Enhanced analytical model for micromachined microphones

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Abstract. The advent of silicon micromachining has opened up numerous opportunities for the commercialization of many miniaturized sensors. Coupled with matured silicon technology, one of the beneficiaries is the capacitive micromachined microphone, a simple yet very elegant microsensor. For earlier MEMS microphones, because of the constraints of surface micromachining, a thin layer of air is enclosed within an etched cavity between a diaphragm and a backplate. Bulk micromachining, coupled with wafer bonding and DRIE (Deep Reactive Ion Etching), provides another attractive avenue of fabricating better performance and robust MEMS microphones. As a result, a more accurate and reliable modeling approach is required to reflect the shift in fabrication techniques. The theory of a condenser microphone is reviewed. With reference to a B & K MEMS microphone, the theoretical results are compared, which demonstrate good agreements with those reported experimental ones. In addition, the positive effect of an acoustic slot around the circumference of a backplate is also demonstrated.

1. Introduction
Microphones are electromechanical transducers that convert an incident pressure into a corresponding electrical output. There are many well-established transduction principles but the capacitive (or condenser) microphone [1] stands out due to its high sensitivity, low power consumption, high noise immunity and flat frequency response. An elastic diaphragm and a perforated rigid backplate constitute a pair of sensing electrodes, which behaves like a variable capacitor. Fine arrangement of holes in the backplate weakens the air dampening effects, which ensures a flat frequency response.

In the design of earlier MEMS microphones [2–4], only a thin air gap was implemented. Thus, holes in the backplate assist in removing the sacrificial layer between the diaphragm and the backplate to release the diaphragm and create an air gap. So, the usual backplate design is to provide for numerous uniformly distributed etched holes. However, numerous holes may lead to a degradation of the microphone sensitivity through an excessive capacitive signal loss. Although it can be overcome by an increase in the polarization voltage, the diaphragm pull-in voltage is severely limited by the thin air gap. Only a thin backplate material can be deposited by surface micromachining. Thus, the stiffness of the backplate is further compromised by the presence of numerous holes. The outcome is a pair of deformable electrodes, which is an undesirable scenario that many will attempt to avoid.

Bulk micromachining, together with wafer bonding and DRIE, offers another attractive option to fabricate MEMS microphones, as demonstrated recently in [5]. For a thin rigid backplate, a stiffer material, such as silicon nitride, can be selected. If silicon is preferred, then a thicker layer has to be used. With DRIE, etching through-holes in a thick silicon wafer to form acoustic holes is now a relatively simple task. With wafer bonding, a large air gap, as well as an acoustic slot around the
circumference of the backplate, can be realized. These two features enable the elimination of numerous etched holes, which are primarily needed to reduce the air damping effects. The expected sensitivity drop is not an issue as the large air gap permits a large polarization voltage. Therefore, a more accurate model is required to reflect the shift in the fabrication techniques.

A common approach to model a microphone is the lumped elements method [2–4]. Through the use of analytical expressions, mass, compliance and damping have their equivalent electrical counterparts in inductance, capacitance and resistance respectively. Although these expressions are easy to apply, they do have their inherent limitations. Earlier MEMS microphone designs did not cater for an acoustic slot around the circumference of the backplate. Hence, the beneficiary incentive that accompanied the slot was not examined and fully exploited. In this paper, the theory of a condenser microphone by Zuckerwar [7] is reviewed. With reference to a B & K MEMS microphone [5], the theoretical results are compared, which demonstrate good agreements with those reported experimental ones. The effect of an acoustic slot on frequency response and air resistance (or mechanical-thermal noise [6]) plots are presented and discussed. Table 1 tabulates the parameters of the B & K MEMS microphone. Figure 1(a) illustrates the nomenclature of the B & K MEMS microphone while figure 1(b) illustrates the arrangement of acoustic holes and slot in the backplate.

