A MUSICAL INSTRUMENT IN MEMS

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***Abstract* — In this work we describe a MEMS instrument that resonates at audible frequencies, and with which music can be made. The sounds are generated by mechanical resonators and capacitive displacement sensors. Damping by air scales unfavourably for generating audible frequencies with small devices. Therefore a vacuum of 1.5 mbar is used to increase the quality factor and consequently the duration of the sounds to around 0.25 s. The instrument will be demonstrated during the MME 2010 conference opening, in a musical composition especially made for the occasion.**

***Keywords* — Musical instrument, capacitive sensor, comb drive**

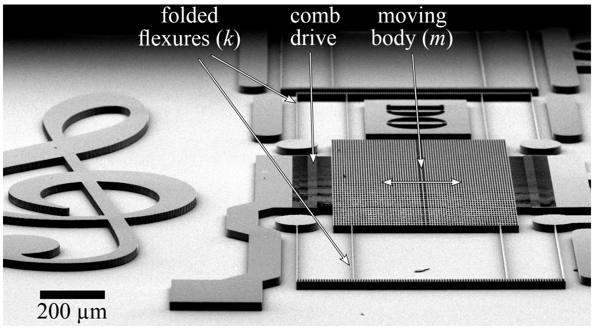

Figure 1: *Scanning electron micrograph of one of the resonators of the MEMS instrument. The perforated structure is the moving body (mass m), suspended by folded flexures on both sides. The mass is 'plucked' by a comb drive on one side, and the mass's displacement is measured by a comb drive on the other side.*

I – Introduction

In 1997, researchers at Cornell University fabricated the world's smallest guitar, about the size of a human blood cell [1]. Two years later, a micro harp was made [2]. In 2003, laser light was used to strum the 'strings' of a nanoguitar [3]. However, no human has heard the sound of these instruments; the strings vibrate at frequencies on the order of tenths of megahertz. With the advent of a microphone for MEMS structures [4], there seems to be a growing interest in the field of MEMS musical instruments.

In this work we describe a MEMS instrument, consisting of micromechanical mass-spring resonators that can be 'plucked' using electrostatic comb-drive actuators. The instrument's vibrations are sensed by capacitive displacement sensors using comb structures as sensing elements. The measured capacitance is used as the audio signal.

In the following, first the design of the instrument will be explained, after which measurements of the MEMS instrument's tone will be discussed.

II – Theory and design

Our instrument consists of individual resonators for each note, similar to a harp. The resonators are (relatively large) masses suspended by folded flexures. Each resonator is actuated by a comb drive. A resonator behaves according to the well known differential equation

$$m\frac{\mathrm{d}^2x}{\mathrm{d}t^2}+\gamma\frac{\mathrm{d}x}{\mathrm{d}t}+kx=F_{\mathrm{comb}}, \tag{1}$$

where m is the mass of the resonator, x the displacement, γ the coefficient of viscous damping by air, k the suspension spring constant, and F_{comb} the comb-drive force. The solution of (1) is the expected comb-drive displacement after it has been excited,

$$x(t)=e^{-\alpha t}\sin(2\pi f_0 t), \tag{2}$$

with $\alpha=\gamma/2m$. The free resonance frequency for an underdamped system is

$$f_1=\frac{1}{2\pi}\sqrt{\frac{k}{m}-\alpha^2}\approx f_0\left(1-\frac{1}{8Q^2}\right), \tag{3}$$

with $f_0=2\pi\sqrt{k/m}$, and $Q=\pi f_0/\alpha$. The approximation is correct for low damping. Tailoring the mass and spring constant, resonators with different resonance frequencies are made. In order to obtain resonance frequencies in a range from 400 Hz to 1000 Hz, large structures are needed compared with common MEMS structure sizes.

A. Scaling issues — Q-factor

For our mass-spring-damper system resonators, the quality factor equals

$$Q=\frac{\sqrt{mk}}{\gamma}. \tag{4}$$

The duration of a note after being excited/struck, is proportional to the Q-factor and inversely proportional to the resonance frequency.

