PRELIMINARY RESULTS OF A SILICON CONDENSER MICROPHONE WITH INTERNAL FEEDBACK

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Abstract

During the last decade, several silicon condenser microphones have been realized. The microphones need a d.c. bias voltage, which can be accomplished by a built-in electret or by an external supply. This bias-voltage should be as large as possible in order to get a high sensitivity. However, a too large bias voltage will reduce the operating range and shock resistibility of the microphone. In order to overcome this and to increase the bandwidth of silicon condenser microphones with small air gaps, an electrostatic feedback system is presented that will reduce the movement of the diaphragm of the microphone.

It is shown that a reduction of the movement of the diaphragm of 10 times is possible for microphones with an air gap of 35 μm. However, to get a reduction of about ten times over a wide range of frequencies, an actuator with a larger sensitivity is needed. This can be achieved by use of a smaller air gap, which may also increase the sensor sensitivity.

Introduction

During the last decade, several silicon condenser microphones have been realized [1-5]. These microphones need a d.c. bias voltage for a proper operation. In some designs a bias voltage of several hundreds of Volts is needed which is accomplished by a built-in electret [3-5], whereas other designs need only a small bias between 10 and 20 V, which is accomplished by an external d.c. voltage [1,2].

In order to obtain a large electrical sensitivity, the bias voltage should be chosen as large as possible, resulting in a large static deflection of the diaphragm. However, if the static deflection is too large, problems concerning shock resistibility and desired operating range can be expected, which may result in a collapse of the diaphragm to the back plate.

Another problem is the frequency dependence of the sensitivity of the microphone. If the air-gap between the diaphragm and the back plate is very small, the acoustic resistance of the air-gap will reduce the mechanical sensitivity of the microphone for higher frequencies. With an air-gap of 2 μm, a cut-off frequency of 2 kHz has been measured by Hohm et al. [1].

In order to reduce the effects as mentioned above, a mechanical feedback system is proposed, which will reduce the acoustically induced movement of the diaphragm.

Theory of the feedback microphone

In Fig. 1 a feedback microphone is presented, containing two electrodes on the diaphragm. One of them (E_1) is used as the sensor electrode, and the other (E_2) is used as an actuator electrode. The electrode E_2 is used to generate an electrostatic force between the diaphragm and the back plate. As can be seen from Fig. 1, an increase in the deflection of the diaphragm due to an acoustic pressure will cause a decrease in the sensor voltage. This results in a decrease in the actuator voltage v_a, causing a decrease in the electrostatic attractive force between diaphragm and back plate. This decreasing electrostatic force will compensate the change of the deflection as mentioned above.

Unfortunately, a few problems will reduce the performance of the system.

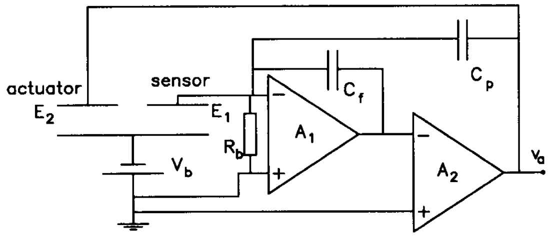

Fig.1 Feedback microphone with additional electronic circuit (V_b is the d.c. bias voltage).

The feedback force will only be present between the actuator electrode and the back plate. This force differs from the force between the sensor electrode and the back plate. A mechanical deformation of the diaphragm can be expected. This effect can be reduced by using interdigitated electrodes E_1 and E_2, as shown in Fig. 2. The more fingers are used, the smaller the deformation of the diaphragm will be.

A disadvantage of choosing a very fine structure with many fingers, as shown in Fig. 2, is the increase in the parasitic capacitance C_p between E_1 and E_2. As can be seen from Fig. 1 this parasitic capacitance acts as a positive feedback which will reduce the stability of the feedback system. To overcome this effect a capacitance C_f is introduced, as will be discussed later.

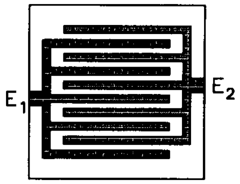

Fig.2 Shape of the sensor (E_1) and the actuator (E_2) electrode.

An additional problem will be the over-all stability of the feedback microphone. The dynamic behavior of the microphone and the bandwidth of the amplifiers will determine the dynamic performance of the system.

The three problems will be discussed in the next Sections.