| Parameters                        | Symbol | Value         |
|-----------------------------------|--------|---------------|
| Diaphragm radius                  | \( a \) | 1.95 mm       |
| Diaphragm thickness               | \( d \) | 0.5 \( \mu \)m |
| Diaphragm mass surface density    | \( \sigma_M \) | 0.0015 kgm\(^{-2}\) |
| Diaphragm tension                 | \( T \) | 170 Nm\(^{-2}\) |
| Backplate radius                  | \( b \) | 1.4 mm        |
| Unpolarized air gap               | \( h \) | 20 \( \mu \)m |
| Backchamber volume                | \( V \) | 7.6 \( \times \) 10\(^{-8}\) m\(^3\) |
| Location of slot                  | \( a_1 \) | 1.675 mm      |
| Slot width                        | \( r_1 \) | 0.55 mm       |
| Slot depth                        | \( l_1 \) | 0.15 mm       |
| Number of holes per radius ring   | \( b_2 \) | 4             |
| Location of radius ring           | \( a_2 \) | 0.55 mm\(^a\) |
| Hole radius                       | \( r_2 \) | 0.04 mm\(^a\) |
| Hole depth                        | \( l_2 \) | 0.15 mm       |
| Polarization voltage              | \( E_0 \) | 200 V         |
| Microphone capacitance            | \( C_{mic} \) | 3.5 pF        |
| Preamplifier input capacitance    | \( C_i \) | 0.4 pF        |
| Stray capacitance                 | \( C_s \) | 5.1 pF        |

\(^a\)Approximated from the optical microscope photograph in [5].

2. Review of condenser microphone theory
The pull-in voltage and the transfer functions of the microphone will be presented, which follow the analysis of Zuckerwar [7]. The theoretical considerations are based on a circular diaphragm with a radius \( a \).

2.1. Pull-in voltage
For a piston model and a rigid backplate, the critical diaphragm pull-in voltage can be given by


\[
E_{\text{critical}} = \left( \frac{64Th^3}{27\sigma_M a^2} \right)^{1/2}
\]

(1)
where \( \varepsilon_0 \) is the dielectric permittivity of free air \((8.85 \times 10^{-12} \text{ Fm}^{-1})\). If the diaphragm is very thin and has a high residual stress, then the pull-in voltage needs to be multiplied by a factor of 0.82 \([1, 8]\).

**Figure 1.** B & K MEMS microphone: (a) Nomenclature and (b) Arrangement of acoustic holes and slot in the backplate \([5]\).

### 2.2. Electrical transfer function

The electrical transfer function of the microphone can be approximated by

\[
M_e = \frac{E_c}{h_0} \left(1 - \frac{b^2}{2a^2}\right)
\]

where \( h_0 \) is the dynamic air gap. The correction factor of \((1-b^2/2a^2)\) \([9]\) significantly improves the electrical description of the microphone.

### 2.3. Mechanical transfer function

Each hole is assigned a number \((k = 1, 2, \ldots q)\) where \( q \) is the total number of holes. If a slot is present, it is assigned as \( k = 1 \). An equivalent circuit of the backplate and the backchamber is shown in figure 2.

**Figure 2.** Equivalent circuit of the acoustic slot and holes in the backplate.

The equations of the impedance circuit can be written in a matrix form

\[
P = ZU
\]

where \( P \) is the \((q \times 1)\) pressure matrix, \( U \) is the \((q \times 1)\) volume velocity matrix and \( Z \) is the \((q \times q)\) acoustic impedance matrix,
The acoustic impedance of the backchamber, $Z_C$, can be given as

$$Z_C = \frac{\gamma \rho_c c_T^2}{j \omega V}$$  \hspace{1cm} (5)$$

where $\gamma$ is the specific heat ratio of air (1.403), $\rho_c$ is the air density (1.205 kgm$^{-3}$), $c_T$ is the isothermal sound speed in air (290.2 ms$^{-1}$) and $\omega$ is the angular frequency. The acoustic impedance of the $k$th opening of the backplate can be given as

$$Z_k = \left( \frac{8 \omega \rho_c \mu}{\pi r_k^2} \right)^{1/2} \left( 1 + \frac{l_k}{2 r_k} \right) + j \frac{\omega \rho_c (l_k + 1.7 r_k)}{2 \pi r_k^2}$$  \hspace{1cm} (6)$$