Scaling the dimensions of the mass with factor l, the mass scales cubically, $m\propto l^3$. The spring constant should scale proportionally to the mass in order to maintain the same resonance frequency, hence $k\propto m$. The viscous

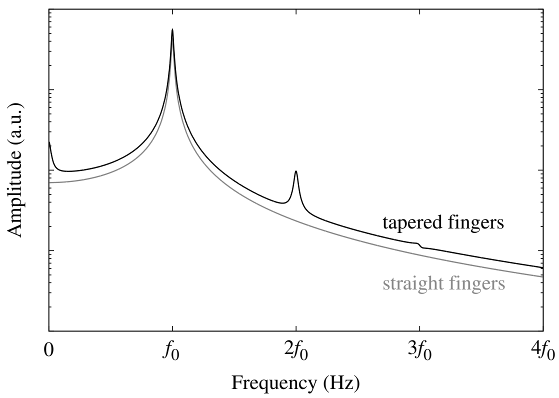

Figure 2: *The Fourier transform of the simulated capacitance of comb drives with straight and tapered fingers for an exponentially decaying sinusoid displacement. The non-linear capacitance versus displacement of tapered fingers gives rise to higher harmonics besides the fundamental (first harmonic).*

damping is proportional to the area of the mass, $\gamma \propto l^2$. Consequently, the Q-factor scales with l; reducing the dimensions of the system results in a proportionally reduced Q-factor. In general, at equal resonance frequencies, a smaller mass-spring oscillator will experience more damping and will sound a shorter note than a larger oscillator. To solve this issue of small MEMS instruments, we decrease γ by placing the instrument in a vacuum chamber.

B. Capacitive read-out

We use a comb drive together with capacitance measurement circuitry to generate the audio signal. Besides ease of fabrication, the use of a comb drive allows us to adjust the timbre of the note, by modifying the comb-drive finger shape. For straight comb drive fingers, the capacitance is linearly proportional to the displacement. However, the capacitance of a comb drive with tapered fingers depends non-linearly on the displacement x [5],

$$C_{\text{tapered}} = 2\varepsilon_0 h \frac{x + x_0}{g - (x + x_0)\tan\alpha}, \tag{5}$$

where x_0 and g are the initial overlap and gap between fingers respectively, h is the comb-drive height, and α the angle of the tapering. This non-linearity gives rise to higher harmonics in the audio signal, resulting in a more interesting tone. The upper bound on the angle α is set by fabrication limits; $\alpha = 0.72°$ for our designs. Figure 2 shows the Fourier transform of the simulated capacitance for both straight and tapered fingers using (2) for displacement x. Besides the fundamental, the second harmonic is clearly present. However, the relative amplitude of the second harmonic is small due to the small angle α.

C. Instrument design

The designed instrument contains six resonators at different frequencies. The instrument is designed such that the notes form part of a major diatonic scale. We chose six notes with $n = \{0, 2, 4, 5, 7, 12\}$, where n indicates the number of semitones above a ‘C’ [6]: Do, Re, Mi, Fa, So, and (high) Do. The instrument is not tuned to a particular existing instrument. A frequency for our ‘C’ is chosen at 396 Hz, from which the subsequent note frequencies follow from [6],

$$f_n = 2^{\frac{n}{12}} \times 396\,\text{Hz}. \tag{6}$$

The general layout of our instrument chip is shown in Figure 3. Both the suspension spring stiffness k and the moving body mass m of the resonators are adjusted to obtain the desired resonance frequencies. The spring stiffness of the folded flexure suspension equals [7]

$$k = \frac{2Ehb^3}{L^3}, \tag{7}$$

where E is the effective Young's modulus of silicon, h the spring height, $b = 3\,\mu\text{m}$ the spring width, and L the spring length. The effective mass of the resonator m_{eff} is equal to the moving body mass plus the folded flexure truss mass. Because the folded flexure trusses move only half the distance, only half their mass contributes to the effective mass. The moving body and trusses need to be perforated because of the used fabrication process. The perforation consists of $5\,\mu\text{m} \times 5\,\mu\text{m}$ square with $3\,\mu\text{m}$ silicon beams in between. This results in an area reduction R_{perf} of approximately

$$R_{\text{perf}} \approx \frac{8^2 - 5^2}{8^2}. \tag{8}$$

Only one dimension of the moving body is adjusted. Referring to Figure 3, $B = 1.2\,\text{mm}$ is fixed, W is adjusted. The area of the perforated trusses A_{truss} is the product of the width and length, $32\,\mu\text{m}$ and $W + 333\,\mu\text{m}$, respectively. The total area A_{fingers} of the comb-drive fingers on both sides of the resonator equals $3.84 \times 10^{-8}\,\text{m}^2$. We find for the effective mass,

$$m_{\text{eff}} = \rho_{\text{Si}}\, h \cdot \left[A_{\text{fingers}} + R_{\text{perf}}\left(WB + A_{\text{truss}}\right)\right]. \tag{9}$$

First L is chosen such that the resonators fit on the chip, according to the layout shown in Figure 3. Subsequently, W is adjusted. The dimensions are listed in Table 1.

