ANALYSIS OF A CONDENSER-MICROPHONE USING GENERAL-PURPOSE CIRCUIT SIMULATION PROGRAMS

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ABSTRACT

Equivalent circuit modelling of a parallel plate microphone makes simulation of acoustical sensitivity extremely simple with SPICE. In this paper the macromodel for the design of a condenser-microphone suitable for applications in hearing aids is proposed. As all the mechanical lumped elements are parameterized, it is simple for the designer to vary these parameters and measure the effects on the microphone performance. Moreover, the designer can simulate geometrical variations to estimate the performance of the designed microphone.

1. INTRODUCTION

For many years the design and fabrication of a fully integrated microphone compatible with standard IC fabrication process has been an area of great research. The first subminiature microphone was a hybrid transducer because the diaphragm and the backplate were fabricated separately [1 to 5]. Today, the second generation of fully integrated microphones uses silicon micromachining techniques, which allows accurate control of the dimensions with good reproducibility. Furthermore, no bonding techniques are required [6,7]. However, all the condenser microphones that have been reported up to now do not meet the acoustical sensitivity for application in hearing aids in the entire audio frequency range.

To investigate the electromechanical performance of a parallel plate system, a macromodel for the design of a condenser microphone suitable for applications in hearing aids is proposed. The paper is organized as follows. The dynamic analysis and the mechanical sensitivity S_m of the microphone are presented in section 2. The electrical model of a condenser microphone and its preamplifier is discussed in section 3. Comparison between experimental data reported previously and those given with our macromodel are presented in section 4. At the end of the paper the conclusions are given.

2. ELECTROACOUSTIC ANALOGY

The average diaphragm displacement $W_p(s)$ in the Laplace variable s is given by [3], [8]

$$W_P(s) = \frac{AP}{s z_m} \qquad (1)$$

where A is the diaphragm area, P is the sound pressure and z_m is the mechanical impedance of the microphone. Because the acoustical behaviour of the air-gap due to streaming resistances and compliances determines the frequency behaviour of the microphone, we can optimize the sizing of the microphone with a model of discrete acoustical impedances. The definitions of these elements can be found elsewhere [3], [8 to 10]. The average diaphragm displacement in terms of the microphone parameters is given by

$$W_p(s) = AP\left[s^2\left(L_r + L_e + L_d\right) + sR_r + \left(\frac{1}{C_d} + \frac{1}{C_v}\right) + sL_g H(s)\right]^{-1} \qquad (2)$$

In this electroacoustic analogy, inductance is equivalent to mass, capacitance to compliance and resistance to friction. The Eq.(2) considers a backchamber, which is used in some electroacoustic transducers [2,4,11,12]. Furthermore, *H(s)* is a function that depends strongly on the constructional features of the air-gap:

$$H(s) = \frac{s^3 + s^2 \frac{R_h \| R_a}{L_g} + s\frac{1}{L_{bp}C_{bp}} + \frac{R_h \| R_a}{C_{bp}L_{bp}L_g}}{s^2 + s\frac{R_h \| R_a}{L_{bp}} + \frac{1}{L_{bp}C_{bp}}} \qquad (3)$$

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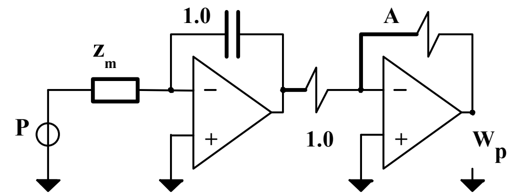

Figure1. Electrical circuit to simulate dynamic displacement of the diaphragm.

An acceptable design of the microphone means reducing function $H(s)$ in Eq.(2). When $H(s) \rightarrow 0$ the average diaphragm displacement is enhanced and $W_p(s)$ can be analyzed as a second order system [9]. To predict both bandwidth and mechanical sensitivity, linear blocks are used, which require only ideal op amps, resistors and capacitors as shown in Fig 1. In the frequency domain the response of the circuit is the increase in the deflection of the microphone diaphragm, resulting from an increase in the pressure acting on the diaphragm. In Fig. 1 sound pressure is similar to excitation voltage and gas flow to current.

