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Capacitance-based wireless strain sensor development

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Abstract
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Keywords
Wireless sensor, Structural health monitoring, Capacitive strain sensor, AC Wheatstone bridge

Disciplines
Civil Engineering | Structural Engineering | VLSI and Circuits, Embedded and Hardware Systems

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Capacitance-based wireless strain sensor development

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ABSTRACT

A capacitance based large-area electronics strain sensor, termed soft elastomeric capacitor (SEC) has shown various advantages in infrastructure sensing. The ability to cover large area enables to reflect mesoscale structural deformation, highly stretchable, easy to fabricate and low-cost feature allow full-scale field application for civil structure. As continuing efforts to realize full-scale civil infrastructure monitoring, in this study, new sensor board has been developed to implement the capacitive strain sensing capability into wireless sensor networks. The SEC has extremely low-level capacitance changes as responses to structural deformation; hence it requires high-gain and low-noise performance. For these requirements, AC (alternating current) based Wheatstone bridge circuit has been developed in combination a bridge balancer, two-step amplifiers, AM-demodulation, and series of filtering circuits to convert low-level capacitance changes to readable analog voltages. The new sensor board has been designed to work with the wireless platform that uses Illinois Structural Health Monitoring Project (ISHMP) wireless sensing software Toolsuite and allow 16bit low-noise data acquisition. The performances of new wireless capacitive strain sensor have been validated series of laboratory calibration tests. An example application for fatigue crack monitoring is also presented.

Keywords: Wireless sensor, Structural health monitoring, Capacitive strain sensor, AC Wheatstone bridge

1. INTRODUCTION

The wireless structural sensor networks (WSSN) has been promising solutions for full-scale structural health monitoring (SHM) in practice. WSSN allows automated monitoring of structural behaviors with dense array of low-cost sensors. Various kinds of multimetric sensor hardware and software have been developed, implemented in WSSN, and demonstrated the performance through many full-scale SHM applications using the WSSN [1–3].

Strain based structural sensing has been widely used in measuring static and dynamic deformation of structures with advantages in broadband accuracy, low-cost and easy installation. The most commonly used strain sensor is the resistive type strain gauges that convert strain deformation into resistance change of the gauge; which are low-cost, accurate, and easy to integrate with existing wireless platform. However, it has several limitations for practical applications due to the small sizes and fragility induced by rigid material composition[4–6]. When the strain gauge is used for concrete structures, non-homogeneous material features cause measurement errors in global displacement reconstruction and lack of flexibility causes easy failure along the crack growth[7]. For fatigue monitoring of steel structures, huge numbers of strain gauges in dense array are required to cover large area of potential, but unknown, fatigue crack location for effective monitoring; which is not so practical[4,5].

Recent advances in structural sensing lead various kinds of strain sensor developments to address the problems. In order to measure large area strain accurately, several types of sensors have been developed and studied, such as fiber optic strain sensor, resistive sensor sheet, and carbon nanotube-based sensor [8–10]. Besides, Soft elastomeric capacitive (SEC)

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sensor has been developed for meso-scale strain sensing application. The SEC is a capacitance-based strain sensor that has various features suitable to the SHM applications; which are low-cost, various size manufacturability, durability, and extended linearity up to 20% elongation [4–6,11,12]. Recent researches utilized the SEC to demonstrate the potential for various SHM applications, including steel structure fatigue crack detection, large-scale structure sensing in static/dynamic strain responses [4,5,12,13]. While, high-sensitivity acceleration and strain sensors for WSSN have been developed and demonstrated [2,3], the capacitance based wireless strain sensor has not been developed yet. In this study a capacitance-based strain sensor board for wireless sensor platform MEMSIC's Imote2 is developed and the performances are validated for SHM application. This sensor board converts low-level capacitance changes into measurable analog voltages and are designed to interface with Imote2 for power supply(5V) to utilize the AD conversion, wireless data transmission, and onboard signal processing capability of the Imote2 platform. The AC-Wheatstone bridge was employed to convert the dynamic capacitance variation into voltage changes, multi-step signal amplification and filtering, and peak envelope detection circuits were employed to accurately extract the dynamic strain signals from the modulated AC Wheatstone bridge outputs. The performance of sensor board was validated through lab-scale tests.

