AN INTEGRATED SURFACE MICROMACHINED CAPACITIVE LATERAL ACCELEROMETER WITH $2\mu\text{G}/\sqrt{\text{Hz}}$ RESOLUTION

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ABSTRACT

A capacitive position measurement interface minimizes noise from parasitics in the electromechanical interface and uses correlated double sampling to achieve better than $10^{-3}\text{\AA}/\sqrt{\text{Hz}}$ displacement resolution. This translates into $2\mu\text{G}/\sqrt{\text{Hz}}$ acceleration resolution when the device is operated in a vacuum.

INTRODUCTION

Surface micromachined accelerometers are finding widespread commercial use [1,2] in automotive and industrial applications. However, owing to the small proof-mass, the resolution of present devices is limited to $100\mu\text{G}/\sqrt{\text{Hz}}$ or more. Substantially better performance is achievable with bulk micromachined devices [3-6], albeit at the expense of a much larger proof-mass and more expensive fabrication technology.

This paper analyzes the factors governing accelerometer resolution to design a surface micromachined device with a noise floor of $0.75\mu\text{G}/\sqrt{\text{Hz}}$ from electronic sources only. When operated in a vacuum to minimize Brownian noise, $2\mu\text{G}/\sqrt{\text{Hz}}$ acceleration resolution is achievable, which is comparable to the performance of bulk-micromachined parts.

DISPLACEMENT SENSING

A pendular accelerometer consists of a mechanical transducer converting acceleration to displacement followed by a displacement sensor. The resolution of the device is governed by the sensitivity, i.e. the magnitude of the response for a given input, and the noise. It can be improved by either increasing sensitivity, or by lowering the noise.

Transducer sensitivity can be improved by lowering the resonant frequency, as shown by the diagonal line in Figure 2. All else being equal, a device with lower resonant frequency will exhibit better resolution. Since, however, reducing the resonant frequency also lowers the device's tolerance to mechanical shock, practical considerations set an application dependent lower bound on acceptable resonant frequency. The transducer is also responsible for noise. Brownian noise is usually the dominant source, but flicker noise and thermal noise from the electromechanical interface also contribute.

Figure 3 plots the displacement resolution of several accelerometers [1-14] to factor out transducer performance. It is

Figure 1. Block diagram of a displacement transducer

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Figure 2. Comparison of Noise floor

Figure 3. Comparison of displacement resolution

interesting to note that alternative detection schemes such as electron tunneling have no apparent performance advantage over capacitive sensors. Another observation from Figure 3 is that the achieved displacement resolution is worse in high precision accelerometers that use a larger proof-mass than those use a smaller mass, indicating that the performance of the high precision accelerometers is fundamentally limited by Brownian motion noise. In order to develop high precision accelerometers with $\mu\text{G}/\sqrt{\text{Hz}}$ or sub- $\mu\text{G}/\sqrt{\text{Hz}}$ resolution, it is crucial to reduce Brownian noise.

This work uses the switched capacitor sensing technique, which is often associated with increased noise due to folding of

broadband thermal noise. However, it is seen in Figure 3 that this work has achieved a better than $10^{-3}\text{\AA}/\sqrt{\text{Hz}}$ displacement resolution, on par with the best reported results.

ACCELEROMETER DESIGN

The capacitive lateral accelerometer has been designed and fabricated using an integrated MEMS technology with a $6\mu\text{m}$ -thick mechanical polysilicon layer and $0.8\mu\text{m}$ transistor feature size for CMOS electronics. Figure 4 shows the die photo of the fabricated device. The complete die size is $3.5\text{mm}\times 3.5\text{mm}$ in which $1.1\text{mm}\times 1.1\text{mm}$ has been specified as the mechanical structure area. The $920\mu\text{m}\times 880\mu\text{m}$ sense element weighs $3.6\mu\text{g}$ ram. Differential sense capacitors are formed using parallel plate comb fingers. Limit stops are set to prevent snapping of the comb fingers and the proof mass is allowed to displace a maximum of $\pm 1\mu\text{m}$ from its resting position before hitting the limit stops. A thin conductive polysilicon layer underneath the proof mass is electrically connected to the proof mass through the suspension anchors and it has the same potential as that of the proof mass. Consequently, there will be no electrostatic force between the proof mass and the shield layer even when the potential on the proof mass alternates between two different potentials during sensor operation.