3. GENERAL MODEL OF THE MICROPHONE WITH A MOS PREAMPLIFIER CIRCUIT

Because the condenser microphone can be considered as a sound-pressure-sensitive voltage source V_m with an output capacitance C_m, we can calculate the acoustical sensitivity, $S_v=\partial V_{out}/\partial P$, and the frequency response with the electrical model shown in Fig. 2. In this equivalent circuit a bias element having a resistance R_b and a parasitic capacitance C_b is used to provide the input gate with a well defined dc voltage. The preamplifier MOS is assumed to consist of an ideal amplifier of unitary gain with non zero input capacitance C_{in}. Finally, C_p is a parasitic capacitance due to wiring and the total circuit is biased with a dc voltage V_{DD} using an external voltage source. The bias resistance together with the parallel combination of the three capacitance determines the low-frequency cutoff of the microphone:

$$\omega_c = \frac{1}{R_b\left(C_b + C_p + C_m\right)} \qquad (4)$$

Above ω_c the resistance presents a negligible load on the condenser microphone. However, even above ω_c, the stray capacitance still presents a load to the microphone and acts to reduce the acoustical sensitivity. Thus, the output of the preamplifier is

$$V_{out}(s) = KW_p(s)\left(1 + \frac{C_b + C_p + C_{in}}{C_m}\right)^{-1}\left(\frac{s}{s+\omega_c}\right) \qquad (5)$$

where K is given by

$$K = V_{DD}\left(d_{30} + \frac{\varepsilon_3}{\varepsilon_1}\right)^{-1} \qquad (6)$$

and d_{30} is the height of the air-gap, D the diaphragm thickness and ε_1 and ε_3 are the dielectric constants of the diaphragm material and air [13].

4. SIMULATION RESULTS

To investigate the electromechanical performance of the condenser microphone in the entire audio frequency range we can use a general purpose circuit simulator program, such as HSPICE [14]. Using HSPICE we can use just one model for both the frequency domain and the time domain. Furthermore, with this one model we can predict bandwith and acoustical sensitivity (also phase shift, rise time, settling time, overshoot, etc). Because the modelling of a new device requires the determination of all necessary functions, sub-circuits and dependences to generate the desired output, the library file for parameters and constants for the macromodel of the condenser microphone is shown in Fig. 3. The transducer function file, is common for any condenser microphone and is shown in Fig. 4. These functions are created using the LRC equivalent circuit presented in [9].

To determine the validity of the macromodel, we have used the condenser microphone reported in [5,6]. Table I shows the physical dimensions of that design as well as parameters of the fabrication process. The proposed macromodel circuit suitable for the frequency domain is shown in Fig. 5. In the analysis, we have assumed a bias resistor of 25 GΩ [3] and a pressure source of 1 Pa. As Fig. 6 shows, the macromodel (solid lines) correctly simulates

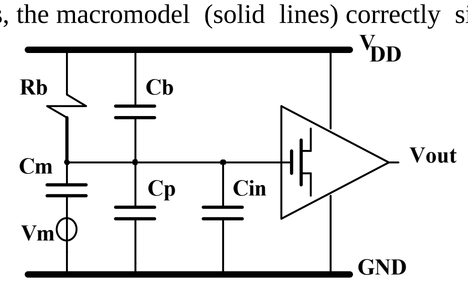

Figure 2. Condenser microphone and its electrical model.