2. DEVELOPMENT OF CAPACITANCE-BASED STRAIN SENSOR BOARD

2.1 Considerations for high-sensitivity capacitance sensing

The first step in the design of capacitance-based strain sensor board is to convert capacitance changes into voltage change. There are several methods to transduce capacitance to voltage, oscillator-based and Wheatstone bridge-based methods are the most widely used. Oscillator-based sensing method is suitable to measure wide capacitance variation. However, to measure very small-range capacitance variation with oscillator requires to have high-performance jitter clock which is expensive. Another way is Wheatstone bridge-based method which is suitable to measure small range capacitance change allowing high-amplification. In this study, AC-Wheatstone bridge-based circuit in combination with amplifier and peak envelope detection circuit was employed to convert capacitance change to measurable voltage change.

The second consideration is the interface with wireless platform. The new sensor board was aimed to work with existing wireless platform Imote2 supporting high-fidelity 16-bit sensing capability, regulated power supply of 5V and internal data processors. For compatibility with Imote2, the amplifier is set to 0~5V range for data acquisition. Because, AC Wheatstone bridge utilize AM-modulated signal for capacitance variation, peak envelope detection circuit was employed to extract actual dynamic capacitance variation from modulated signals. Then, an analog low-pass filter was applied for clear output in desired bandwidth. Figure 1 is the block diagram of the sensor module showing the capacitance sensing principle.

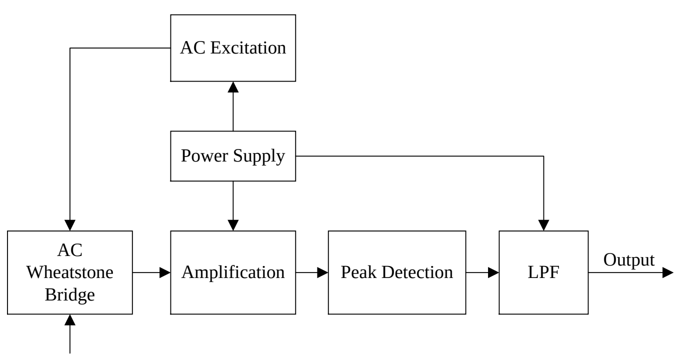


Figure 1. Block diagram of the wireless capacitive strain sensing module

2.2 AC Wheatstone Bridge & Amplification

As mentioned, high sensitivity is essential for strain sensing for SHM. To achieve the required sensitivity, a precisely controllable AC Wheatstone bridge circuit was designed as illustrated in Figure 2.

The AC Wheatstone bridge with two capacitors and two resistors as the simplest AC bridge configuration for comparing the two capacitor values is known as AC Wheatstone bridge. In this design, a sine wave AC signal is used to excite the bridge. Considering the cost effectiveness and difficulties in finding a proper sine wave chip with the bandwidth required of the amplifier, a square wave to sine wave conversion scheme is employed. This strategy uses a 32.768kHz square wave oscillator with a 4-order Sallen-key low pass filter for square wave to sine wave conversion.

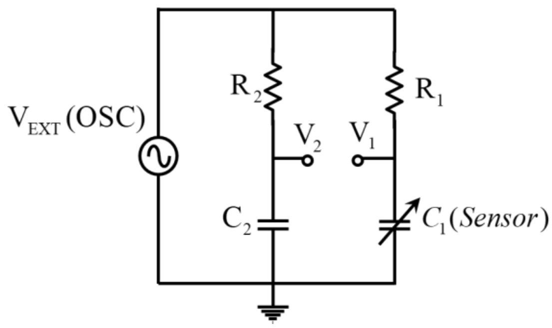


Figure 2. AC Wheatstone bridge design

The AC Wheatstone bridge is composed of a reference capacitor (C2), a capacitive sensor (C1) and two potentiometers as variable resistors (R_1 and R_2) for bridge balancing as shown in Figure 2. One of the capacitors is the sensor (DUT, Device Under Test), while the other is the reference (quarter bridge). The final output signal (i.e. ΔV_{out}) from the AC Wheatstone bridge with the two-step amplifier can be derived as follows. First, by using the configuration in Figure 2, the balanced condition is $R_2 / R_1 = C_1 / C_2$. The initial state voltage (no strain) of bridge can be expressed as