The mechanical deformation of the diaphragm

As mentioned above, a small number of fingers of both electrodes will reduce the parasitic capacitance C_p between E_1 and E_2. However, the mechanical deformation of the diaphragm will increase. In order to estimate this deformation, a beam with clamped edges is considered, as shown in Fig. 3.

A homogeneous load P_t, acting on the beam between the two edges, and a homogeneous load P_a, counteracting at discrete areas, which are homogeneously distributed along the beam, are considered.

The beam with a length L an a constant width d has no initial stress and only bending is considered, with a linear relation between load and deflection. The calculations are a superposition of a number of homogeneous loads acting on the beam from the beginning ($x=0$) to a distance $x=A_i$.

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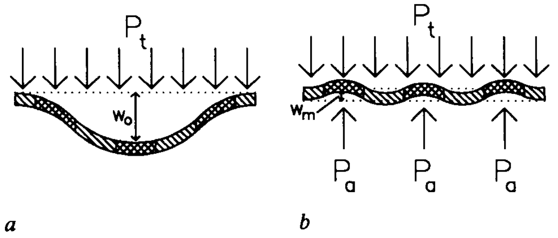

Fig. 3 (a) Deflection of a beam without feedback and (b) with feedback.

The value of P_a is chosen in such a way that the mean value of the deflection equals zero. Then a reduction ratio R is calculated, which is the ratio of the maximum deflection w_m of the beam, when both P_t and P_a are present, and the maximum deflection w_o, when only P_t is present.
In Fig. 4 the simulation results are presented. It shows the reduction ratio as a function of the number of fingers of the actuator. The calculations are provided for three values of the ratio of the total actuator area and the total beam area L·d.

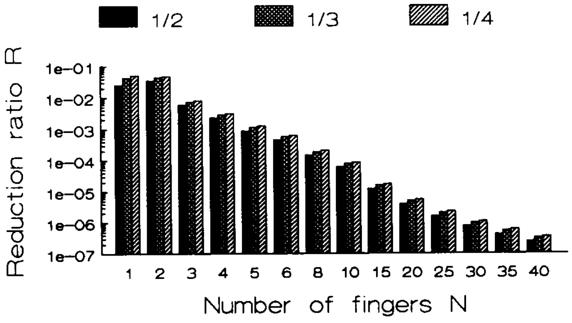

Fig.4 Reduction ratio of the deflection of the beam when actuation at discrete areas is used, for three ratios of the actuator area and the total area L·d.

As can be seen from Fig. 4, a reduction of the deflection of 20 can be reached if only one or two fingers of the actuator electrode are used. If a larger reduction of the deflection is required, more fingers have to be used.

The parasitic capacitance between the electrodes

The capacitance will increase with the number of fingers of the two electrodes. In order to estimate this capacitance, two plates with a length L and width w (L»w), placed at a distance s of each other in one plane, are considered. By using Laplace's equation in two dimensions, $\frac{\partial^2\phi}{\partial x^2}+\frac{\partial^2\phi}{\partial y^2}=0$, and the proper axes of symmetry and boundary conditions, it is possible to calculate the electrical potential ϕ for an infinite repetition of the two plates, if the voltage between the two plates is given. When ϕ is known, the electric field $E=-\mathrm{grad}(\phi)$ and the charge density on the two plates can be calculated, and thus the capacitance C' per unit length between the two plates. The total capacitance between the interdigitated electrodes (Fig. 2) will be:

$$C_p = C'L\,N\,\frac{1+\epsilon_r}{2} \tag{1}$$

with N the repetition rate and ϵ_r the relative permittivity of the diaphragm material.
In Fig. 5 the values of the capacitance C', in pF/mm, are shown as a function of w/s. Note that w/s=1 and w/s=1/2 correspond to the ratio of actuator and diaphragm area of respectively 1/3 and 1/4. With a microphone length L of 2 mm, $\epsilon_r=4$ and N=5, the parasitic capacitance will be 0.42 pF for w/s=1 and 0.33 pF for w/s=1/2.

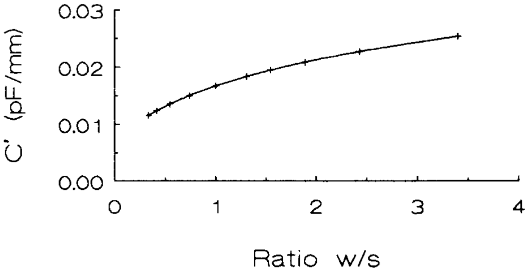

Fig.5 The parasitic capacitance C' per unit of length as a function of the w/s.

