric MEMS microphones has been a relatively high noise floor. Table 1 provides the A-weighted noise floor of several piezoelectric MEMS microphones. While most capacitive MEMS microphones have a noise floor ranging from 30 dB(A) to 35 dB(A), piezoelectric MEMS microphones are typically more than 10 times (20 dB) higher. This has limited piezoelectric MEMS microphones to high sound pressure level applications such as aeroacoustic testing [2].

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Piezoelectric Material</th>
<th>Noise Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Royer et al.</td>
<td>1983</td>
<td>ZnO</td>
<td>66 dB(A)</td>
</tr>
<tr>
<td>Franz</td>
<td>1988</td>
<td>AlN</td>
<td>70 dB(A)</td>
</tr>
<tr>
<td>Ried et al.</td>
<td>1993</td>
<td>ZnO</td>
<td>57 dB(A)</td>
</tr>
<tr>
<td>Schellin et al.</td>
<td>1994</td>
<td>PVDF</td>
<td>60 dB(A)</td>
</tr>
<tr>
<td>Kressman et al.</td>
<td>1996</td>
<td>PVDF</td>
<td>55 dB(A)</td>
</tr>
<tr>
<td>Littrell et al.</td>
<td>2009</td>
<td>AlN</td>
<td>35 dB(A)</td>
</tr>
</tbody>
</table>

In this paper, we will use the example of a piezoelectric cantilever for ease of computation. We will first introduce the cantilever model and present equations for all values of interest to this analysis. We will then discuss the circuitry used to buffer and amplify the signal from the piezoelectric transducer and show that much of the design and analysis can be performed irrespective of the specific amplifying circuitry to be used. We will also include the influence of the package in this analysis. Following this, we will discuss the optimization of a cantilever-based piezoelectric MEMS microphone and provide a closed form solution to the minimum achievable noise floor of a microphone, given a specific sensing structure and back cavity volume.

CANTILEVER MODEL

Piezoelectric MEMS microphones can be constructed from many different structures including membranes and plates with a range of shapes and boundary conditions [1] – [7]. For this analysis, we will assume that we are using a multi-layer fixed-free cantilever beam as the sensing structure as shown in Figure 1. We will also assume aluminum nitride (AlN) as the piezoelectric material because it is ideal for low noise piezoelectric microphones due to its low dissipation factor. The properties of AlN also enable us to make the assumption of small piezoelectric coupling, which can be made whenever \( d_{31}/(\eta_{33}s_{11}) \ll 1 \) where \( d \) is the piezoelectric coupling coefficient matrix, \( \eta \) is the electric permittivity matrix, and \( s \) is the compliance matrix [8]. This assumption significantly simplifies the piezoelectric beam analysis such that the sensitivity can be determined by calculating the mechanical response of the piezoelectric beam while ignoring the affect of the electric field, and then determining the electric field from the computed strain.

For the cantilever beam shown in Figure 1, subject to a uniform pressure load, the output voltage across a piezoelectric layer, \( k \), is given as

\[
V_k = \frac{PbL^2d_{31}Z_{ok}}{12EI\eta_{33}s_{11k}}
\]

where \( V \) is voltage, \( P \) is uniform pressure, \( b \) is beam width, \( L \) is beam length, \( E \) is the effective modulus of elasticity of the multi-layer composite beam, \( I \) is the second moment of area, and \( Z_{ok} = (z_{k1}-zn)^2-(z_{k1}+zn)^2 \) where \( z_{k1} \) and \( z_k \) are the distances to the bottom and top of the piezoelectric layer respectively and \( zn \) is the distance to the neutral axis [8]. This analysis assumes that the basal portion of the beam, which is not free from the substrate, has negligible
length compared to the length of the beam because it would otherwise act as stray capacitance and reduce the output voltage.

FIGURE 1. This is a multilayer cantilever beam with uniform pressure applied to the top. The thicker red layers represent AlN and the thinner blue layers represent the electrode material. The beam has length, L, and width, b.

In addition to sensitivity, the capacitance and acoustic compliance are important metrics for this analysis. The capacitance of the piezoelectric layer is calculated in the standard way, \( C = \frac{\eta_{33}bL}{(z_k-z_{k-1})} \), and the acoustic compliance of the beam is calculated as

\[
C_a = \frac{b}{P} \int_0^L w(x)dx = \frac{b^2L^5}{20EI} = \frac{3bL^5}{5Eh^3} \tag{2}
\]

where \( w \) is the beam deflection and \( h \) is the total beam height. Note that although we assume voltage sensing, the sensitivity can easily be converted to charge sensing by multiplying the voltage across the piezoelectric layer by the capacitance.