$$V_{initial} = V_{EXT}\left(\frac{\frac{1}{j\omega C_2}}{R_2 + \frac{1}{j\omega C_2}} - \frac{\frac{1}{j\omega C_1}}{R_1 + \frac{1}{j\omega C_1}} \right) \tag{1}$$

and when the capacitance of SEC increases by ΔC, the total capacitance of the SEC sensor is $C_1^{'} = C_1 + \Delta C$ and the voltage under test (strain) of the bridge is

$$V_{test} = V_2 - V_1 = V_{EXT}\left(\frac{\frac{1}{j\omega C_2}}{R_2 + \frac{1}{j\omega C_2}} - \frac{\frac{1}{j\omega\left(C_1 + \Delta C\right)}}{R_1 + \frac{1}{j\omega\left(C_1 + \Delta C\right)}} \right) \tag{2}$$

For a balanced status, $C_1R_1 - C_2R_2$ is zero and according to the SEC sensitivity, the capacitance change ΔC is very small compared to nominal capacitance of the SEC; thus, ΔC can be neglected in the denominator of (2), resulting in following Eqn.:

$$V_{test} = V_{EXT}\left(\frac{j\omega R_1}{\left(1 + j\omega C_1 R_1\right)\left(1 + j\omega C_2 R_2\right)} \Delta C \right) \tag{3}$$

Eqn. (3) gives a linear expression transducing a change in capacitance into a change in voltage. Because the capacitance change is very small, an amplification is necessary. However, due to the parasitic effect, the balance could not be perfectly achieved, which means there is always a DC component in the output signal from the bridge. Therefore, amplification circuit is used in this design. AD8226 was employed for the amplification due to their low cost, appropriate power supply range (2.2V to 36V), proper bandwidth (1.5Mhz), and sufficient amplification capability up to 1000 times. Differential voltage from the AC Wheatstone bridge is amplified by the amplification with variable potentiometers.

2.3 Peak Envelope Detection

According to Eqn. (3) with amplification, the output signal from the amplification part would be an amplitude modulated (AM) sine wave. So, amplitude envelope detection is employed to make the final voltage proportional to the capacitance change. Figure 3 shows the circuit for peak envelope detection.

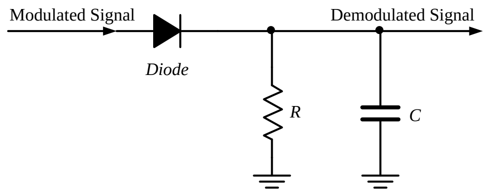


Figure 3. Circuit for peak detection

In this circuit, the values for R and C should be carefully designed to ensure the demodulated signal reflects the actual message (i.e. dynamic capacitance variation of capacitive sensor). In this board design, the target frequency bandwidth of the structural response signal is 0~40Hz. On the other hand, the carrier frequency of the modulated signal that comes from the AC sine-wave excitation for the bridge is much higher than the message frequency. Therefore, to extract the message from the modulated signal, the relationship shown in Eqn. (4) must be satisfied.

$$\frac{1}{f} \ll \tau = RC \ll \frac{1}{\omega} \tag{4}$$

where f is the frequency of the carrier, ω is the bandwidth of the message, and τ is the charging time of the RC circuit.

In addition, a third-order active LPF using the Sallen-Key configuration has been incorporated after the peak envelope detectionfor cleaner final outputs.

