**1. Mechanical/Physical Sensors and Microsystems**

# A 3-AXIS ACCELEROMETER AND STRAIN SENSOR SYSTEM FOR BUILDING INTEGRITY MONITORING

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The need for sensing signals, in fields such as building integrity, from a wide range of capacitive MEMS/NEMS-based devices (such as accelerometers and strain sensors with different actuation voltages, sensitivities and resolutions) requires innovative, flexible and power efficient readout architectures. Resolution requirements of 1mg and 10με, for the accelerometer and strain sensor respectively, and a range of ±2.0g and ±20,000με over a 100Hz bandwidth are required to sense displacements and stresses, essential for the assessment of structures during seismic events.

We propose a unique low-power system which can be matched to either MEMS-based comb finger capacitive accelerometers or strain sensors in a half-bridge configuration [1]. Its gain can be set by a number of integration pulses *N*, optimizing SNR and bandwidth with power. In addition the architecture suppresses motion artifacts [2, 3].

Two types of MEMS-based sensors were used and their specifications are given in Table 1. The accelerometer consists of 2 transverse comb finger structures for the X and Y axis and, a pendulating one for the Z axis (Figure 1). The strain sensor is a longitudinal comb finger capacitor, the figure also shows a single channel architecture readout and the fabricated ASIC.

The strain sensor fabrication procedure starts with a SOI wafer with a 500μm thick handle, 50μm thick fingers and 2μm thick oxide layer with 400 fingers in the sensor and it has a sensitivity of 0.133fF/με. Two anchors were etched-out of the surface to create the necessary clamps to attach the sensor to the rebar of a pillar. The fingers are protected with a borosilicate class cap.

Figure 2 shows the measurements of the strain sensor with the proposed readout. A range of ± 20,000με was measured and the resolution and non-linearity were 10με and <0.6%, respectively. The combination of high range and high resolution makes the sensor novel and unique for building integrity assessment.

The accelerometer was fabricated with a surface micro-machined process from a SOI wafer 85μm thick. The sensor has 78 fingers with a total sensitivity of 2.02pF/g. The Z sensor has an area of 2.17mm$^2$ per plate. Innovative cap through connections were used. The main tradeoff in the design of the accelerometer is the sensitivity-bandwidth-linearity in all three axes, a challenge for the design given the different used structures.

Figure 3 shows the noise PSD measurements for a sine-wave vibration of 70Hz as well as the X, Y and Z transient signals of the readout (insert in Figure 3). The measured acceleration range is ±2.5g. The resolution is 80db (13-bit) for vibration tones between 10-100Hz and non-linearity < 1%.

Figure 4 shows the measurements of the sensitivity versus the integrated number of pulses *N* for the accelerometer. To first order the sensitivity of the readout is proportional to the number of pulses *N*, while the integrated noise is proportional to $\sqrt{N}$.

The proposed architecture suppresses residual motion effects via an accurate sin(x)/x response. Noise measurements of the accelerometer plus the readout show an equivalent noise floor of 70μg/√Hz. The total integrated noise in the bandwidth of 100Hz is equal to an equivalent noise of 733μg [4]. After subtracting the noise of the readout, the equivalent residual motion noise is 500μg.

Compared to the figures of merit proposed in [5] and [6] we get $4.41\times10^{-20}$ F√(W/Hz) and 881μW·μg/Hz, respectively. Our architecture has the lowest reported equivalent acceleration noise level, highest bandwidth and has the unique advantage of offering tradeoff between SNR, bandwidth and power. The design was fabricated on TSMC 0.25μm CMOS. The total power consumption of the 3 channels is 15μW. The clock and excitation voltages for the sensors are external.