CIRCUITRY

Circuitry must be used to buffer the output of any piezoelectric MEMS microphone. Many different circuit topologies have been used to buffer and amplify the output of the MEMS transducer including voltage and charge amplifiers. It is tempting to assume that the circuitry is a voltage amplifier with fixed noise and gain. Under this assumption, the microphone input referred noise is minimized by maximizing the sensitivity of the MEMS transducer. This design strategy does not work for two reasons: (1) the noise and gain of a voltage (or charge) amplifier are not fixed but are a function of the sensor capacitance and (2) the sensitivity of the MEMS transducer can be increased almost without bounds at the expense of sensor capacitance.

A source follower circuit is commonly used to buffer the output of a microphone. A schematic of this circuit is shown in Figure 2. Here, there is a large input resistor, \( R_i \), that sets the gate voltage. This input resistor is a source of noise but the noise is filtered by the R-C circuit created by this resistor and the MEMS chip capacitance, \( C_{mic} \). As the MEMS chip capacitance increases, the noise decreases. This is one way in which the circuit noise is a function of the MEMS transducer capacitance. The JFET will have some input capacitance as well. This input capacitance looks like stray capacitance and will attenuate the signal as it enters the amplifier. Figure 3 shows the gain and input noise of a source follower circuit with a range of capacitor sizes in place of the MEMS transducer.
FIGURE 2. Source follower circuit. This is a common circuit used to buffer the output of microphones. \( C_{mic} \) is the capacitance of the MEMS transducer, \( V_{mic} \) is the voltage out of the MEMS transducer, \( R_b \) sets the JFET bias, and \( R_L \) is the load resistor.

FIGURE 3. Measured gain and input referred noise of a source follower circuit. When the capacitance is very low, the signal is attenuated by the input capacitance of the JFET. The input referred noise is reduced as the transducer capacitance increases because the larger capacitance attenuates the bias resistor noise.

Although the gain and noise of the buffer/amplifier circuit is a function of the MEMS transducer capacitance and a wide range of circuitry can be used, the majority of the MEMS optimization can be done irrespective of the circuitry used. Take, for example, a microphone built using the beam shown in Figure 4. This beam has six distinct electrodes that can be wired in various ways to achieve different sensitivities and capacitances. The stress in the top and bottom AlN layers will have opposite polarity when the beam bends. If the beam is symmetric about the center electrode and the AlN orientation is consistent between the layers, then the top and bottom electrodes will be at the same potential relative to the center electrode. For this reason, it makes sense to always connect the top and bottom electrodes together.

FIGURE 4. Beam with 6 distinct electrodes. These electrodes can be connected in two different combinations and the output energy remains constant.

In order to maximize capacitance, the beam electrodes can be connected as shown in Figure 5(a). In this case, the sensitivity will match that of the beam in Figure 1 but the capacitance will be twice as high. On the other hand, the beam can be wired to maximize sensitivity by wiring as shown in Figure 5(b). This will result in twice the sensitivity as the beam in Figure 1 but the capacitance will be half as large. In both cases, the output energy (energy
= \frac{1}{2}CV^2) due to an input pressure is the same. This idea can be extrapolated beyond two sets of electrodes in order to continue to increase microphone sensitivity at the expense of capacitance. Note that although this is explained from the perspective of voltage sensing, the same argument can be made when utilizing a charge sensing scheme.

![Figure 5](image1)

**FIGURE 5.** The electrodes in these beams can be connected in two different combinations and the output energy remains constant. If the electrodes are wired as shown in (a), then the capacitance is maximized. If the electrodes are wired as shown in (b), then the sensitivity is maximized.

This method of breaking up electrodes and wiring to adjust device capacitance has been discussed before [4]. We expand on this idea by using output energy as a mechanical design metric. Therefore, the mechanical design can be optimized without regard for the circuitry by maximizing the output energy of the MEMS transducer. This enables the MEMS designer to compare a wide range of potential structures and sizes of structures without modeling the circuitry along with the mechanics.

**PACKAGED MICROPHONE**

The previous analysis assumed that the microphone consisted of a cantilever beam with uniform pressure on the top side. Without a back cavity, the acoustic pressure would equalize on the top and bottom and the beam would not function as a microphone. Therefore, it is necessary to build the microphone with an enclosed back cavity. A packaged microphone can be seen in Figure 6. This microphone consists of the MEMS beam inside a box with a hole for acoustic input. A conductive box has the added benefit of shielding the sensor and circuitry from electromagnetic interference.

