ICA 2013 Montreal
Montreal, Canada
2 - 7 June 2013

Engineering Acoustics
Session 2aEA: Directional and Non-Directional Microelectromechanical Microphones

2aEA4. Leveraging microelectromechanical microphones inherent matching to reduce noise using multiple microphone elements

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Signal-to-noise ratio (SNR) is a critical parameter in the adoption of small scale (~1 mm) microphones for use in hearing aids. As a result, electret microphones have dominated the market since their invention in the 1960’s. Significant effort is being invested to increase the SNR of microelectromechanical (MEMs) microphones near that of electrets. This work covers the approach of using multiple microphone elements to increase SNR. It explores the theory, examines the dependence of the SNR improvement on the matching of the microphone elements and compares measurements on a single element microphone versus a multiple element microphone. Finally, it examines why the MEMs fabrication process lends itself to this usage and compares the trade-offs in scaling elements versus scaling size.

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

Until the 1960’s, condenser microphone usage in hearing aids was made difficult by the need for a polarization voltage of several 100’s of volts and the small capacitance of the microphone element. For these reasons, hearing aid manufacturers were using balanced armature and piezoelectric-ceramic microphones [1]. With the discovery of polymer electret materials in the 1960’s electret condenser microphones (ECMs) became a commercial success and have been the microphone of choice in hearing aid application for the past half a century [2]. Many of the factors that influenced ECMs adoption in the late 60’s and early 70’s exist today for MEMS condenser microphones. These include low-cost, ease of manufacture and environmental stability. Still, it has been difficult to reproduce the SNR achieved by ECMs with MEMS. This paper examines the use of multiple condenser elements in MEMS microphones to reduce SNR to levels more in line with hearing aid ECMs.

NOISE REDUCTION WITH MULTIPLE ELEMENTS

By connecting multiple microphone elements in parallel, a reduction in parallel noise sources can be achieved while maintaining the same signal output [3]. Figure 1 illustrates the circuit equivalent of an $n$ sized array of microphone elements connected to a load $Z_L$.

Assuming linearity, we can solve for the voltage across the load using superposition. This gives

$$
V_{out} = V_1 \frac{Z_2 \parallel Z_3 \parallel \ldots \parallel Z_n \parallel Z_L}{Z_1 + (Z_2 \parallel Z_3 \parallel \ldots \parallel Z_n \parallel Z_L)} + V_2 \frac{Z_1 \parallel Z_3 \parallel \ldots \parallel Z_n \parallel Z_L}{Z_2 + (Z_1 \parallel Z_3 \parallel \ldots \parallel Z_n \parallel Z_L)} + \ldots + V_n \frac{Z_1 \parallel Z_2 \parallel \ldots \parallel Z_{n-1} \parallel Z_L}{Z_n + (Z_1 \parallel Z_2 \parallel \ldots \parallel Z_{n-1} \parallel Z_L)} \tag{1}
$$

where $\parallel$ represents the equivalent impedance operator for two parallel circuit elements

$$
Z_1 \parallel Z_2 = \frac{Z_1 Z_2}{Z_1 + Z_2}. \tag{2}
$$

Assuming identical microphone element voltage $V = V_1 = V_2 = \ldots = V_n$ and matched element impedances equation (1) can be reduced to

$$
V_{out} = \frac{V_1 + V_2 + \ldots + V_n}{n} = V. \tag{3}
$$

FIGURE 1. Equivalent circuit for microphone elements connected in parallel
Following the same procedure from (1) we can calculate the noise. Assuming it is uncorrelated we must take the sum of the noise power

\[
N_{out}^2 = \left( \frac{N_1}{n} \right)^2 + \left( \frac{N_2}{n} \right)^2 + \ldots + \left( \frac{N_n}{n} \right)^2
\]  

(4)

and from (4) we find that

\[
N_{out} = \frac{N}{\sqrt{n}}
\]  

(5)

Where \( N = N_1 = N_2 = \ldots = N_n \).

This leads us to an SNR of

\[
SNR_{dB} = 20 \log_{10} \left( \frac{V_{out}}{N_{out}} \right) = 20 \log_{10} \left( \frac{V_{out}}{N} \right) + 10 \log_{10} (n).
\]  

(6)

The first term on the right of (6) is just the SNR for a single MEMS element. The second term is the benefit we see with the addition of multiple elements. With 2 elements, we will see an SNR increase of 3 dB relative to a 1 element configuration. For 4 elements the benefit will be 6 dB.

The above analysis is valid for noise sources that are in parallel like diaphragm-backplate (motor) damping and barometric relief noise. Other noise sources such as electrical noise from the integrated circuit (ASIC) and thermal noise from resistive acoustic elements prior to the microphone element will not be reduced.

