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Sound Generation Using a Magnetostrictive Microactuator

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In this paper, we present the design and performance of a MEMS-device based on the magnetostrictive effect, which can be used as a micro-loudspeaker. The device basically consists of a comb structure of monomorph bending cantilevers with an active area up to $3.0 \times 2.5 \text{ mm}^2$. It produces a sound-pressure-level up to 101 dB at 400 Hz in a standard 2 ccm measurement volume. We show our measurement setup as well as a mechanic-acoustic-coupled lumped element model to calculate sound pressure. The model incorporates finite element results for mechanical behavior. Measurement results validate our model assumptions. © 2011 American Institute of Physics. [doi:10.1063/1.3554200]

I. INTRODUCTION

Since silicon microphones have created a huge impact on the MEMS market, analysts predict a promising market share for MEMS-loudspeakers.¹ But until now, there does not exist any commercial integrated MEMS-device for sound generation in the audio range. However, some effort has been made using electromagnetic, electrodynamic or piezoelectric actuation principles.^{2–5}

Here, we propose a design for a microactuator based on the magnetostrictive effect, which can be used as a micro-loudspeaker.^{6–9} We demonstrate its performance in generating sound pressure in a standard 2 ccm measurement volume. The main advantages of magnetostriction compared to other actuation principles are the high energy density and contactless operation as well as the possibility of low driving voltages due to low electrical actuator impedances.^{10–12}

In this contribution we will first give a brief outline of our MEMS-device before explaining the measurement setup for measuring sound-pressure-level. We introduce a lumped element model of the coupled mechanical-acoustical system and show measurement as well as calculation results. We conclude with an outlook on the next development steps.

II. MAGNETOSTRICTIVE MICRO ACTUATOR

Magnetostriction is a physical effect that implies nonlinearities and hysteresis behavior. Extensive treatment of the topic can be found in literature.^{10–13} In this contribution it will be sufficient to consider only linear magnetostriction $\lambda = \Delta L/L_0$ that results from applying a longitudinal magnetic field on a sample of length L_0 , which thus changes its length by ΔL . A magnetic DC-field has to be applied to setup such a linear working point.

Our MEMS-device consists of a comb structure of long and narrow monomorph bending cantilevers on a silicon substrate. There are two rows of cantilevers opposite to each other. Each cantilever consists of one active, magnetostrictive layer and at least one passive layer. Fig. 1 shows the

cross section of one cantilever including layer thicknesses. If an external magnetic field is applied, parallel to the cantilevers in x -direction, the lower, magnetostrictive layer elongates and the cantilevers bend upwards. We use Vanadium Permendur ($\text{Fe}_{49}\text{Co}_{49}\text{V}_2$) as magnetostrictive layer and the epoxy-based negative photoresist SU8-3000 (MicroChem Corp., Newton, MA, USA) as main passive layer. Cantilever width is always $75 \mu\text{m}$ and distance between them is $10 \mu\text{m}$. Below the cantilevers there is a hole to the backside of the substrate to ensure a certain backvolume for sound generation. We fabricate different sizes of the device with cantilever lengths of $750 \mu\text{m}$ and $1000 \mu\text{m}$ with a total number of 40 cantilevers each and lengths of $1250 \mu\text{m}$ and $1500 \mu\text{m}$ with a total number of 58 cantilevers each. The corresponding active areas are $1510 \times 1710 \mu\text{m}^2$, $2010 \times 1710 \mu\text{m}^2$, $2510 \times 2475 \mu\text{m}^2$ and $3010 \times 2475 \mu\text{m}^2$. Variations of the design and the fabrication process have been discussed in detail.^{6–9}

Tip deflection $\hat{y}$ of a magnetostrictive monomorph cantilever can be derived as

$$\hat{y} = \frac{1}{2} \lambda \frac{l_c^2}{t_c},$$

with its length l_c and the total thickness t_c . The displaced air volume can be approximated as $\Delta V = \frac{1}{2} l_c w_c k \hat{y}$ with the width w_c of one cantilever and the quantity of cantilevers k in one MEMS-device. By applying the linearized adiabatic state equation, we arrive at a proportionality between sound pressure Δp and cantilever length and quantity

FIG. 1. Cross section of one bending cantilever.

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FIG. 2. Photography of measurement setup.

$$\Delta p \sim l_c^3 k.$$

Thus for high sound pressure long cantilevers are needed

III. MEASUREMENT SETUP

Our measurement setup is displayed in Fig. 2. A motor driven wheel with inserted small permanent magnets generates the magnetic AC-field. Any sound generated by this setup lies in frequency bands clearly distinguishable from the AC-field frequency and its harmonics and thus does not interfere with the sound measurement. Field strength is adjusted by changing the distance between measuring position and wheel using plastic spacers of different thickness. Frequency is controlled by a Hall-sensor. To define a linear working point, a DC-field, parallel to the AC-field, is generated by a current-driven coil and guided to the measuring position via a ferrite yoke. We connect the 2 ccm standard measurement volume (RA0038, G.R.A.S., Denmark) to the MEMS-device via a small rubber tube. The tube leaves the volume at a diameter of 1 mm over a length of 5 mm and then changes its diameter to 5 mm over a length of 1.5 mm. The open end of the tube is pressed against the MEMS-device from above. The microphone (1/2 in., type 4189, Bruel&Kjaer, Denmark) is attached directly to the measurement volume.