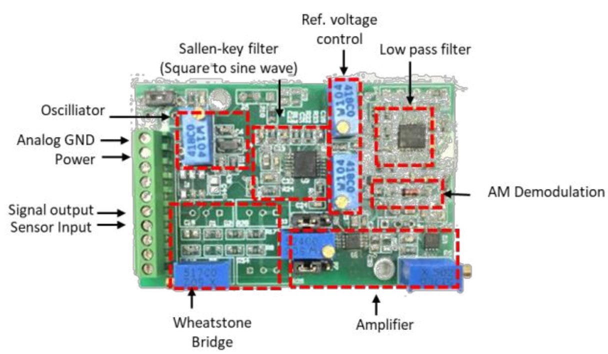


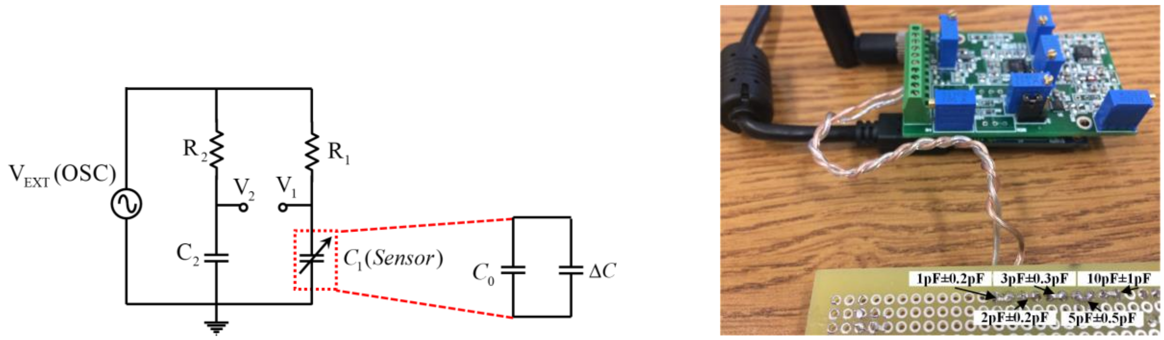
Figure 4. Top view of prototype capacitance sensor board

3. EXPERIMENTAL VALIDATION

3.1 Test procedure

The performance of the developed strain sensor board was verified through lab-scale tests. In order to demonstrate the capacitance to voltage conversion, linearity of this capacitance sensing was tested. A 1000pF capacitor is used to as the nominal capacitance of the real sensor and several small value capacitors are parallelled with this 1000pF capacitor one by one to simulate the capacitance change of the sensor. Figure 5(a). shows the schematic of this test and Figure 5(b) shows the test field. In Figure 5(b), C_0 is the 1000pF capacitor, ΔC is the small value capacitor, whose value is from 1pF±0.2pF to 10pF±1pF shown in Figure 5(b). For power supply and data acquisition, Imote2 was used for developed sensor board and for capacitnace comparision, a commercial wired capacitance measurement kit PCAP-02 was used.

For Dynamic excitation test, a capacitive strian sensor SEC (1.4×1.4 in. , nominal capacitance : 210pF) attached on steel plate with 7-story shear building was used shown in Figure 6. Specimen was placed in 6th story of shear building and strain gauge was installed back side for comparision. As excitations, 0.5 Hz sine wave was used with 80 and 400 micro strain level amplitudes. An APS400 Electrodynamic shaker with an APS145 amplifier was used to generate the dynamic load excitation. For comparison, strain responses were measured by an OMEGA KFH-3-120-C1-11L3M3R, which is a foil-type strain gauge having a nominal resistance of 120±0.35Ω. Test results from the three DAQs (i.e. NI DAQ, PCAP02, and Imote2) are compared in Figure 8. For each test, the AC Wheatstone bridge was balanced precisely.



(a) (b)

Figure 5. Linearity test setup: (a) Schematic for the linearity test; (b) Test field

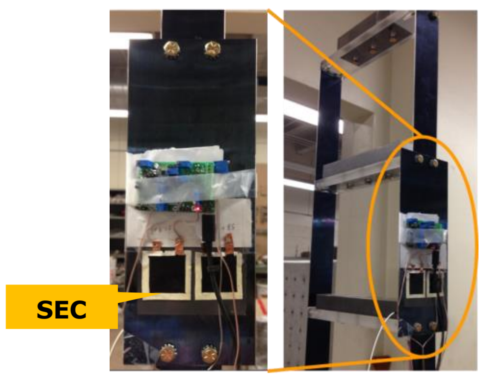


Figure 6. Dynamic test setup

3.2 Test result

Figure 7 shows the test results for the linearity test. The initial state is not shown because it has been used for the bridge balance. As shown, the output voltage is changed according to the capacitance change linearly. Considering the tolerance shown in this Figure 7, the linearity is pretty good.