where $\mu$ is the absolute air viscosity (17.9 x 10$^{-6}$ Nsm$^{-2}$) and $r_k$ is the hole radius. The acoustic impedance of the slot in the backplate can be given as

$$Z_k = \left( \frac{2 \omega \rho_c \mu}{\pi r_k a_k r_k} \right)^{1/2} \left( 1 + \frac{l_k}{2 r_k} \right) + j \frac{\omega \rho_c l_k}{2 a_k r_k}$$  \hspace{1cm} (7)$$

where $r_k$ is the slot width. Without going into the details of further mathematical derivations, of which can be found in [7, 10], the mechanical sensitivity of the microphone can be written down as

$$M_m = \frac{1}{TK^2} \cdot \frac{J_2(Ka)}{J_0(Ka) + D}$$  \hspace{1cm} (8)$$

where $J_0(Ka)$ and $J_2(Ka)$ are the zero and second order Bessel functions of $Ka$ respectively and $D$ is given in [7].

Figure 3 illustrates the acoustical lumped elements equivalent circuit of the microphone. At frequencies well below the first resonant frequency of the diaphragm, the diaphragm mass, diaphragm compliance, air compliance and air resistance can be expressed respectively as

$$M = \frac{4\sigma M}{3\pi a^2}$$  \hspace{1cm} (9)$$

$$C_M = \frac{(\pi a^2)^2}{8\pi T}$$  \hspace{1cm} (10)$$
The mechanical-thermal noise can be expressed by

\[ n = \sqrt{4k_BT \Delta f_A} \]  

where \( k_B \) is the Boltzmann constant and \( T \) is the absolute temperature (K).

3. Results and discussions

As illustrated in figure 4 and table 2, the theoretical results are in good agreements with those reported experimental ones.

**Figure 4.** Normalized frequency response of the B & K MEMS microphone. Measured response is taken from [5].

**Table 2.** Theoretical and experimental results of the B & K MEMS microphone.

| Parameters          | Symbol | Theoretical | Experimental [5] |
|---------------------|--------|-------------|------------------|
| Pull-in voltage     | \( E_{critical} \) | 254 V       | 255 to 263 V     |
| Open-circuit sensitivity | \( M_{oc} \) | 23 mVPa\(^-1 \) | 22 mVPa\(^-1 \) |
| Bandwidth           | \( BW \)   | 15 kHz      | 15 kHz           |
| Thermal noise\(^b\) | \( V_T \)  | 23.0 dBA    | 23.0 dBA         |

\(^b\)Theoretical values at 250 Hz.
3.1. Effect of acoustic slot

There is an optimum size [9, 10] for the backplate that states that the ratio of the backplate radius to the diaphragm radius is 0.8165, which implies an acoustic slot around the circumference of the backplate. The B & K design has a ratio of 0.7179 and for comparison purpose, the slot is intentionally removed. Figure 5(a) and 5(b) illustrate the effect of a slot on the frequency response and $R_A$ plots respectively. No significant deviations in microphone sensitivity, bandwidth and $R_A$ are observed between B & K design (0.7179) and the optimum design (0.8165). For the frequency response plot, with a slot, the bandwidth is significantly larger. For the $R_A$ plot, with a slot, $R_A$ drops significantly. With a slot, the surface area of the backplate is reduced. This reduction in surface area leads to less damping and thus, a subsequent increase in bandwidth and a decrease in $R_A$.

Figure 5. Effect of an acoustic slot on (a) frequency response and (b) $R_A$.

4. Conclusion

The shift in the fabrication of MEMS microphones from surface to bulk micromachining necessitates a more accurate and reliable modeling approach. The theory of a condenser microphone, covering both the electrical and the mechanical transfer functions, is reviewed. With reference to a B & K MEMS microphone, the theoretical results are in good agreements with those reported experimental ones. It is concluded that an acoustic slot, which is absent from earlier MEMS microphones due to fabrication constraints, is essential for fabricating better performance microphones.

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