Figure 4. Die photo

Figure 5. Electromechanical interface model

Considerations have been put on reducing parasitic capacitances and parasitic resistances caused by the polysilicon wirings in the mechanical sense element, which is essentially a distributed RC network. The lumped electrostatic interface model shown in Figure 5 has been used in the design of the displacement sensing interface circuit. Most of the parasitic resistances are due to the polysilicon wirings from the fixed sense comb fingers to the CMOS circuitry. The parasitic resistances due to parallel plate sense comb fingers are negligible because these sense comb fingers are connected in parallel. Most parasitic capacitances are due to the anchor capacitances and the wirings through the ground polysilicon layer. The capacitance across the differential sense comb fingers is minimized by maximizing the gap between the adjacent comb fingers.

The accelerometer operates as an open-loop sensor. The sensor outputs are differential analog signals. Open loop sensing enables direct measurement of the individual noise contributions, which can also be used to characterize sensor dynamics. A better understanding of the open-loop sensor helps in designing a closed-loop sensor.

Depending on the mechanical design, the sensor can be mechanical noise dominated or electronic noise dominated. In this design, number of sense fingers has been designed to maximize performance in vacuum. For a sensor operating in air, fewer sense combs should be used.

A fully differential switched capacitor interface circuit has been designed to measure the sense capacitance mismatch in response to acceleration signals. The voltage on the proof mass alternates between V_{PM1} and V_{PM2} at a 50% duty cycle in each sampling period. The correlated double sampling technique similar to that reported in [15] is used to reject $1/f$ noise, $k_B \cdot T/C$ noise due to reset switches, amplifier offset and switch charge injection.

The differential analog outputs of the sensor are converted to a single-ended analog output using an instrumentation amplifier on the test board. The lateral accelerometer has been tested on a shaker table excited by a signal generator. The shaker table generates a vibration perpendicular to the table surface. A reference accelerometer has also been mounted on the shaker table to calibrate the measurement results. To prevent the resonant frequencies of the test board from affecting the measurement results, the test board has been attached tightly to a rigid mounting block. The device has been tested in air as well as in vacuum.

NOISE CHARACTERISTICS IN AIR

A comprehensive analysis of all noise sources is essential to maximizing resolution. To gain more insight, we have developed techniques for measuring individual noise contributions separately.

Periodic spikes were observed in the differential analog outputs. These spikes are caused by inductive coupling between the bond wires and capacitive coupling of the digital/clock signals. Since the energy of these spikes is at frequencies no less than the sampling frequency of the sensing circuit, the effect of these spikes on sensor noise performance is negligible.

A HP35665A dynamic signal analyzer was used to characterize the sensor output noise and the output noise spectrum was obtained after averaging 100 measurements. Figure 6 shows three results, all taken at the atmospheric pressure.

The top trace ($V_s = 4.5V$) exhibits a characteristic 2nd order roll-off for frequencies above the resonant frequency of the sensor, which is at approximately 1.5kHz. It includes all noise sources and

Figure 6. Output noise spectra

is dominated by Brownian noise ($32\mu\text{G}/\sqrt{\text{Hz}}$). It underscores the need for operation in vacuum. The mechanical sense element is found over-damped in air with $Q = 0.44$. Using the measured ω_n and Q , the Brownian noise floor at atmospheric pressure is calculated to be $32\mu\text{G}/\sqrt{\text{Hz}}$, which confirms the accuracy of the noise measurement. It is already known that the output Brownian noise is shaped by the sensor transfer function. If Brownian noise is the dominant noise source, the output noise spectrum reflects the sensor transfer function. Hence, characterization of the accelerometer output noise is equivalent to characterization of the sensor dynamics. $330\mu\text{m}$ long and $2\mu\text{m}$ wide parallel plate sense comb fingers were designed to maximize the ratio of sense capacitance to parasitic capacitance. For a certain sense capacitance, fewer anchors are needed using longer comb fingers and hence less parasitic capacitance, at the expense of lower finger resonant frequency. The resonant frequency of sense comb fingers was designed to be 25kHz . However, an over-etch of about $0.3\mu\text{m}$ in device fabrication reduces the comb finger width and lower their resonant frequency to about 20kHz . Brownian motion noise of these comb fingers is mechanically amplified near the finger resonance and the displacement of the sense comb fingers is picked up by the displacement sensing electronics. In the plot, Brownian motion noise of comb fingers appears at around 20kHz .

The electronic noise can be measured separately when no sense step voltage ($V_s = 0\text{V}$) is applied across the sense capacitors and corresponds to $0.75\mu\text{G}/\sqrt{\text{Hz}}$. At frequencies below approximately 10kHz , Brownian noise is the dominant noise source. Electronic noise dominates above 10kHz . Due to correlated double sampling, the electronic noise has a white spectrum and the $1/f$ noise corner is below 1Hz . The droop of electronic noise at frequencies above 30kHz is caused by low-pass filtering provided by the on-chip output buffer. The overall sensor bandwidth is limited by the sensor dynamics.