Several other benefits derive from placing microphone elements in parallel and increasing the overall capacitance by a factor of \( n \). First, the circuit noise is reduced because a smaller impedance is connected to it. Second, the \( kT/C \) thermal noise from the high pass filter formed by the condenser and the high impedance ASIC input is reduced. Third, the voltage divider between the motor capacitance and the parasitic capacitances becomes more favorable increasing signal. This will act to increase the SNR because only the acoustical and mechanical components of the noise scale with the increase in sensitivity; thus the total SNR of the system is reduced if electrical noise is a significant contributor.

**ELEMENT PERFORMANCE VARIATION**

We assume above that the microphone elements sensitivity, impedance, and noise are well matched. One may question how valid this assumption is. MEMS microphones are manufactured using a batch process while hearing aid ECMs’ components are manufactured individually and then assembled. As a result, feature dimensions are held to tighter tolerances on MEMS than ECMs. This means MEMS microphones have the potential for less variation of sensitivity and noise than hearing aid ECMs.

Still, stress build up within the MEMS wafer can cause changes to diaphragm compliance. To combat this, it was suggested to discard the traditional clamped diaphragm design in favor of a free-plate diaphragm [4]. Figure 2 shows a two-dimensional cross section of the simply supported, free-plate diaphragm. If the diaphragm uses a free-plate, the stresses are relieved when the diaphragm is released and as long as thickness is well controlled, diaphragm compliance is tightly distributed.
EFFECTS OF VARIATION ON ELEMENTS IN PARALLEL

With hearing aid ECMs, the standard sensitivity tolerance is +/- 3 dB from nominal sensitivity. To further explore what happens when our preceding assumption fails and elements are poorly matched, let’s assume two microphones were picked from the extremes of this specification. Figure 3 below shows the elements connected to an open load assuming their output impedance are identical.

This gives an SNR of

\[ SNR = 20 \log_{10} \left( \frac{v}{N} \right) + 2.55. \]  

The first term on the right represents the SNR of a single motor with output voltage \( v \) and noise voltage \( N \). The second term is the SNR benefit from adding the additional motor with 6 dB more sensitivity and noise. This term is 0.45 dB less than what two perfectly matched microphones would give us in the same configuration according to (6).

ELEMENT SCALABILITY

Another advantage of multiple microphone elements in silicon design is scalability. By starting with a single microphone element and iterating it to create an array, MEMS design can be tailored to the package size of a specific application while circumventing the need to redesign the MEMS condenser structure. Figure 4 shows several MEMS element array options and how their scale can be modified to fit a particular package.
MULTI-ELEMENT MICROPHONE TESTING

Microphone and Test Setup

Five pieces each of the single, dual and quad MEMS microphones similar to those shown in Figure 4 above were built and tested to identify improvements in SNR. Seven ECMs were also tested. MEMS die were placed inside of a package measuring 2.50 x 3.35 x 0.96 mm$^3$ as illustrated in Figure 5. The ECMs measured 2.55 x 3.55 x 1.04 mm$^3$.

Because parts were taken from a production environment, normalizing all of the variables involved in their construction was not possible. Table 1 highlights all differences between the assemblies. MEMS and electret possess a pierce through the diaphragm which is specified relative to the quad. Note that pierce size is applicable to each element of the MEMS die; thus, the single has one large pierce while the quad has four smaller pierces. The quad MEMS dimensions follow those given from Figure 4 above. The back volume is shown on the next line of the table. The final rows refer to front volume, sound inlet dimensions and the ASIC used as an impedance buffer as well as to supply the bias voltage to the two plates of the MEMS microphones.

TABLE 1. Comparison of the MEMS packages
Both response and noise were measured from 100 Hz to 20 kHz. Response was measured in free field conditions using a ½ inch reference microphone. Noise was measured using a PXI-based spectrum analyzer with parts placed inside of a sound isolating fixture.

### Results and Discussion

Figure 6 shows the response curve measured in free field. There is a deviation in the corner frequency of the single MEMS and electret from that of the dual and quad which is due to differences in the pierce resistance and the back volume compliance. In the mid-band the mean sensitivity of the MEMS groups ranges from -57.1 dB on the quad to -58.1 on the dual. Since there are a number of factors influencing sensitivity such as nominal back volume compliance, lot-to-lot variation in mechanical compliance and position of the diaphragm, variation in encapsulant dispensing within the back volume, etc. it’s difficult to isolate the cause. The expectation is that mean sensitivity would be greatest on the quad and least on the single over a large sample. This may be why the quad’s sensitivity is 1 dB higher than the dual for a near similar back volume using the same ASIC. The mean sensitivity of the electrets is -55.2. The high frequency data shows within the MEMS group the quad has the lowest peak frequency while the single has the highest. Since the single MEMS front volume is the smallest and the quad MEMS is the largest, this is consistent with what we would expect. The electrets peak frequency is lower than all MEMS by roughly 5 kHz and is significantly more damped.

