Amplitude-modulated electro-mechanical feedback system for silicon condenser microphones

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Abstract. Miniaturization of sensors and actuators has become an important topic during the last decade. For silicon condenser microphones, narrowing the air gap as a part of the miniaturization process causes, however, a reduction of the bandwidth of the microphone. By introducing an actuator electrode on the diaphragm for electro-mechanical feedback, it is possible to increase the bandwidth of condenser microphones with a narrow air gap.

In this paper a feedback system is presented, which uses an amplitude-modulated actuator signal with a carrier frequency far above the audio-frequency range. With feedback, the bandwidth of the microphone is increased by at least a factor 10.

1. Introduction

Present hearing-aid condenser microphones are generally provided with a built-in high-voltage electret [1]. One of the most important design topics nowadays is the miniaturization of these microphones, resulting in, amongst others, a narrowed air gap of only a few micrometers, which allows a much lower bias voltage [2–4]. A major disadvantage of a narrowed air gap appears to be the increased damping of the air in the gap, resulting in a limited bandwidth of the condenser microphone [2–4].

A solution for this problem was presented by Bergqvist *et al* in 1991, who designed a condenser microphone with a highly perforated backplate, resulting in a reduction of the air damping [5].

An alternative solution has been presented by van der Donk *et al* [6], who introduced an electro-mechanical feedback system as shown in figure 1, which reduced the movement of the diaphragm of the condenser micro-

phone by driving it with an electrostatic force counter-acting the force originating from the sound pressure. Unfortunately, this system suffered from stability problems due to the presence of a parasitic capacitance between the actuator part and the sensor part of the diaphragm. This capacitance caused a positive feedback in the system.

In this paper a feedback system will be presented that eliminates the effect of this parasitic capacitance.

2. Theory of electro-mechanical feedback

In figure 1(a) a simplified representation of the electro-mechanical feedback system is shown. The diaphragm of the condenser microphone is provided with two interdigitated electrodes E_1 and E_2 , as shown in figure 1(b). A bias voltage V is used to obtain a DC electric field in the air gap.

E_1 is used as the sensor electrode, and the other

Figure 1. (a) The electro-mechanical feedback system for a condenser microphone. (b) Top view of the diaphragm with the sensor (E_1) and the actuator electrode (E_2).

electrode E_2 is used to drive the diaphragm with an electrostatic force. As can be seen from figure 1(a), an increase in the deflection of the diaphragm due to an acoustic pressure causes a decrease in the sensor voltage v_s . Due to the positive gain of the amplifier, A , the actuator voltage v_a decreases too, causing a decrease in the electrostatic attractive force between the actuator electrode and the backplate. Consequently, this actuator force compensates the initial movement of the diaphragm.

Unfortunately, a capacitance C_d between the two electrodes on the diaphragm, which depends on the number of fingers and the lay-out of the wiring, acts as a positive feedback, causing an unstable behaviour of the system if the gain A of the amplifier is chosen to be too large [6]. By driving the actuator with a high-frequency electrical signal and using filtering techniques, it is possible to eliminate the positive feedback of the capacitance between the two electrodes, as will be explained in the next section.

3. Amplitude-modulated actuator signal

The attractive force per unit area between the two plates of a condenser microphone, which have opposite charges, can be expressed as

$$P_a = (\epsilon_0/2s_a^2)(v_a + V)^2 \quad (1)$$

where s_a is the air-gap thickness, ϵ_0 the electrical permittivity of vacuum, V is the DC voltage between the diaphragm electrode and the backplate, and v_a is a

driving AC voltage, the actuator signal. By using an amplitude-modulated actuator signal, having the shape

$$v_a = \hat{v}_0(1 + \alpha \sin \omega_a t) \cos \omega_c t \quad (2)$$

with $\hat{v}_0$ and ω_c the amplitude and the frequency of the carrier signal and $\alpha \sin \omega_a t$ the audio-frequency modulation depth, the expression of the driving actuator force per unit area can be calculated by substituting equation (2) into (1). The components of the force with frequencies of the order of ω_c and higher will not have any effect on the movement of the diaphragm, because of the limited bandwidth of the microphone. If only the low-frequency terms of P_a are considered, P_a becomes

$$P_a = (\epsilon_0/2s_a^2)(V^2 + \frac{1}{2}\hat{v}_0^2 + \frac{1}{4}\alpha^2\hat{v}_0^2 + \alpha\hat{v}_0^2 \sin \omega_a t - \frac{1}{4}\alpha^2\hat{v}_0^2 \cos 2\omega_a t). \quad (3)$$

If $\alpha \ll 1$, the AC part of P_a becomes proportional to the amplitude $\alpha\hat{v}_0$ of the modulation signal. In figure 2 the feedback system is shown, which uses an amplitude-modulated actuator signal. The low-pass filter is used to extract the actual sensor signal, which is proportional to the diaphragm movement, and to eliminate the high-frequency terms.