**Word Count: 599.**

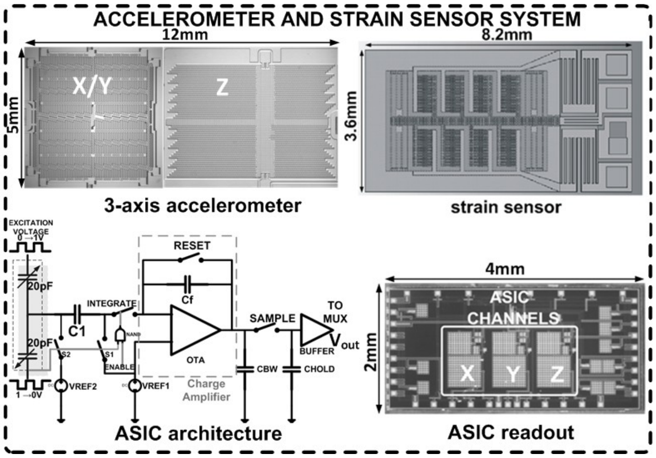

*Figure 1: Microphotographs of the accelerometer, strain sensor and readout ASIC and topology of a single channel capacitive readout.*

*Table 1. Accelerometer and strain sensor specifications. The X, Y axis sensors and Y axis are given separate.*

| Parameter | Accelerometer | Strain sensor |
|---|---|---|
| **Basic Capacitance** | *20pF (X,Y)*<br>*20pF (Z)* | *5.3pF* |
| **Proof mass weight** | *0.34mgrams (X,Y)*<br>*0.5mgrams (Z)* | *N.A.* |
| **Mechanical Sensitivity** | *0.4-0.06µm/g* | *3nm/ µε* |
| **Electrical Sensitivity** | *0.23-2.02pF/g (X,Y)*<br>*0.38-0.94pF/g (Z)* | *0.133fF/µε* |
| **Resonant Frequency** | *785-2080Hz (X,Y)*<br>*780-1015 (Z)* | *56 kHz* |
| **Pull-in voltage** | *2.3-5.4V (X,Y)*<br>*0.95-1.3V (Z)* | *N.A.* |
| **Finger gap** | *3µm* | *4µm* |

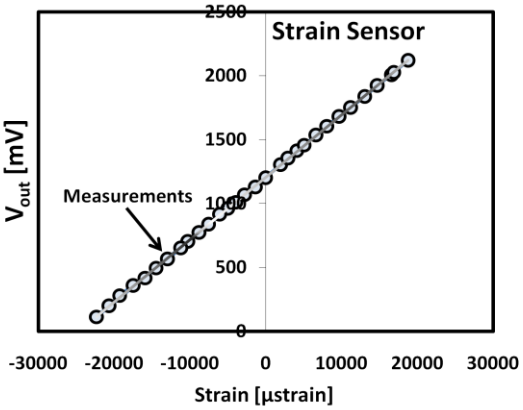

*Figure 2: Measured DC output signal for a comb finger strain sensor (N=24pulses).*

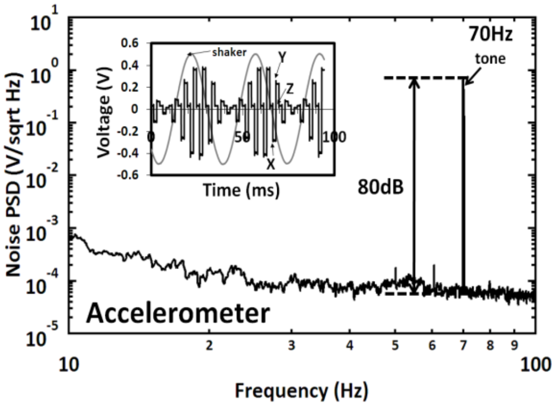

*Figure 3. Noise power spectral density for a 70Hz tone for the accelerometer. The insert shows the multiplexed output of the 3 channels(X, Y and Z) for an input sine-wave in the readout (N=24 pulses).*

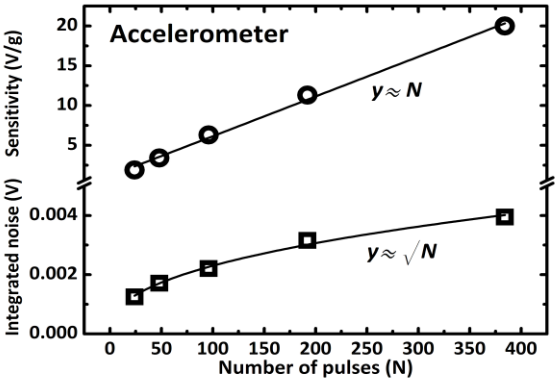

*Figure 4. Measured sensitivity and total integrated noise for the accelerometer vs. number of pulses N.*

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