<table>
<thead>
<tr>
<th>MEMS Elements</th>
<th>Single</th>
<th>Dual</th>
<th>Quad</th>
<th>Electret</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Package Size (L x W x H)</td>
<td>3.35 x 2.50 x 0.96</td>
<td>3.35 x 2.50 x 0.96</td>
<td>3.35 x 2.50 x 0.96</td>
<td>3.55 x 2.55 x 1.04</td>
<td>mm³</td>
</tr>
<tr>
<td>Pierce Diameter</td>
<td>~4X Quad</td>
<td>~2.5X Quad</td>
<td>Ref</td>
<td>~2X Quad</td>
<td>-</td>
</tr>
<tr>
<td>MEMS (L x W)</td>
<td>~0.5 x ~0.5</td>
<td>~1 x ~0.5</td>
<td>~1 x ~1</td>
<td>-</td>
<td>mm²</td>
</tr>
<tr>
<td>Back Volume</td>
<td>2.7</td>
<td>2.5</td>
<td>2.4</td>
<td>3.9</td>
<td>mm³</td>
</tr>
<tr>
<td>Front Volume</td>
<td>.12</td>
<td>.22</td>
<td>.31</td>
<td>.60</td>
<td>mm³</td>
</tr>
<tr>
<td>Sound Inlet – (Diameter)</td>
<td>0.25 mm</td>
<td>0.25 mm</td>
<td>0.33</td>
<td>-</td>
<td>mm</td>
</tr>
<tr>
<td>– (H x W)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.28 x 1.02</td>
<td>mm²</td>
</tr>
<tr>
<td>ASIC</td>
<td>Type A</td>
<td>Type B</td>
<td>Type B</td>
<td>Type C</td>
<td>-</td>
</tr>
</tbody>
</table>
FIGURE 6. Response from 100 Hz to 20 kHz

Table 2 summarizes the A-weighted noise, 1 kHz sensitivity and the input-referred, A-weighted noise (EIN) for the four unit types tested. A-weighted noise applies the A-weighting filter to the power spectral density curve and then integrates the bands from 20 Hz to 20 kHz. EIN then takes this output-referred noise voltage and transforms it into an equivalent input-referred noise pressure using the 1 kHz sensitivity. Both the A-weighted noise and EIN exhibit a trend of lower noise with increasing number of microphone elements. EIN of the electrets and quad MEMS are within a ½ dB of one another.

Table 2. Summary of noise and sensitivity performance for single, dual and quad MEMS microphones.

<table>
<thead>
<tr>
<th>MEMS</th>
<th>A-weighted Noise (dBVrms)</th>
<th>1 kHz Sensitivity (dB re 1 Vrms/0.1 Pa)</th>
<th>EINA (dB SPL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single</td>
<td>-101.0</td>
<td>-57.2</td>
<td>30.2</td>
</tr>
<tr>
<td>Dual</td>
<td>-102.9</td>
<td>-58.1</td>
<td>29.1</td>
</tr>
<tr>
<td>Quad</td>
<td>-103.7</td>
<td>-57.1</td>
<td>27.3</td>
</tr>
<tr>
<td>Electret</td>
<td>-102.2</td>
<td>-55.2</td>
<td>27.0</td>
</tr>
</tbody>
</table>

Figure 7 shows the input-referred noise in third-octave bands, a standard method for presenting noise in hearing aids. Note that in this case, no A-weighting is present. Again we see a reduction in the noise over the test frequency band with increasing number of MEMS elements. The reduction is most pronounced at the high frequencies where damping noise persists. At low and mid-frequencies reduction noise reduction is from the pierce. The quad MEMS noise is slightly better than the electret in all frequency bands.
CONCLUSION

Use of multiple elements in parallel to improve SNR brings MEMS condenser microphones performance closer to ECMs. It also allows for better scalability of design based on package size. A MEMS batch process based on a free-plate design lends itself to multiple element design because it assures well matched elements within wafer.

ACKNOWLEDGMENTS

Time to produce this report, microphones and measurements were all done in conjunction with Knowles Electronics. Thanks to the prototype operators for assistance in data collection and Daniel Warren for his recommendation to write this paper.

REFERENCES