the flat acoustical sensitivity response of the microphone in the entire audio frequency range. The two sets of curves show excellent agreement with the corresponding curves in ref. [5], p. 562, and ref. [6], p. 152. Notice how the experimental data is limited to the range 10 Hz to 10 kHz. On the other hand, as H(s) has a small value its contribution in Eq. (2) can be neglected, which means

```
*PARAM pi=3.1416
+Vdd=2.0                     *bias voltage [V]
+fcb=20                      *low cutoff frequency [Hz]
                             (variable value)
+esin=6.5                    *silicon nitride dielectric constant
+eo=8.854e-12                *vacuum dielectric permitivity [F/m²]
+Do=1.22                     *air density [kg/m³]
+C=3.534e+2                  *sound velocity [m/s]
+Dd=3.3e+3                   *silicon nitride density [kg/m³]
+DAl=2.7e+3                  *aluminum density [kg/m³]
+d30=2.0e-6                  *air-gap height [m]  (variable value)
+D=0.15e-6                   *diaphragm thickness [m]
+De=0.1e-6                   *electrode thickness [m]
+Vair=17.1e-6                *air viscosity [Pa·s]
+Sv=10.0e-3                  *acoustical sensitivity [V/Pa]
+TD=10.0                     *diaphragm tensile stress [N/m]
                             (variable value)
+no=600                      *number of acoustic holes
                             (variable value)
+Ah=1.6e-9                   *acoustic hole area [m²]
                             (variable value)
+A="30*Sv*d30*TD/Vdd"        *diaphragm area [m²]
+Ao="no*Ah/A"                *fraction of area occupied by the
                             acoustic holes
+Cm="eo*A*(1-Ao)/d30"        *capacitance of the microphone [F]
+Rb="1/(2*pi*fcb*Cm)"        *bias resistance [Ω]
+Ae="A"                      *electrode area [m²]
```

Figure 3. Library file for parameters and constants for the macromodel of the condenser microphone.

```
.PARAM
+Ko="log(1/Ao)-(Ao-3)*(Ao-1)/2"
+Rh="Ko*3*Vair*A*A/              *resistance due to acoustic holes
     (pi*no*d30*d30*d30)"        [N·s/m]
+Cb="1/(30*TD)"                  *compliance of the back-plate
                                 [m/N]
+Lb="A*D*Dd*pi*pi*pi*pi/64"      *mass of the back-plate[kg]
+Cd="1/(30*TD)"                  *compliance of the diaphragm
                                 [m/N]
+Ld="A*D*Dd*pi*pi*pi*pi/64"      *mass of the diaphragm [kg]
+Le="Ae*De*DAl*pi*pi*pi*pi/64"   *mass of the electrode [kg]
+Lr="(8/3)*Do*sqrt(A/pi)*
     sqrt(A/pi)*sqrt(A/pi)"      *mass of the air [kg]
+Rr="fo*fo*Do*A*A/(2*pi*C)"      *resistance due to incident sound
                                 [N·s/m]
+Lg="Do*d30*A*pi*pi*pi*pi/64"    *mass of the air between plates
                                 [kg]
```

Figure 4. Library file listing equations that govern condenser microphone operation.

Table I

Parameter	ref. [5]	ref. [6]
A	1.0x1.0 mm²	1.5x1.5 mm²
Acoustic hole area	-	30x30 μm²
Number of acoustic holes	144	800
d_{30}	2.0 μm²	3.3 μm²
V_{DD}	28 V	12.0 V
D	150 nm	1.0 μm
Tensile stress of the diaphragm	45 N/m	150 N/m
Tensile stress of the backplate	-	110 N/m
Diaphragm material	Si_3N_4	Si_3N_4
C_{in}	2.0 pF	2.0 pF
C_m	12.31 pF	4.1 pF

Table I. Physical dimensions and electrical parameters for the design of condenser microphones.

that the damping of the diaphragm is reduced and the average diaphragm displacement can be assumed equivalent to a biquad. Fig. 7 shows the simulation response (given by our macromodel) and the experimental data of the microphone reported in [4]. As can be seen from this plot, the resonant frequency of the microphone is approximately 122 kHz, which agrees well with experiment data. In the second order approximation the resonant frequency is given by

$$f_0 = \frac{1}{2\pi}\left[\frac{\frac{\pi^6}{32}T}{\frac{8}{3}\rho_{air}\left(\frac{A}{\pi}\right)^{3/2} + \frac{\pi^4}{64}\rho DA\left(1+\frac{\rho_e D_e A_e}{\rho DA}\right)}\right]^{1/2} \qquad (7)$$

where ρ is the density of the diaphragm material, T is the tensile stress of the diaphragm, ρ_{air} is the density of air, A_e is the electrode area that makes contact with the diaphragm, and ρ_e is the density of the electrode material and D_e is its thickness. Because Eq. (7) is a better result with respect to those given in [4], we can use this mathematical model to determine the tensile stress of the