4. Experimental procedure

For the experiments, two types of microphones, with $s_a = 2 \mu\text{m}$ and $V = 7 \text{ V}$, are used:

Type I. Microphones with interdigitated electrodes with 2 fingers and 16 acoustic holes in the backplate.

Type II. Microphones with electrodes with 10 fingers and 81 acoustic holes.

In figure 3(a) a typically measured open-loop sensitivity for sound pressure is shown for both microphone types. In order to analyse in addition the frequency dependence of the open-loop actuator sensitivity, the actuator has been driven with a signal as described in equation (2) with $\hat{v}_0 = 5.8 \text{ V}$ and $\alpha = 2.5/5.8 = 0.43$. In figures 3(b) and 3(c) the amplitude and the phase of the sensor voltage v_u are shown as a function of the frequency f for both open-loop actuated microphone types. From figures 3(a) and

Figure 2. The amplitude-modulated feedback microphone.

Figure 3. (a) Typical measured open-loop sensitivity of microphones, (b) typical measured open-loop amplitude, and (c) phase of the sensor voltage of microphones, actuated with an amplitude-modulated signal with a carrier frequency of 1 MHz.

Figure 4. Typical measured frequency response of a feedback microphone, with a carrier frequency of 1 MHz, for two microphone types.

3(b) it can be seen that the microphones have a first-order frequency response for sound pressure and for an electro-mechanical driver, with a cut-off frequency at approximately 30 Hz for type I and 400 Hz for type II. From figure 3(c) it can be seen that the phase difference between the modulation signal and v_u is much more than the 90 degrees which would be expected for a first-order system. This extra phase shift is probably due to a mechanical coupling between the actuator and the sensor as will be explained in the discussion, and may cause an unstable closed-loop system if the gain A of the amplifier, which is shown in figure 2, is chosen to be too large.

In figure 4 the normalized output voltage v_u of the closed-loop system of figure 2 is shown, for an optimally matched gain A being approximately 800 for microphone type I and 2500 for type II. Larger values of A cause a large resonance peak or even instability of the feedback system. Smaller values of A result in a smaller bandwidth of the feedback system. In spite of this limitation, a comparison of figures 3(a) and 4 shows an improvement of the frequency response of approximately 7 times for type I and 17 times for type II, if feedback is used. The bandwidth has become 200 Hz for type I and 7 kHz for type II.

5. Discussion

As mentioned in the previous section, an unfavourable phase shift between the modulation signal and the sensor signal, which is a measure of the movement of the diaphragm, occurs. This phase shift can be explained by a lateral flow of the air in the air gap; this effect is modelled by the piston system, shown in figure 5.

The diaphragm is considered to consist of two pistons, being the actuator piston (left) and the sensor piston (right). The actuator force F_a drives the left piston directly, and the sensor piston indirectly. Both parts of the diaphragm are characterized by a mechanical sensitivity, described by the two springs with a stiffness constant c_0 . The mechanical coupling between the two parts of the diaphragm is described by the spring with a stiffness constant c_c .

The chambers below the pistons represent the air gap

Figure 5. Mechanical representation of the condenser microphone.

below the two parts of the diaphragm. The air can flow into or out from the air gap through the acoustic holes on the bottom of the chambers. The damping of this air flow is described by the mechanical resistance R_a . It is also possible that the air flows from the left chamber into the right chamber in a lateral direction, introducing a counteracting force on the right piston. Consequently, the sensor piston moves in the opposite direction, introducing an extra phase shift. This effect is determined by the mechanical resistance R_1 , and becomes more dominant with increasing values of R_a and for high frequencies.

Microphone type II has a relatively stiff coupling spring c_c , because more electrode fingers are used compared with type I, and a relatively small value of the resistance R_a , because of the larger number of acoustic holes in the backplate compared with type I. This explains that the best results are obtained with microphone type II, which allows a larger gain A before instability occurs.

A quantitative approach for this piston is beyond the scope of this paper, but will be discussed in a forthcoming paper.

6. Conclusions

A significant increase in the bandwidth of condenser microphones can be obtained if electro-mechanical feedback is used. The maximum bandwidth that can be obtained depends mainly on the shape of the electrodes on the diaphragm and the number of acoustic holes in the backplate, determining the values of R_a , R_1 , c_0 and c_c in the model of figure 5.

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