Infrasonic Power-Harvesting and Nanowatt Self-powered Sensors

Shantanu Chakrabartty+ and Nizar Lajnef*

Department of Electrical and Computer Engineering†,
Department of Civil and Environmental Engineering*

Michigan State University
East Lansing, Michigan - 48824, USA
{Shantanu, lajnefni}@egr.msu.edu

Abstract—Many signals of interest in structural engineering, for example seismic activity, lie in the infrasonic range (frequency less than 20 Hz). This poses a significant challenge for developing batteryless sensors that are required not only to monitor rare infrasonic events but also to harvest the energy for sensing, computation and storage from the signal being monitored. In this paper, we show that a linear injection response of our previously reported piezo-floating-gate sensor is ideal for self-powered sensing and computation of infrasonic signals. Our experimental results demonstrate that the sensor fabricated in a 0.5µm CMOS technology can compute and record level crossing statistics of an input seismic event. Collected data are in good agreement with results obtained using a standard data acquisition system. Also, the sensor consumes less than 100nA of current, which makes its operation based on infrasonic power-harvesting feasible.

I. INTRODUCTION

Autonomous structural health monitoring has received significant attention in recent years due to the declining state of aging civil infrastructure in the United States [1, 2]. As new “smart” structures are being designed, special consideration has been paid towards embedding health monitoring capabilities directly into the construction material during the manufacturing and deployment process [2, 3]. One particular technology, which our group has been working on, is called the “smart” pebble technology which refers to a batteryless sensor whose size is comparable to the grain size of the construction material (for example concrete). A multitude of these sensors can then be embedded inside the structure during construction and can monitor the statistics of localized strain which could be particularly important for determining the effect of sudden extreme events such as earthquakes.

Vibrations are induced in structures due to commonly occurring dynamic loads such as wind, traffic movement, and more severe loadings such as ground motion (earthquakes). Most civil engineering structures have fundamental vibration modes that occur at frequencies less than 5 Hz. Furthermore, typical dynamic load frequency spectra range from 0 to 5 Hz. Figure 1 shows the ground acceleration data and its corresponding spectrum for a well studied and commonly used earthquake time-history benchmark—the 1940 El Centro earthquake, which is available from the US Geological Survey. It can be seen from the spectrum that the maximum energy content in such a seismic event lie at lower infrasonic frequency range.

In [4], we proposed a long-term health and usage monitoring technique based on the physics of piezoelectric mechanical-to-electrical energy conversion in conjunction with device physics of impact ionized hot-electron injection (IHEI) process on floating-gate transistors [5, 6]. One of the attractive properties of piezoelectric transducers is its ability to generate large voltage swings (>5V), but at nano-amperes current level. This property is ideal for triggering IHEI floating-gate transistors. In [7], we demonstrated the feasibility of long-term sensing, computation and storage at power levels less than 1µW. In this paper, we exploit the piezo-floating-gate injection mechanism for embedded monitoring of short-term instantaneous events such as earthquakes.

The paper is organized as follows: In section II, the feasibility analysis of infrasonic power harvesting and energy scaling of piezoelectric transducers is discussed. This will determine the size of the sensor. In section III, the short term monitoring property of the piezo-floating-gate sensor and a circuit level implementation are presented. In section IV, measured results...
using a prototype fabricated in a 0.5μm CMOS technology subject to an emulated seismic event load are presented. Results are compared to the output of a standard data acquisition system.

II. INFRASONIC POWER HARVESTING AND ENERGY SCALING IN PIEZOELECTRIC TRANSDUCERS

The direct piezoelectric effect is the ability of certain crystalline materials to generate electric charge from an applied mechanical stress. For a piezoelectric material with dimensions $L \times b \times h$ polled through its thickness, the open-source voltage generated across the material (V) for an applied mechanical force (F) along its length is given by:

$$ V = \frac{F g_{31}}{b} = S Y^E h g_{31} = \frac{S Y^E d_{31} h}{e} \quad (1) $$

where $g_{31}$ and $d_{31}$ are piezoelectric constants, $S$ is the applied mechanical strain, $Y^E$ is the short circuit elastic modulus and $e$ is the electrical permittivity. Another important property of piezoelectric materials is its intrinsic capacitance given by:

$$ C = \frac{L b e}{h} \quad (2) $$

Typically, the infrasonic loading is an order of magnitude lower than the transducer resonant frequency. As a result, the piezoelectric transducer can be modeled by a quasi-static electrical circuit [8, 9] (Figure 2) that consist of an open AC loading of 100με. The power delivered to the processor (load), given by $P_z$ at 1Hz, can be optimized with respect to the load. The optimal $R_z$ is then obtained as $R_z = 1/2 \pi f C$. Combining with equations (1) and (2), the maximum power density (watts per volume) that can be delivered to the load can be written as:

$$ P_z = 2 \pi f Y^E d_{31} h^2 / e \quad (3) $$

Figure 3 shows the power density plot obtained for two different classes of piezoelectric material: lead zirconate titanate (PZT) and semi-crystalline plastic polyvinylidene fluoride (PVDF). These two materials have very different properties ($Y_{E, d_{31}}$) and are typically used for different applications. In Figure 2, the strain level is assumed to be 100με. It can be seen that for a “smart” pebble of dimensions less than 1cm, the maximum power that can be delivered to the sensor is 10μW. Considering losses due to coupling, approximately 1%-10% of the power could be transferred to the sensor which leads to a nanowatt power budget.

![Figure 2: Quasi-static electric model of a piezoelectric transducer.](image)

III. PIEZO-FLOATING-GATE SENSOR

A simplified piezo-floating-gate sensor consists of a p-channel floating-gate metal-oxide-semiconductor (MOS) transistor which is connected to a constant current source $I_0$ that is powered by the piezoelectric transducer. The vibration energy harvested by the piezoelectric transducer is used to inject electrons from the transistor channel onto the floating gate of the floating node $V_g$. The injection current $I_{inj}$ can be expressed as:

$$ I_{inj} = \beta I_0 e^{V_{sd}/V_{th}} \quad (5) $$

where $V_{sd}$ is the drain to source voltage and $I_0$ is the source current. In weak-inversion, the expression for source current through the pMOS transistor is given by:

$$ I_s = I_0 e^{-V_{g}/V_{th}} \quad (6) $$

where $I_s$ is the drain current, $V_g$ is the floating gate voltage, $\kappa$ is the floating gate efficiency and $V_T$ is the thermal voltage (26mV at room temperature). For a fixed reference current $I_0$, the gate transistor current, according to the IHEI model, is given by:

$$ I_g = \beta I_0 e^{V_g/V_{th}} = -C_i \frac{dV_g}{dt} \quad (7) $$

where $\beta$ and $V_{th}$ are constants, and $C_i$ is the total capacitance of the floating node $V_g$. The solution of equation (7) gives the change in floating gate voltage $V_g$ with respect to time $t$ and drain current $I_0$ as:

$$ V_g(t) = -\frac{1}{K_2} \log(K_1, K_2 + e^{-K_2 t}) \quad (8) $$

where $V_{th}$ is the initial gate voltage, and $t$ represents the total duration for which the injector is operational. The constants $K_1$ and $K_2$ are device parameters and can be written as:

$$ K_1 = \left( \frac{\beta I_0}{C_i} \right) \left( \frac{I_0}{I_s} \right) \quad ; \quad K_2 = \frac{\kappa}{I_{inj}} \quad (9) $$

![Figure 3: Maximum power that can be delivered to the sensor using two different piezoelectric materials when subjected to mechanical loading of 100με at 1Hz.](image)
Figure 4 shows a typical response of the output voltage $V_{out}(t)$ measured as a function of injection duration $t$. The response as shown in Figure 4 consists of two distinct regions. The linear region is characterized by the condition $t \ll \exp(-K_2/V_{g0})/K_1K_2$. In this region, equation (8) can be simplified to:

$$V_{out}(t) = V_{g0} - \frac{K_1K_2}{\exp(-K_2/V_{g0})}t$$

where the approximation $\log(1+x) = x$ has been used. Thus in the linear region, the change in the output voltage is linear with respect to the injection duration and therefore is suitable for short-term monitoring (typically less than 100 loading cycles).

A circuit implementation of an array of floating-gate injectors with an integrated current reference is shown in Figure 5. The micrograph of the fabricated sensor is shown in Figure 6.

The reference current generator circuit is implemented using transistors M1-M8 and resistor R. Transistors S1, S2 form a start up circuit for the current reference. The reference current is copied by mirrors P1, P3, P5, which drive the floating gate cells F1-F3. Diode connected transistors D1-D2 are used to control the potential drop between the supply terminal and source (O1, O2, and O3) of the floating gate transistors, which ensures that each of the floating gate cells (F1-F3) start injecting at different supply potential ($V^+/V^-$). Thus the circuit in Figure 5 measures the duration of events when the amplitude of the input signal exceeds different thresholds.

Figure 7: Experimental setup to test the piezoelectric bimorph generator.