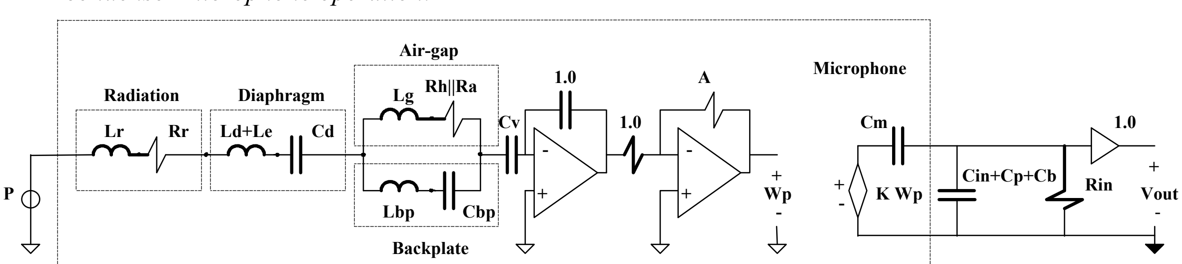

Figure 5. Macromodel equivalent circuit for a condenser microphone.

diaphragm when the microphone is excited with an electrical signal beyond the audio frequency range.

To design a condenser microphone suitable for hearing-aid applications we have scaled the microphone shown in Fig. 8. In this design the polarization voltage was assumed to be 2.0 V. Furthermore, the microcavities reduce the damping of the diaphragm and the floating Si_3N_4-elements form an acoustical hole density per unit area, n. That hole density is responsible for reducing the acoustical resistance $R_a \| R_h$ (any acoustical resistance is defined by $R = R/A^2$ where A is the area of the active face). If $R_a >> R_h$ the cutoff frequency is given by

$$\omega_{cutoff} = \left[\frac{\frac{3\eta A}{\pi n d_{30}^3}\left[\ln\frac{1}{A} - \frac{1}{2}(A_0-3)(A_0-1)\right]}{2\left[\frac{8}{3}\rho_{air}\left(\frac{A}{\pi}\right)^{3/2} + \frac{\pi^4}{64}\rho DA\left(1+\frac{\rho_e D_e A_e}{\rho DA}\right)\right]}\right]^{1/2} \qquad (8)$$

where A_0 is the fraction of the backplate occupied by the acoustic holes and η is the viscosity of air. The simulation results of the proposed microphone in Fig. 9 show that a flat response is possible when the backplate is provided with many acoustic holes (568, 40.0x10.0 µm² each) and an air-gap height of 1.0 µm. The bias resistor has a value of 1.0 GΩ, which can be implemented with the cross-.coupled current-cancellation technique proposed in [15]. As shown in Fig.8, the acoustical sensitivity is 10 mV/Pa and the cutoff frequency is approximately 70 kHz. Furthermore, using a pressure reference of 25 µPa (at 1.0 kHz) the equivalent noise pressure is about 22 dB(A). This microphone would be adequate for many low-noise applications [16].

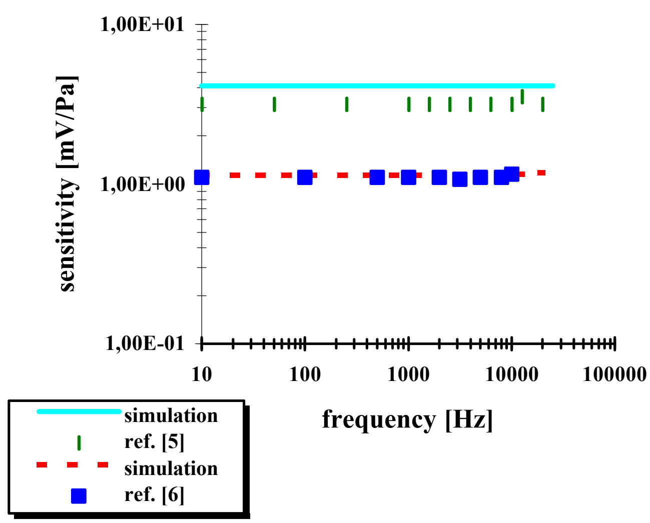

Figure 6. Acoustical sensitivity versus frequency. Solid line and dotted line: simulation. Symbols: experimental data.