![Figure 6](image2)

**FIGURE 6.** Microphone package cutaway without (a) and with (b) the MEMS transducer. The package completely encloses the MEMS chip and circuitry except for an acoustic hole that is below the MEMS transducer. Part of the cap is cut-away in order to show the inside of the package.

This package not only prevents pressures from equalizing on either side of the sensor but also affects the response of the microphone. The package and MEMS transducer together can be modeled using an equivalent circuit as shown in Figure 7. The beam is represented as a second order system with mass represented by an inductor, L, and stiffness represented by a capacitor, C. The acoustic resistance around the beam is represented by R. The back cavity compliance is represented by capacitor C. Through the flat part of the frequency response, this package acts as a capacitive divider between capacitors C and C. As the back cavity becomes smaller, C decreases and the sensitivity is reduced.
FIGURE 7. Equivalent circuit of a microphone package. In the flat part of the response, the sensitivity of the transducer is reduced by the capacitive divider created by the acoustic compliance of the transducer \(C_t\) and the back cavity \(C_b\).

**OPTIMIZATION**

A smaller back cavity reduces the microphone output so it would seem that the best performance would be obtained from a microphone with a large back cavity. However, it is often desirable to achieve the best performance with a limited back cavity volume. In order to minimize the microphone noise with a limited back cavity volume, we can combine the ideas of the previous sections and maximize the output energy of the beam with a fixed back cavity. The output energy due to an input pressure can be calculated as

\[
V^2C = \frac{bL^2d_{31}Z Q_k}{12EI\eta_{33}s_{11}} \left( \frac{C_b}{b^2L^2 + 20EI} \right)^2 \left( 2\eta_{13}bL \right) \frac{z_k - z_{k-1}}{z_k - z_{k-1}}.
\]

This equation can be rearranged and written in terms of \(b\) and \(L\), noting that \(I\) is a function of \(b\) and introducing the term \(\alpha\) to collect the remaining terms

\[
V^2C = \alpha \frac{bL^5}{C_b + \frac{3bL^5}{5Eh^3}}.
\]

This output energy is maximized where the derivative equals zero. The derivative with respect to \(b\) or \(L\) equals zero when the back cavity compliance is equal to the beam compliance. This means that the output energy of a cantilever beam-based piezoelectric microphone with a fixed back cavity volume is maximized when the acoustic compliance of the beam equals the compliance of the back cavity,

\[
\frac{\partial}{\partial b} \left( \frac{V^2C}{P^2} \right) = 0, \quad \frac{\partial}{\partial L} \left( \frac{V^2C}{P^2} \right) = 0 \rightarrow C_b = \frac{3bL^5}{5Eh^3}.
\]

With this knowledge, we can calculate the maximum output energy of microphones for specific device geometries. For example, we can assume a microphone built with the structure shown in Figure 1. If we assume that the electrodes have zero thickness, then \(E\), the effective modulus of elasticity of the beam, is equivalent to \(1/s_{11}\), the modulus of elasticity of AlN in the x-y plane. If this is the case, then the maximum output energy is

\[
\left( \frac{V^2C}{P^2} \right)_{\text{max}} = \frac{1}{16} \frac{bL^5 d_{31}^2}{6h^2 \eta_{33}} = \frac{5}{48} C_b \frac{d_{31}^2}{s_{11}\eta_{33}}.
\]

Because we are ultimately interested in the noise floor of the sensor, we can easily take the noise of the film into account and compute a noise floor. If the dissipation factor of the film is given as \(\tan(\delta)\), then the noise due to this dissipation factor can be computed in volts and converted to a pressure using Equation 6. When converted to an equivalent pressure, the noise is equal to

\[
R. Littrell and K. Grosh

\[
P_n^2 = \frac{64}{\omega} \frac{kT}{bL^5} \frac{h^3 \tan(\delta) \eta_{31}}{d_{31}^2} = \frac{192}{5} \frac{kT}{\omega} \frac{1}{C_b} \frac{\tan(\delta) \eta_{31} \delta_{11}}{d_{31}^2}
\]

(7)

where \( k \) is Boltzmann’s constant, \( T \) is temperature, and \( \omega \) is radian frequency.

We can use this to compute the minimum noise floor achievable by a microphone of this geometry with a given back cavity volume. For example, if the back cavity volume is 3 mm³, then the acoustic compliance of the back cavity equals 21.1 \( \times 10^{-15} \) m³/Pa for air at standard temperature and atmospheric pressure. If we assume that we are using AlN with properties given in Table 2, then the A-weighted noise floor is 27 dB(A) using Equation 7.