III – Experimental Details and Results

The MEMS instrument is fabricated from a (100) single-crystal highly boron-doped silicon-on-insulator wafer, with a $50\,\mu\text{m}$ thick device layer (determining height h of the comb drive and springs) and an oxide thickness of $3\,\mu\text{m}$. The structures are made by deep reactive-ion etching (DRIE) [8, 9], after which the (movable) structures are released by HF vapour phase etching [10] of the oxide layer. Large structures, like the moving body of the resonator, need to be perforated to allow etching of the underlying silicon oxide. The result is shown in Figure 1.

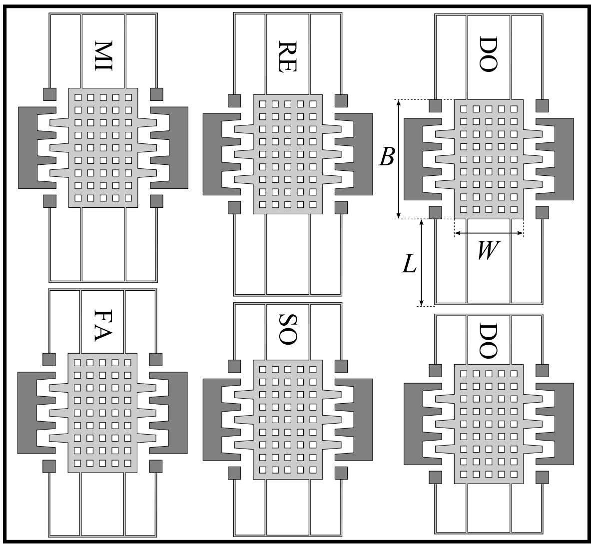

Figure 3: *Layout of the* 7 mm × 7 mm *instrument chip. Six resonators fit on the chip. The comb drives and length B are equal for all resonators, only the spring length L and mass width W are varied to obtain the correct resonance frequencies.*

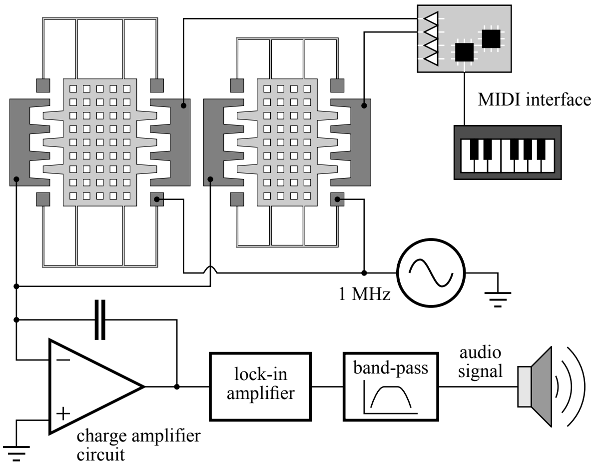

Figure 4: *Simplified drawing of the used measurement setup. The displacement of a resonator is measured from the comb-drive capacitance, using a charge amplifier circuit and lock-in amplifier. In total, six resonators are connected in parallel to one charge amplifier circuit (only two resonators are drawn). The resonators are actuated by high-voltage amplifiers that are controlled through a MIDI interface.*

Table 1: *Frequencies of the instrument notes and the resulting design parameters for the spring length L and moving body size W. The measured frequencies and the relative deviation from the design are listed on the right.*

Note	f_0 (Hz) design	L (µm)	W (µm)	f_0 (Hz) meas.	out-of-tune
Do	396	1050	670	475	20%
Re	445	950	718	592	33%
Mi	499	890	693	-	
Fa	530	840	735	695	31%
So	595	770	758	778	31%
Do 2	788	690	589	1031	31%

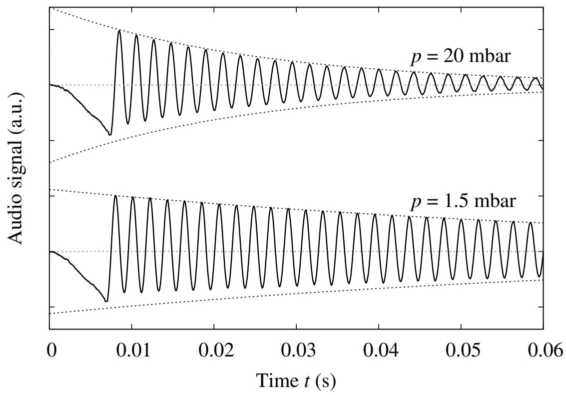

Figure 5: *The recorded tone of the low Do note at two different vacuum pressures. The sine frequency equals* 475 Hz. *The dashed curves are equal to* $\pm e^{-\alpha t}$, *with* α *equal to* 13 s^{-1} *at* 1.5 mbar *and* 40 s^{-1} *at* 20 mbar.

