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Large signal performance of micromachined silicon inductive microphones

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Abstract

A mathematical model for the open-circuit output voltage of a micromachined silicon inductive microphone is presented. The model, basically a sine-series function, can easily yield closed-form expressions for the amplitudes of the output components resulting from a multisinusoidal input acoustic pressure. The special case of an equal-amplitude two-tone acoustic pressure input is considered in detail. The results show that, the microphone generates both even and odd-order harmonic and intermodulation products.

Keywords: Inductive microphones; Sensors; Intermodulation

1. Introduction

Capacitive micromachined silicon microphones enjoy high sensitivity, low temperature coefficients, flat frequency response, long term stability and low noise level [1–3]. However, their integration with the electronics on the same chip requires specific materials and fabrication technology that are not directly compatible with integrated circuit technology [3–5].

Inductive micromachined silicon microphones were, therefore, proposed [3–5]. This is attributed to the feasibility of monolithic integration with electronics using a standard

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CMOS 0.8 μm micromachining process [4]. The inductive microphone comprises an internal inductor L_2 fabricated on top of a flexible suspended membrane and a fixed external inductor L_1, on top of the substrate, and carrying a constant current, thus generating a constant magnetic field surrounding the inductor L_2. Due to the incident acoustic energy, the suspended membrane will vibrate. This vibration, proportional to the amplitude of the incident acoustic pressure, will change the mutual inductance, M, between the two inductors L_1 and L_2. The variation of the mutual inductance will generate a time varying voltage in inductor L_2, that is proportional to the amplitude of the incident acoustic pressure. This voltage will be processed by the electronic circuits integrated on the same chip [3–5].

While the performance of the micromachined inductive microphone depends on many parameters, for example, the size and built in stress of the suspended membrane and the bias voltage, the main concern of this paper is the dependence of the induced voltage in inductor L_2 on the incident acoustic pressure. In fact it is this dependence that will decide the linearity of the inductive microphone and, therefore, the feasibility of using it as an electro-acoustic sensor.

2. Mutual inductance between inductors

The mutual inductance between the inductors L_1 and L_2 will depend on the distance between the two plans of L_1 and L_2. For simplicity, and without loss of generality, the two inductors will be assumed as two parallel conductors of the same length. The normalized mutual inductance between two parallel conductors of the same length can be calculated using Greenhouse formula of Eq. (1) [6].

$$M = \frac{M(l,d)}{\frac{\mu_0 l}{2\pi}} \approx \left[\ln\left(\sqrt{1+\left(\frac{l\exp^{\frac{w^2}{12d^2}}}{d}\right)^2} + \frac{l\exp^{\frac{w^2}{12d^2}}}{d} \right) - \sqrt{1+\left(\frac{d}{l\exp^{\frac{w^2}{12d^2}}}\right)^2} + \frac{d}{l\exp^{\frac{w^2}{12d^2}}} \right] \tag{1}$$

where $M(l,d)$ is the mutual inductance between two conductors, l is the length of the conductor, d is the length separation, w is the width of the conductor and μ_0 is the permeability of the air. Eq. (1) can be rewritten in the form

$$\frac{M(l,d)}{\frac{\mu_0 l}{2\pi}} = M_0 + M(\Delta d) \tag{2}$$

where M_0 is the initial value of the normalized mutual inductance corresponding to the length separation d, and $M(\Delta d)$ is the change in the normalized mutual inductance resulting from a change in the length separation equal to Δd.

Assuming, for simplicity, that the length separation d is linearly proportional to the incident acoustic pressure, Eq. (1) represents the nonlinear relationship between the incident acoustic pressure and the resulting mutual inductance. On the other hand, the open-circuit output voltage of the microphone can be expressed as

$$v_0 = I_{L_1}\frac{\mathrm{d}M(l,d)}{\mathrm{d}t} = I_{L_1}\frac{\mu_0 l}{2\pi}\frac{\mathrm{d}M(\Delta d)}{\mathrm{d}t} \tag{3}$$