It can be concluded that the parasitic capacitance can not be neglected compared to the microphone capacitance of about 1 pF. The influence of the capacitance will be considered in the next Section.

The dynamic performance of the feedback system

As mentioned before, the parasitic capacitance between sensor and actuator C_p will act as a positive feedback in the electronic circuit, causing instabilities. In addition, an increase in this capacitance will reduce the noise performance of the microphone and its preamplifier [6]. In order to compensate these effects, the capacitance should be taken as small as possible and also an extra capacitance C_f is introduced, as shown in Fig. 1. If the amplification A_2 is adjusted well, the positive feedback contribution of C_p is compensated by a negative feedback contribution of C_f.

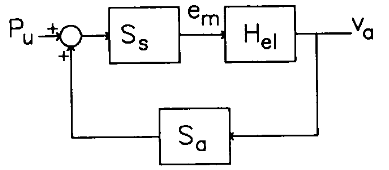

Fig.6 Block diagram of the feedback microphone.

The circuit of Fig. 1 can be replaced by a block diagram as shown in Fig. 6. S_a is the actuator sensitivity $\partial P_e/\partial v_a$ which is equal to

$$S_a = \lambda\epsilon_o V_b/s_a^{\,2} \tag{2}$$

with V_b the electret or external bias voltage and v_a the actuator voltage ($v_a \ll V_b$). The air gap has a thickness of s_a, and the parameter λ depends on the shape and area of the actuator electrode. S_s is the open-loop sensitivity of the microphone e_m/P_u, with e_m the open-loop sensor signal being proportional to the displacement of the diaphragm. S_s, which has a negative value, depends on the diaphragm material, its thickness and its initial tensile stress, the air gap s_a and the voltage V_b. An ideal performance of the feedback system will reduce e_m to zero. The transfer of the sound pressure P_u to v_a in the Laplace domain is

$$\frac{v_a(s)}{P_u(s)} = \frac{s\,R_bA_1A_2C_sS_s}{1+sR_b(C_{tot}+A_1(C_f-A_2C_p)-A_1A_2C_sS_aS_s)} \tag{3}$$

and of P_u to e_m:

$$\frac{e_m(s)}{P_u(s)} = \frac{1+sR_b\,(C_{tot}+A_1(C_f-A_2C_p))}{1+sR_b(C_{tot}+A_1(C_f-A_2C_p)-A_1A_2C_sS_aS_s)}S_s \quad (4)$$

By choosing $C_{tot}+A_1(C_f-A_2C_p)=0$ and A_1 as large as possible, e_m and thus the displacement of the diaphragm will be very small, and Eq. (4) becomes

$$\frac{e_m(s)}{P_u(s)} = \frac{1}{1+sR_b\frac{(C_{tot}+A_1C_f)}{C_p}C_sS_aS_s}S_s \qquad (5)$$

In order to get a good low frequency performance, it is necessary that $\omega R_b\frac{(C_{tot}+A_1C_f)}{C_p}C_sS_aS_s$ is much larger than 1 even for low frequencies and should be equal to 10 in order to get a reduction of the diaphragm movement of 10 times. Thus for $\omega=100$ rad/s ($f=16$ Hz) with R_b = 5GΩ, $|S_aS_s|=0.001$, $C_f=1$pF and $C_s=C_p$, a value of A_1 of 20,000 is needed. For $\omega=0$ there will be no reduction of the movement at all.
At high frequencies phase shifts will occur, due to the dynamic behavior of the microphone and the limited bandwidths of the amplifiers. The amplifiers are considered to be first order systems:

$$A_1 = \frac{k_1}{1+s\tau_1} \text{ and } A_2 = \frac{k_2}{1+s\tau_2} \qquad (6)$$

whereas the microphone can be considered as a second order system, with S_o the d.c. open-loop sensitivity:

$$S_s = \frac{S_o}{1+2\frac{\zeta s}{\omega_n}+\left(\frac{s}{\omega_n}\right)^2} \qquad (7)$$

By using these expressions, Eqs. (3) and (4) can be rewritten into expressions with a fifth-order polynomial function of s in the denominator. By numerical calculations the stability of the fifth-order system has been analyzed. It appeared that the system will be unstable when the value of k_2 is chosen larger than $(C_{tot}/k_1+C_f)/C_p$. When the damping factor ζ is small, a large resonance-peak appears at frequencies around $\omega_n/2\pi$, which even causes oscillations for very small values of ζ.
The bode plots of $e_m/P_u/S_o$ and $v_a/P_u/S_o$ are shown in Figs. 7 and 8, respectively for a few values of ζ and $|S_aS_o|$.