The measurement setup, shown in Figure 4, consists of a charge amplifier, lock-in amplifier and an additional amplifier with band-pass filter. The resulting audio signal can either be played through a loudspeaker or recorded using the soundcard of a PC.

The resonators are actuated by a programmable microcontroller with a D/A-converter and a high-voltage amplifier. At rest, the applied voltage is 0 V. A note is ‘plucked’ by ramping the applied voltage in about 8 ms up to the actuation voltage V_{act}, and subsequently rapidly reducing the applied voltage back to 0 V. The ramp prevents sounding a note upon both the increase and decrease of the applied voltage. This simulates manually pulling back the resonator and releasing it, similar to plucking a string. The height of the actuation voltage V_{act} is determined from the velocity parameter received in the MIDI messages from the MIDI keyboard.

Figures 5 shows the recorded audio signal of the low Do resonator, for two pressures of respectively 1.5 mbar and 20 mbar. The audio signal is a decaying sine wave, that is slightly asymmetric due to the non-linearity of the sensing comb drive. The damping α is estimated by fitting an exponential curve to the decaying sine; Q equals 115 and 37 at 1.5 mbar and 20 mbar, respectively. Clearly, the duration of the note is greatly increased at a reduced pressure. At ambient pressure, only a very brief oscillation was measured.

The Fourier transform of the audio signal at 1.5 mbar is shown in Figure 6. The fundamental frequency equals 475 Hz. As expected from the non-linear capacitance versus displacement curve of the tapered comb-drive fingers, a second peak at double the resonance frequency (951 Hz) is visible, compare with Figure 2. The measured resonance frequencies of the other resonators are listed in Table 1. There is no measurement of the Mi resonator as it broke before it was measured. All notes

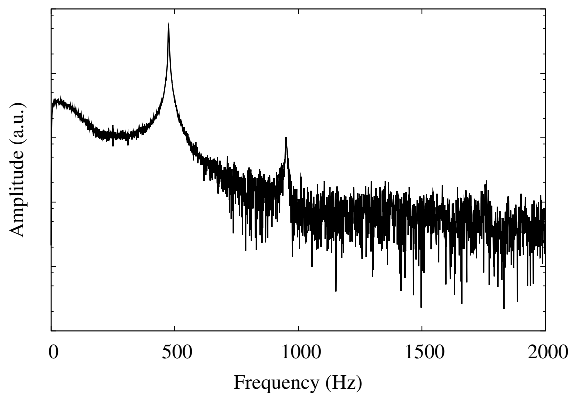

Figure 6: *Fourier transform of the audio signal of the low Do note, showing a large peak at* 475.1 Hz. *A second peak at* 951 Hz *is visible, caused by the non-linear capacitance versus displacement curve of the tapered comb-drive fingers.*

resonate at a much higher frequency than the design predicted. However, the instrument is still largely in-tune with itself, because the frequency increased with an almost equal factor for Re, Fa, So and the high Do. The instrument is pitched close to a C5 major scale (except for the low Do, that is closest to A♯4). It should be noted however, that a second chip was more out of tune. The large increase in frequency may be explained by a strong increase in spring stiffness, because their thickness was larger than originally designed.

IV – Discussion

Because of intrinsic uncertainties in fabrication, there is a large uncertainty in the resonance frequencies after fabrication. Clearly, tuning of the instrument is necessary. There are several methods of tuning. Because the comb-drive finger shape is tapered, applying an offset voltage to both the actuating and sensing comb drives would result in a lower spring stiffness [11]. Another method to lower the spring constant is heating the springs, which lowers the Young's modulus of the silicon [12], for example by flowing an electrical current through the springs. Large frequency adjustments can be realised through subsequential mass fine-tuning performed by manually depositing additional material on the moving body.

V – Conclusion

In this work we show that it is possible to make a musical instrument in MEMS. Viscous damping by air is relatively large for micro resonators at audible frequencies, resulting in a short tone. A vacuum of 1.5 mbar was required for a short note around 0.25 s. The frequencies of the fabricated notes are 20% to 33% higher than expected, however, the instrument is still mostly in-tune with itself. Improvement of the fabrication method is necessary to correctly tune the device by design, without the need for tuning after fabrication.

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