IV. MODEL SETUP

Since the physical dimensions of our MEMS-device are small compared to audio wavelengths in air, it is possible to model the acoustic network using lumped elements.^{14,15} We make use of the electroacoustic analogy which maps the acoustic pressure p to the electric voltage U and the volume flux q to the electric current I . The resulting acoustic lumped element model is depicted in Fig. 3. We are interested in the sound pressure p_0 in the measurement volume which is modeled as an acoustic compliance N_0 . The narrow part of the rubber tube is represented by a mass element M_t and a friction element R_t , whereas the wide part of the tube resembles another compliance N_1 . The air gaps between the cantilevers are modeled with a friction element R_a . The corresponding equations are^{14,15}

$$N_{0,1,2} = \frac{V_{0,1,2}}{\rho c^2}, \quad R_a = \frac{12\eta l_c}{w_a^2 A_a},$$

$$M_t = \frac{\rho(l_t + r_t \pi/2)}{\pi r_t^4}, \quad R_t = \frac{8\eta l_t}{\pi r_t^4},$$

FIG. 3. Lumped element model.

where $V_{0,1,2}$ are the volumes of the corresponding cavities, $c = 343$ m/s is the sound velocity, $\rho = 1.2$ kg/m³ is the air density, $\eta = 1.8 \cdot 10^{-5}$ kg/m/s is the viscosity of air, l_t is the length of the narrow part of the tube, r_t is its radius, t_c is the thickness of one cantilever, w_a is the width of the airgap between two cantilevers and A_a is the total area of the airgaps between the cantilevers.

The moving cantilevers act as an acoustic source at connectors A and B. To describe this source, we additionally model the mechanical behavior of the microactuators and use the electromechanical analogy. Velocity v corresponds to voltage U and force F corresponds to current I . We apply a sinusoidal force source F_0 and describe the cantilevers' mechanical behavior by their admittance $1/Z_m$ (Fig. 3), since the chosen analogy behaves reciprocal concerning impedances.^{14,15} The mechanical impedance Z_m of the cantilever is derived from a finite element simulation¹⁶ for each length. In the simulation the cantilever is clamped on one side and a sinusoidal force in x -direction F_x is applied to each node inside the magnetostrictive layer (Fig. 1). Z_m as a function of frequency f is then derived from the sum of the applied forces and the average velocity in y -direction as

$$Z_m(f) = \frac{\sum F_x(x, y)}{\bar{v}_y(f, x)}.$$

The coupling between the mechanical and the acoustical networks follows the gyrator-type equations depicted in Fig. 3.

V. RESULTS

Measurement data as well as calculation results for the sound pressure level (SPL) in the measurement volume are presented in Fig. 4 as a function of frequency for MEMS-devices of all cantilever lengths. Different devices from different process cycles were measured. A magnetic flux density with an amplitude of 10 mT was applied in a working point of 10 mT. All measurements were conducted in an anechoic measurement room.

Maximum SPL has been measured as 101 dB at 400 Hz with the 1500 μ m-device. The active areas of the MEMS-devices are different due to different cantilever lengths and quantity. To be able to compare measurement results, all

FIG. 4. Model results (solid line) and measurement data—scaled (dots) for different cantilever lengths.

measured data was scaled to a reference active area according to Eq. (2). As a reference we choose the 1500 μm -cantilever-device. Scaling factors in dB are +21.3 dB for 750 μm , +13.8 dB for 1000 μm and +4.8 dB for 1250 μm -cantilevers. Scaling of measurement data leads to very similar sound pressure levels at frequencies below any resonances. Thus the scaling factor proves to be adequate and allows us to predict SPL for different sizes of MEMS-devices.

In the calculation results in Fig. 4 two cut-off frequencies are clearly distinguishable. The first one at around 450 Hz results from the acoustical resonance of the acoustic network. It can also be observed in the measured data. The second one at higher frequencies results from the mechanical resonance of the cantilevers. With the cantilevers of 1500 μm length, these two frequencies lie close to each other and overlap to one resonance peak. Damping in the mechanic-acoustic system occurs mainly due to the generated sound pressure counteracting the deflection of the cantilevers. Our model reproduces well the measurement results.

The ideal frequency response for a closed membrane will show a constant SPL for low frequencies and higher

SPL in resonance since there is no loss through the airgaps any more. So for a high SPL over a broad frequency range, small airgaps and high mechanical resonances of the cantilevers are needed.

VI. CONCLUSION

In this paper we have presented a MEMS-device which is actuated by the magnetostrictive effect and can be used as a micro-loudspeaker. We showed the setup for measuring sound pressure level (SPL) in a standard 2 ccm measurement volume that is attached to the device. A mechanic-acoustic-coupled lumped element model has been developed to calculate SPL incorporating finite-element results for the mechanical impedance. Measurement data validates the model. A maximum SPL of 101 dB has been measured at 400 Hz. In a next step we will employ the model to optimize the MEMS-design for generating higher SPL over a broader frequency range. Further development will include integrating a field-coil to the device to generate the driving magnetic field on-chip. Other materials such as Terfenol-D may be tested in further studies.

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