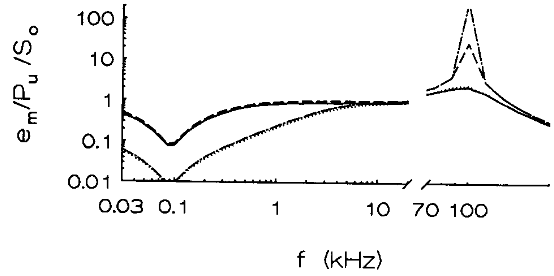

Fig. 7 Bode plots of $e_m/P_u/S_o$ for C_s=0.5 pF, C_p=0.5 pF, C_f=1 pF, R_b=5 GΩ, ω_n=100 kHz, τ_1=100 µs and τ_2=10 ns, for (a) ζ=0.2 and $|S_aS_o|$=0.001, (b) ζ=0.2 and $|S_aS_o|$=0.01, (c) ζ=0.02 and $|S_aS_o|$=0.001, (d) ζ=0.02 and $|S_aS_o|$=0.01.

The values of the capacitances, R_b and ω_n as well as ζ and $|S_aS_o|$ are based on the practical results.
The position of the peak (or dip) at 100 Hz depends on the bandwidth of the amplifiers A_1 and A_2. At this frequency there is no difference in phase between the v_a and e_m and the feedback performance is optimal. For lower frequencies the phase shift between v_a and e_m varies from 0 to 90 degrees (0 Hz). For higher frequencies there is a negative phase shift up to even 180 degrees at the resonance frequency at 100 kHz. At this frequency there is a positive feedback which increases the amplitude of the movement of the diaphragm instead of the desired reduction. This effect increases with decreasing values of the damping ratio ζ.
A good performance of the feedback system can only be expected for values of $|S_aS_o|$ much larger than 0.001, as can be seen from the difference between the curves (a) and (c), and (b) and (d) in Fig. 7. In addition, when $|S_aS_o|$ is very small, the performance of the feedback system is very sensitive to variations of the gain k_2 of the amplifier A_2. A small increase causes instabilities of the feedback system. Finally, only large values of $|S_aS_o|$ will result in values of v_a that are frequency-independent.

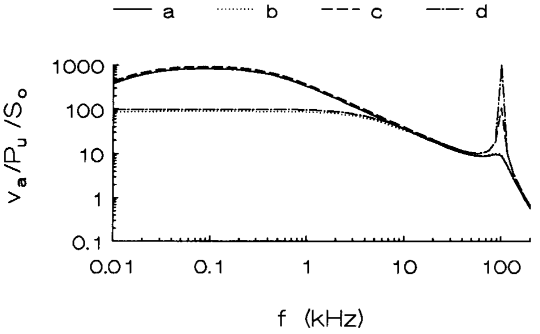

Fig. 8 Bode plots of $v_a/P_u/S_o$ for C_s=0.5 pF, C_p=0.5 pF, C_f=1 pF, R_b=5 GΩ, ω_n=100 kHz, τ_1=100 µs and τ_2=10 ns, for (a) ζ=0.2 and $|S_aS_o|$=0.001, (b) ζ=0.2 and $|S_aS_o|$=0.01, (c) ζ=0.02 and $|S_aS_o|$=0.001, (d) ζ=0.02 and $|S_aS_o|$=0.01.

Experimental

Fig. 9a shows a cross-sectional view of a feedback microphone, used for the first experiments. It consists of a rigid silicon back plate (the lower electrode) with an air cavity of 35 µm deep, covered with a SiO_2-layer of about 1 µm. This layer is charged with a corona charging set-up up to a voltage of 150 V. The back plate contains acoustic holes A to reduce the air damping, and glue holes G which are used to attach the Mylar diaphragm to the back plate. The diaphragm is provided with two Au electrodes. In Fig. 9b the top view of this microphone with the two electrodes is presented. The electrode E_1 is the sensor electrode (the actual microphone), while E_2 is used as the feedback electrode.

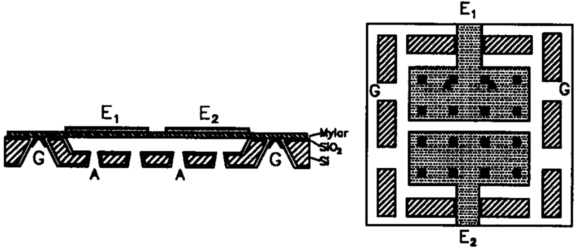

Fig. 9 (a) Cross-sectional view of microphone and (b) top view of the microphone.

