

Dense Network of Large Area Electronics for Fatigue Crack Detection and Localization

SIMON LAFLAMME, JERAMIE VENS, DAJI QIAO,
AUSTIN DOWNEY and JIAN LI

ABSTRACT

Detection and localization of fatigue cracks is a difficult task. Existing technologies enabling nondestructive evaluation and structural health monitoring are expensive to utilize, time consuming, and/or have a complex link signal-to-damage. Recent developments in large area electronics (LAE) have facilitated the deployment of large distributed networks of transducers onto structural surfaces. We have recently developed a soft elastomeric capacitor (SEC), a type of LAE, which transduces strain into a measurable change in capacitance. Deployed in a dense network configuration, the SEC would have the capacity to detect and localize damage over a global surface, analogous to biological skin. A particular network application of the SEC is for detection and localization of fatigue cracks, which has been demonstrated in prior work. However, such network demonstration used a limited number of sensors due to limitations in the off-the-shelf data acquisition system used in the experiment. To enable dense network applications, we propose a dedicated readout circuit. The circuit consists of a relaxation oscillator that produces a square wave based on a differential capacitance input. The period of the square wave is directly related to the change in capacitance, which in turn can be related to a change in strain, also linearly. Preliminary tests were conducted on ceramic capacitors, which simulated eight strain levels from 0% to 3.94% strain. Results show that the readout circuit was linear as a function of strain, stable as a function of time, and that the experimental data closely fit the electrical model.

INTRODUCTION

Detection and localization of damage on mesosurfaces is a difficult task. Off-the-shelf technology, such as resistive foil gauges, are geometrically too small to be capable of detecting a new crack within an acceptable level of probability [1].

A solution is to deploy dense arrays of sensors. For instance, piezoelectric wafer active sensors (PWAS) networks have been proposed for detecting and localizing

Simon Laflamme, Dept. of Civil, Cnstr., and Env. Eng., Iowa State University, Ames, IA, 50011
Jeramie Vens, Dept. of Electrical and Comp. Eng., Iowa State University, Ames, IA, 50011
Daji Qiao, Dept. of Electrical and Comp. Eng., Iowa State University, Ames, IA, 50011
Austin Downey, Dept. of Civil, Cnstr., and Env. Eng., Iowa State University, Ames, IA, 50011
Jian Li, Dept. of Civil, Env. and Arch. Eng., The University of Kansas, Lawrence, KS, 66045

fatigue cracks [2-3], as well as networks of fiber optics-based technologies [4-5]. Refs. [6-8] have studied the deployment of carbon nanotube networks to detect changes in local damages.

The deployment of large-area electronics (LAE) has also been investigated. The utilization of LAE for monitoring of fatigue cracks has gained popularity with recent progresses and discoveries in the field of flexible electronics. Their measurement principle is typically based on monitoring local states over global areas by deploying large arrays of flexible sensing substrates, analogous to sensing skins. In particular, Refs. [9-11] investigated carbon nanotube-based flexible strain sensors, and Refs. [12-13] proposed to utilize flexible sensing sheets of strain gauges.

The authors have proposed a highly scalable sensing skin for measurement of bidirectional strain on large surfaces [14]. The skin is composed of a dense network of soft elastomeric capacitors (SEC). The dielectric of an SEC is fabricated using a styrene-co-ethylene-co-butylene-co-styrene (SEBS) polymer matrix doped with titanium dioxide (TiO_2), and the electrodes are constituted by the same SEBS, but mixed with carbon black particles. The static [15] and dynamic [16] behaviors of an SEC have been characterized, and the proposed skin applied to fatigue crack detection and localization in steel members [17].

While the dense array monitoring technique has shown great scalability and potential at monitoring local strain over mesosurfaces, a dedicated readout circuit (ROC) capable of measuring very small changes in capacitance at a high precision, over a large number of capacitors, needs to be developed. This paper presents preliminary results on a dedicated method of measuring small changes in capacitance, which can greatly increase the sensitivity of the overall system. Past work in the field of capacitance measurement has been focused on sensors for touch MEMS technologies. These technologies tend to have capacitance changes of the same order of magnitude as their nominal capacitance. Much work has been done in the field of capacitance measurement for touch screens and touch sensors; however, due to the physics of the SEC, these systems were found to not be effective.

The design chosen for this system is based on a common and well established oscillator referred to as a relaxation oscillator and a common negative impedance circuit. These were selected due to their robustness and minimal part count along with their stability over large temperature and operating conditions. The minimal part count is invaluable to extend this system to large sensor arrays with each sensor only requiring a single silicon chip, four passive components and a digital potentiometer. The output is a square wave with the capacitance data encoded on the period of the wave. This is easy to measure quickly and accurately with most microcontrollers such as an MSP430, and allows for easy multiplexing of large arrays of sensors to a single microcontroller.

The rest of the paper is organized as follows. The next section presents the background on the sensor, which includes a derivation of its electromechanical model, a summary of prior results on network applications, and a description of the measurement method in array configurations. The subsequent section describes the dedicated ROC and its electrical model. The following section presents and discusses preliminary results. The last section concludes the paper.