For reference, the result from an electronic circuit (*CMOS only*) where the mechanical structure has been replaced with fixed poly-poly capacitors is also included to evaluate the effect of mechanical parasitics on electronic noise. About 6dB noise degradation induced by parasitics is observed. The result is better understood by considering the electromechanical interface model shown in Figure 5. The 650Ω wiring resistance adds noise directly to the capacitive sense interface and parasitic capacitances reduce

Figure 7. Frequency tuning effect

the signal-to-noise ratio by attenuating the signal from the 900fF sense capacitances.

Correlated double sampling eliminates $k_B \cdot T / C$ of the reset switches effectively. Without correlated double sampling, the reset switches at the inputs of the C/V converter contribute $k_B \cdot T / C$ noise equivalent of $2.5\mu\text{G}/\sqrt{\text{Hz}}$. With correlated double sampling, the electronic noise is mainly due to thermal noise of the C/V converter, which is equivalent to $0.7\mu\text{G}/\sqrt{\text{Hz}}$.

TEST RESULTS IN VACUUM

When the sensor operates in vacuum, Brownian motion noise is reduced at low frequencies and mechanically amplified near the sensor resonant frequency. The Brownian noise peak in the output noise spectrum of the vacuum test has been used to measure the sensor resonant frequency and to evaluate the electrostatic frequency tuning effect. During our test, it has been found that when Q is too high, the output amplifier overloads and the output becomes a square wave signal with a frequency corresponding to the sense resonant frequency, hence feedback is required for a robust operation in vacuum. In order to bring Brownian noise down to a comparable level of the electronic noise, a Q of better than 1000 is needed.

Because of the use of parallel plate sense comb fingers, the voltage drop across the sense capacitors generates electrostatic frequency tuning effect. This can be exploited to dynamically reduce the resonant frequency, and hence increase the sensitivity, of the device, without reducing the shock resistance when the device is off. For this purpose, the voltage applied to the sense fingers is separated into a common-mode part, V_{tune} , controlling the resonant frequency, and a differential part, V_s , that sets the magnitude of the sense pulse and hence sensitivity of the interface.

It can be seen from Figure 5 that the sense step voltage V_s is given by $V_s = V_{PM2} - V_{PM1}$. Since the potential on the proof mass switches between V_{PM1} and V_{PM2} at a 50% duty cycle, the frequency tuning voltage V_{tune} is given by

$$V_{tune} = \sqrt{0.5 \cdot [(V_{PM1} - V_{ICM})^2 + (V_{PM2} - V_{ICM})^2]}.$$

Note that V_s and V_{tune} can be adjusted independently. Figure 7 shows the measured frequency tuning effect with $|V_{PM1} - V_{ICM}| = |V_{PM2} - V_{ICM}|$, which corresponds to

Figure 8. Measured accelerometer output response (Acceleration signal at 55Hz and $V_s=4.5V$)

$V_{tune} = 0.5 \cdot V_s$. The frequency tuning effect depends on the comb finger gap. The sense comb finger gap has been extracted to be $2.3\mu m$ instead of the designed value of $2\mu m$. This result has been verified using SEM. Figure 8 shows the sensor output response to acceleration signals at 55Hz. The test was conducted in vacuum with $V_s = 4.5V$ and $V_{tune} = 0.5 \cdot V_s$. The full-scale range of the device is 125mG and the sensitivity is 8.55V/G under this test setup. Parameters of the lateral accelerometer are summarized in Table1.

Table 1. Summary of parameters ($V_s = 4.5V$ unless specified)

Parameters	Measured
Proof mass	3.6 μ gram
Mechanical Resonant frequency ($V_s = 0V$)	2.93kHz
Tuned Resonant frequency	1.488kHz
Quality factor Q	0.44
Sense capacitance	900fF
Sensitivity	8.55V/G
Full scale range	125mG
Comb finger gap	2.3 μm
Brownian noise floor in air	32 μ G/ $\sqrt{Hz}$
Electronic noise floor	0.75 μ G/ $\sqrt{Hz}$
Measured noise floor in vacuum	2 μ G/ $\sqrt{Hz}$
Displacement resolution	2.3 $\times 10^{-3}$ Å/ $\sqrt{Hz}$

CONCLUSIONS

An integrated surface micromachined capacitive lateral accelerometer that resolves $2\mu G/\sqrt{Hz}$ in a vacuum is presented. Displacement resolution is used to decouple the strong correlation between the achieved acceleration resolution and the sensor resonant frequency. Alternative sensing schemes, such as electron tunneling, have no apparent performance advantage over capacitive sensing. Individual noise contributions are identified experimentally. Better than 10^{-3} Å/ $\sqrt{Hz}$ displacement resolution is demonstrated.

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