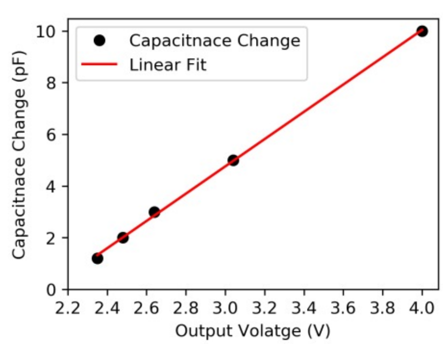
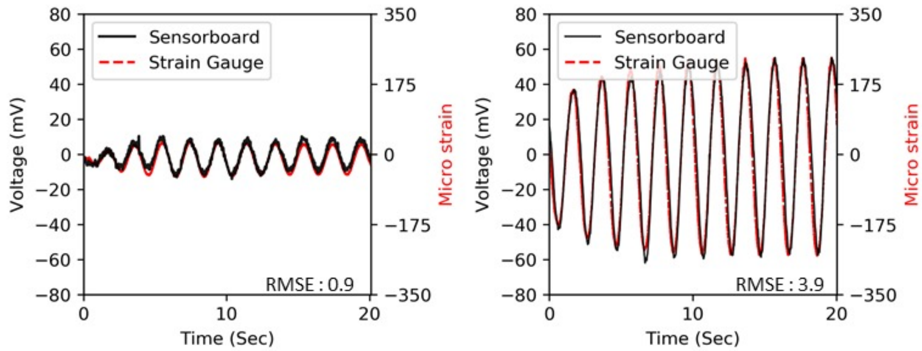
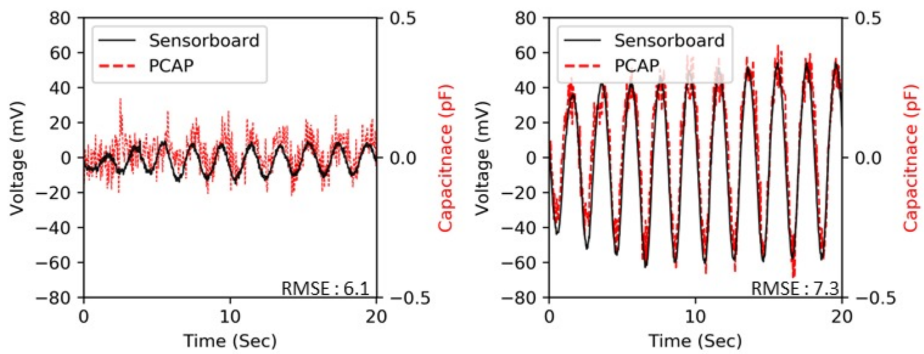


Figure 7. Linearity test results.



(a)



(b)

Figure 8. Dynamic excitation test results under 0.5 Hz, 80 / 400 μ-strain excitation: (a) Comparison of sensor board and strain gauge; (b) Comparison of sensor board and PCAP-02

For dynamic test, as can be observed in Figure 8(a), the measurements taken by the new sensor board showed strong agreement with conventional strain gauge measurements for all amplitude cases with RMSE 0.9mV and 3.9mV for each amplitude case. Comparing with PCAP02 measurements, the new sensor board showed cleaner (lower noise) results as shown in Figure 8(b) with RMSE 6.1mV and 7.3mV for each amplitude case. The RMSE were calculated with converted values from strain and capacitance measurement to voltage using calculated ratios (micro strain to mV : 80/350, pF to mV : 80/0.5). The PCAP02 measurement showed noisy results under 80 micro strain responses. Considering the clean measurement from the sensor board under small excitation (80 micro strain, 0.08 pF in Figure 8(b) left) the sensor board is capable to measure capacitnace change below 0.05%.

4. CONCLUSIONS AND FUTURE WORK

In this study, a capacitance based wireless strain sensor board was developed and the performance of the sensor board was evaluated through a lab tests. The newly developed sensor board was designed to interface with Imote2 wireless sensor platform to take advantage of functions. By employing AC Wheatstone bridge, high-precision bridge balancer, and signal amplification, and peak envelope detection with active low-pass filter was able to measure capacitance variation in linear with good accuracy in dynamic test. This AC bridge-based configuration enabled analog voltage output that can be directly interfaced with the Imote2 platform and is characterized by its simple PCB structure for lowering cost, and high-sensitivity capacitance-based strain measurement. a prototype is developed and mounted onto Imote2 WSSN platform. Several individual ceramic capacitors are used to make the capacitance change for the test of linearity. The dynamic sensor test using 1.4×1.4 in. SEC result showed good performance. Besides, test results show the prototype can sense lower than 0.05% capacitance change of the capacitive sensor. Finally, the sensor board is small and easy to install. The future work will be focused on evaluating performance under high-frequency dynamic excitation with various sizes capacitive strain sensors on steel structure.

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