**TABLE 2.** Published material properties for aluminum nitride. These are used to calculate the values in Table 3.

<table>
<thead>
<tr>
<th>Value</th>
<th>Units</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>( s_{11} )</td>
<td>( 3.53 \times 10^{-12} )</td>
<td>1/Pa</td>
</tr>
<tr>
<td>( d_{31} )</td>
<td>( -2.65 \times 10^{-12} )</td>
<td>C/N</td>
</tr>
<tr>
<td>( \eta_{33} )</td>
<td>( 95 \times 10^{-12} )</td>
<td>F/m</td>
</tr>
<tr>
<td>( \tan(\delta) )</td>
<td>0.001</td>
<td></td>
</tr>
</tbody>
</table>

Although zero thickness electrodes and zero stray capacitance at the beam base are unrealistic, we can approach these conditions with proper design. Further, there is still much room for improvement over this geometry. For example, the AlN at the tip of the beam has almost no stress and therefore acts as stray capacitance. We can improve this design by adjusting the electrode such that it covers only the basal portion of the beam. The ideal electrode length can be calculated by maximizing the output energy. In the same way, the AlN near the neutral axis of the beam has very little stress and so the output can be further improved by using two center electrodes, leaving a center portion of the AlN for structural support only. These improvements to the design are shown in Figure 8.

**FIGURE 8.** Cantilever beam with improved electrode placement. By removing the electrode from the tip, the output energy is increased because, while the capacitance is decreased, the sensitivity is increased. By moving the electrodes such that the film near the neutral axis does not contribute to the output, the output energy is increased because, while the sensitivity is decreased, the capacitance is increased. Optimal electrode locations can be computed for this geometry.

It is important to note that this analysis only includes the noise from the piezoelectric film. Electrical noise in the amplifying circuitry and damping in the package also contribute to the total system noise floor. We have also ignored the resonance of the beam in this analysis. Because beam compliance and resonant frequency are independent, it is possible to build a microphone with the required compliance such that the resonant frequency is well beyond 20 kHz and does not influence the A-weighted noise floor. There is a trade-off, however, between resonant frequency and device area and so designers may choose to reduce the resonant frequency in order to minimize area.

This analysis can be expanded beyond cantilever beam-based piezoelectric MEMS microphones to include a wide range of geometries. Table 3 shows some example sensor geometries and their associated minimum noise floors. As above, this analysis assumes zero-thickness electrodes, and zero stray capacitance at the base.
TABLE 3. Minimum noise floors for fixed-free cantilever and fixed circular diaphragm microphone structures. This analysis assumes a back cavity volume of 3 mm$^3$ but the results scale with back cavity compliance as shown in Equation 7. This analysis also assumes that the electrodes have zero thickness and only accounts for the noise of the piezoelectric film.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Back Cavity Volume</th>
<th>Minimum Noise Floor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 mm$^3$</td>
<td>27 dB(A)</td>
</tr>
<tr>
<td></td>
<td>3 mm$^3$</td>
<td>25 dB(A)</td>
</tr>
<tr>
<td></td>
<td>3 mm$^3$</td>
<td>24 dB(A)</td>
</tr>
<tr>
<td></td>
<td>3 mm$^3$</td>
<td>23 dB(A)</td>
</tr>
<tr>
<td></td>
<td>3 mm$^3$</td>
<td>22 dB(A)</td>
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CONCLUSIONS

Piezoelectric MEMS microphones have the potential to be high performance microphones. To date, most piezoelectric MEMS microphones have had a high noise floor, which has limited their utilization. These microphones have often suffered from low output energy per input pressure, which means that they have a low sensitivity, low capacitance, or both. This is often caused by using a tensioned membrane as a sensing structure or having non-ideal electrode shapes. When this is the case, the noises from the piezoelectric film and from the circuitry both become more significant. In many cases, piezoelectric MEMS microphones have also suffered from poorly matching the device capacitance to its circuitry.

This analysis summarizes the optimization of cantilever-based microphones but the same analysis can be done for any geometry. Analytic expressions for noise, similar to Equation 7, can be derived for many shapes with a range of boundary conditions. When analytic expressions cannot be derived, numeric methods can be used to calculate the minimum achievable pressure noise using the same technique. In our simulations, the addition of stray capacitance, electrode thickness, and circuit noise typically adds about 3 dB to the minimum achievable noise floor but this is highly dependent upon the specific circuitry used. The addition of acoustic damping further increases the noise floor but it is often not necessary to add so much damping that the effect is significant. To date, we have built a piezoelectric MEMS microphone with a 32 dB(A) noise floor and expect to move closer to the theoretical limits as our designs improve.

REFERENCES