A commercially available 35mm diameter piezo-transducer disc (CEB-35D26, CUI Inc., Tualatin, OR) was used as the piezoelectric generator in this experiment. The generator consists of a brass disk of 35mm diameter and 0.28mm thickness, and a unimorph lead-zirconate-titanate piezoelectric (PZT) disk of 25mm diameter and 0.25mm thickness. The electro-mechanical properties of the used transducer were experimentally estimated using a non-linear least square fitting routine. The determined values are: stiffness ($K=986N/m$), damping ratio ($\zeta=1.2\%$), mechanical coupling coefficient ($\Theta=6.25\times10^{-4}C/m$), and capacitance ($C=25.2nF$).
A tip mass of 18g was bolted to the brass disk. The added mass increases the tip displacement under a given excitation resulting in higher generated power. It should be noted that the mass used in this experiment was selected so that sufficient energy was generated to simultaneously power the prototype sensor (with an estimated input impedance of about 40 M$\Omega$) and the data acquisition system (with input impedance of 10 M$\Omega$). In [1], it was shown that the generated power scales linearly with the vibrating mass. In real application environments, only the sensor will be attached to the piezo-generator resulting in a significant decrease in power requirement and subsequently a decrease in the mass and size of the overall system. Figure 8 shows the measured voltage generated by the described piezoelectric generator when subject to the excitation shown in Figure 1. The output voltage was measured across a 500nF capacitor attached after a diode bridge rectifier. The shown voltage was input to the floating-gate array. The sensor cells where first initialized to around 5V so that the sensor will operate in the linear region as described in section III. The injection thresholds were preset for the first three memory cells to 5.3V, 6.1V and 6.9V.

![Figure 8: Observed signal generated by the piezoelectric transducer, under simulated El centro excitation, across a 500nF capacitor and input to the floating-gate sensor](image)

Since the input signal to the array is known (Figure 8), the respective cumulative injection time for each cell can be directly read on the voltage curve. Obtained values are shown in Table 1. After running the simulated earthquake, variations of voltage from the initial 5V value were measured for each floating-gate cell. The obtained variations are also shown in Table 1. Since the gates voltages are linear with respect to cumulative injection time (Figure 4), normalized ratios of injection durations obtained from the known input and experimental measured voltages can be compared as shown in Table 1. A strong correlation was shown between measured and pre-known input characteristics. The observed minor errors could be due to initialization inaccuracies and manufacturing mismatch between different cells. This proof of concept experiment shows that variation of voltages measured at the floating-gates array of the developed sensor could eventually be used to recreate a representation of the time history of input signals generated by random unknown events such as earthquakes. If we calibrate different voltage thresholds to correspond to strain levels in a given structure, the measured results from a network of distributed sensors will recreate the strain distributions that occur during an unknown extreme event (impact, earthquake). The information is given in an integration sense and it is based on correlation between measured relative voltages variations and corresponding injection durations.

### Table 1: Comparison of known input signal and measured sensor output

<table>
<thead>
<tr>
<th>Preset Injection Threshold $x_i$</th>
<th>Cumulative injection time – Input Voltage above the threshold $x_i$ (Read from data acquisition system)</th>
<th>Gate voltage variation Δ$V_i$</th>
<th>Voltage ratios measured from the floating-gate cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3 V</td>
<td>$t_1 = 12.73$ s</td>
<td>$ΔV_1 = 0.0068$ V</td>
<td>$t_1/t_2 = 1.8623$</td>
</tr>
<tr>
<td>6.1 V</td>
<td>$t_2 = 6.83$ s</td>
<td>$ΔV_2 = 0.0042$ V</td>
<td>$t_1/t_3 = 5.6602$</td>
</tr>
<tr>
<td>6.9 V</td>
<td>$t_3 = 2.24$ s</td>
<td>$ΔV_3 = 0.0014$ V</td>
<td>$t_1/t_3 = 3.0393$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time ratios obtained from known input signal</th>
<th>Voltage ratios measured from the floating-gate cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ΔV_1/ΔV_2 = 1.6190$</td>
<td>$t_1/t_2 = 1.8623$</td>
</tr>
<tr>
<td>$ΔV_1/ΔV_3 = 4.8571$</td>
<td>$t_1/t_3 = 5.6602$</td>
</tr>
<tr>
<td>$ΔV_2/ΔV_3 = 3$</td>
<td>$t_1/t_3 = 3.0393$</td>
</tr>
</tbody>
</table>

### V. Conclusion

In this paper we demonstrated that our previously reported self-powered piezo-floating-gate sensor can be used to sense, compute and store statistics of short-term instantaneous events, like earthquakes, experienced by a structure, while consuming less than 100nA of current.

### REFERENCES