Finally, the acoustical sensitivity in the Laplace variable s is given by

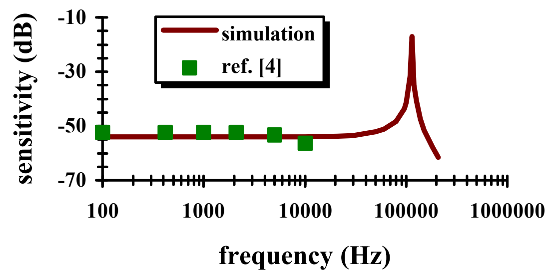

Figure 7. Acoustical sensitivity (referred to1.0 V/Pa) versus frequency. The experiment gives a resonant frequency of 120 kHz [4].

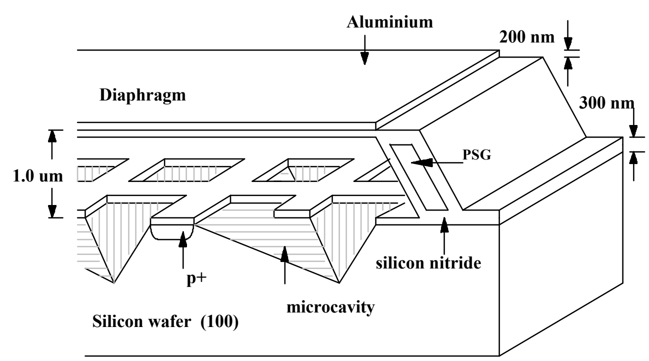

Figure 8. A schematic cross-section of the silicon condenser microphone (not to scale).

$$S_v(s) = K\left(1+\frac{C_b+C_p+C_{in}}{C_m}\right)^{-1}\frac{\left(\frac{As}{s+\omega_c}\right)}{s^2\left(L_r+L_e+L_d\right)+sR_h+\frac{1}{C_d}} \qquad (9)$$

and the open circuit sensitivity $S(s)$ can be found if $R_b=\infty$.

5. CONCLUSIONS

We have tackled the problem of developing a condenser microphone macromodel that can simulate acoustical sensitivity in the frequency domain. The macromodel consists of only 14 passive elements and 3 linear VCVS's. This simplicity of the macromodel together with the fact that only one "pressure source" is employed makes the macromodel suitable for CAD. Furthermore, the macromodel has been verified by comparing the results of circuit simulations with results reported earlier.

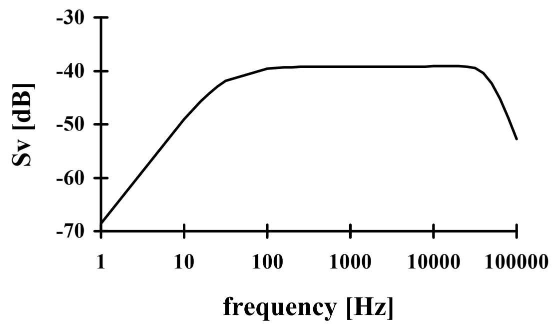

Figure 9. Frequency response for a microphone (referred to 1.0 V/Pa) with diaphragm area of 1.3x1.3 mm², tensile stress of 10 N/m, A_0=0.67, A_e=755.0x755.0 μm², C_m= 5.0 pF, S_m=5.7 nm/Pa and 142 microcavities (90.0x90.0 μm² each).

The goal of this work is to develop tools that allow the IC designer to produce complex designs in less time with an acceptable confidence in the systems's predicted performance.

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