The microphone has been used with the circuit of Fig. 1. In addition to the electret voltage of 150 V, an external bias voltage of 320 V was used, resulting in the best performance of the system. A value of 1 pF was taken for C_f, and the gain of A_1 was about 1500. Because S_aS_o, ζ, ω_n and C_p are not exactly known, the gain of A_2 and the bandwidths of A_1 and A_2 were experimentally determined in order to obtain the best performance of the system. The gain of A_2 was 2, τ_2 about 10 μs and τ_1 about 100 μs. It appeared that the stability of the circuit was very sensitive to variations of these parameters, which could result in an oscillation at a frequency of about 100 kHz. The first amplifier is preceded by a source follower with a JFET and bias resistor R_b of 5 GΩ between the gate and ground. Microphones with several electrode shapes were tested and it appeared that the configuration of Fig. 9 showed the best performance.

The optical measurement set-up

In order to test the performance of the feedback system an optical measurement set-up, developed by Twente Technology Transfer, was used to measure the movement of the diaphragm. The set-up comprises a tip with optical fibers, which can measure the curvature of a diaphragm [7].
The distance between the tip and the diaphragm was taken about 2 millimeters, resulting in the highest sensitivity. The large distance makes the measurement set-up also less sensitive to the possible mechanical deformation of the diaphragm.
The optical measurement set-up did not have to be calibrated, because only the ratio of two measurement values (with and without feedback) had to be measured, which gives the reduction of the movement of the diaphragm and thus the value of $e_m/P_u/S_o$.

Experimental results

The measured values of the reduction of the diaphragm movement $e_m/P_u/S_o$ as well as the actuator voltage v_a as a function of the frequency are shown in Fig. 10.

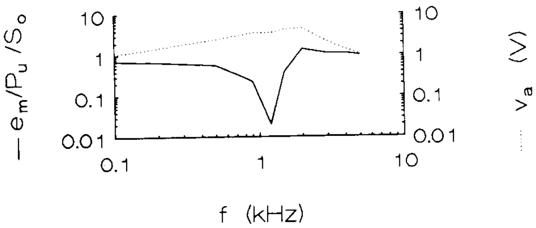

Fig. 10 Measured reduction of diaphragm movement $e_m/P_u/S_o$ and the actuator voltage v_a as a function of the frequency.

The shape of both curves are in good agreement with the curves (a) and (c) in Figs. 7 and 8. Maximum reduction of the diaphragm movement occurs, however, at a frequency of about 1.2 kHz instead of 100 Hz, while the measured lower cut-off frequency of v_a is also higher than about 50 Hz, as would be predicted by Fig. 7. This last effect can be explained by the fact that the value of R_b is frequency-dependent and decreases with increasing frequency [6].
Measurements above about 5 kHz were not possible with the optical measurement set-up, because of its limited bandwidth.
Unfortunately it appears to be impossible to get a reduction of the movement of the diaphragm over a wide range of frequencies, because of the limited value of $|S_aS_o|$, which is apparently about 0.001. However, it is possible to reduce the movement of the diaphragm at least ten times.

Conclusions and suggestions

Feedback of the diaphragm movement in a condenser microphone by means of a controlled electrostatic force between an extra actuator electrode and the back plate is possible, resulting a reduction of the movement of the diaphragm of about 10 times by using two simple rectangular electrodes on the diaphragm. For extra reduction of the movement, interdigitated electrodes with more fingers are needed in order to reduce the mechanical deformation of the diaphragm, as shown in Fig. 4.
The parasitic capacitance between the sensor and actuator electrode causes instabilities due to an electronic positive feedback. By use of an extra capacitor C_f and an inverting amplifier, this effect can be reduced.
Unfortunately, the devices used for the experiments had a too low sensitivity in order to get a reduction of the diaphragm movement over a wide range of frequencies as well as to get a frequency-independent output voltage. According to Eq. (2) the actuator sensitivity can be increased significantly by reducing the air gap of the microphone, which may also result in a larger sensor sensitivity.
The resonance peak at $\omega_n/2\pi$ can be reduced significantly by increasing the damping ratio ζ, which can also be realized by the use of a smaller air gap.
Therefore, new experiments will be done in the future with devices with an air gap of about 1 μm as presented by Scheeper [8].

Acknowledgement

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