BACKGROUND

Electromechanical Model

The electromechanical model of the SEC is derived in Ref. [16]. Briefly, a change in capacitance ΔC can be related to strain by the following equation

$$\frac{\Delta C}{C_0} = \frac{1}{1 - \nu} (\varepsilon_x + \varepsilon_y) \quad (1)$$

with

$$C_0 = e_0 e_r A / h \quad (2)$$

where $\nu \approx 0.49$ is the Poisson ratio of the polymer, ε_x and ε_y are the in-plane strains as shown in Fig. 1, e_0 is the vacuum permittivity, e_r the polymer relative permittivity, $A = w \cdot l$ the initial sensor area with initial width w and length l , and h the initial height of the dielectric. The gauge factor can be taken as $\lambda = 1/(1 - \nu) \approx 2$. Note that this formulation assumes that the material is incompressible and under plane stress ($\sigma_z = 0$).

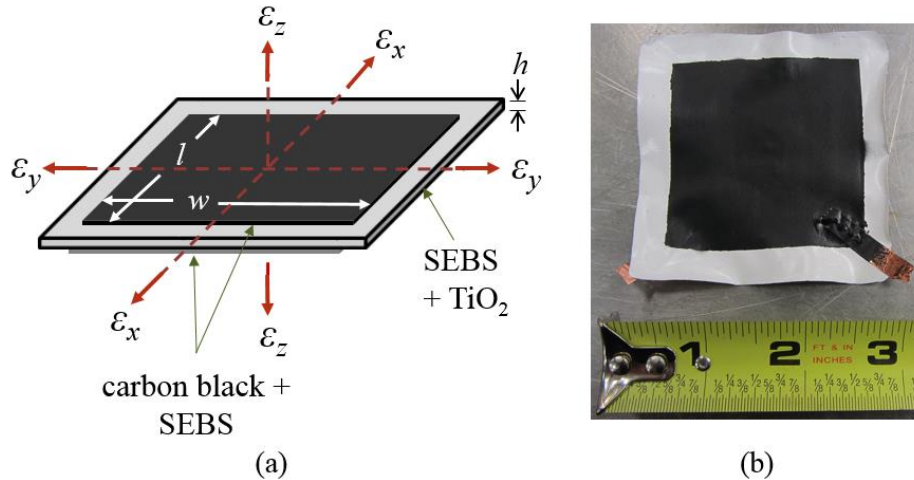


Fig. 1: (a) schematic representation of an SEC; and (b) picture of an SEC (3 x 3 in²)

SEC Network for Fatigue Crack Detection

Network applications of the SEC technology have been investigated. In particular, a demonstration was conducted using four SECs for detecting and localizing fatigue cracks in Ref. [17]. A key result is briefly summarized in what follows.

The experimental procedure consisted of deploying the SECs onto the surface a steel specimen designed following the ASTM E647-13a. The specimens were fabricated with a width of 6 in to accommodate four sensors of dimensions 1.5 x 1.5 in². Prior to the SEC installation, each test specimen was sanded at the sensor location and painted with a primer. The sensors were then deployed onto each specimen using a thin layer of an off-the-shelf epoxy (JB Kwik). The test specimens were gripped to a computer-controlled MTS 810 electric servo-hydraulic via a clevis and pin assembly attached to the top and bottom holes. A fatigue crack was introduced in the specimen using cyclic loading in a tension-tension mode under a maximum and minimum loads of 6.5 kips and 0.65 kips respectively at a frequency of 20 Hz. During the loading process, data

from the SEC were acquired using an off-the-shelf data acquisition system (DAQ) – an ACAM PCap01. The test specimens were visually inspected to monitor crack development, and pictures were taken using a Canon T2i DSLR camera 18.0-megapixel. These pictures were post-processed using a pixel count to determine the crack length and width and correlated with the SEC signal to determine whether the fatigue crack was detectable. Tests were performed three times. Figure 2 shows the test configuration. Figure 3 shows the low-pass filtered time series measurements of the four SECs. Only sensor 1, where the crack is located (Fig. 3(b)), has an observable increase in the time series, demonstrating that a network of SECs can be used to both detect and localize a fatigue crack.

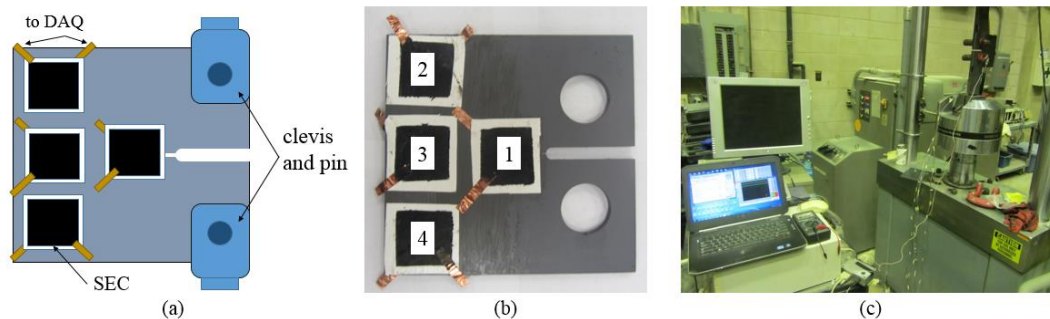


Fig. 2: test configuration: (a) schematic; (b) picture of the specimen; and (c) picture of the configuration

The utilization of very dense arrays of sensors would bring additional performance requirements on the DAQ. The DAQ is required to be capable of extracting information encoded in small changes in electric properties, from all the sensors, at a given level of accuracy and precision, often a high sampling rate. It follows that the performance of the SEC sensor is strongly dependent upon the performance of electronic circuits that provide a read-out of the sensor array with minimally intrusive electronics in the presence of large parasitics and environmental noise. Given these high performance requirements on the DAQ and the typical high cost deploying off-the-shelf DAQ for dense sensor networks, a dedicated DAQ needs to be developed to provide a cost-effective sensing strategy.

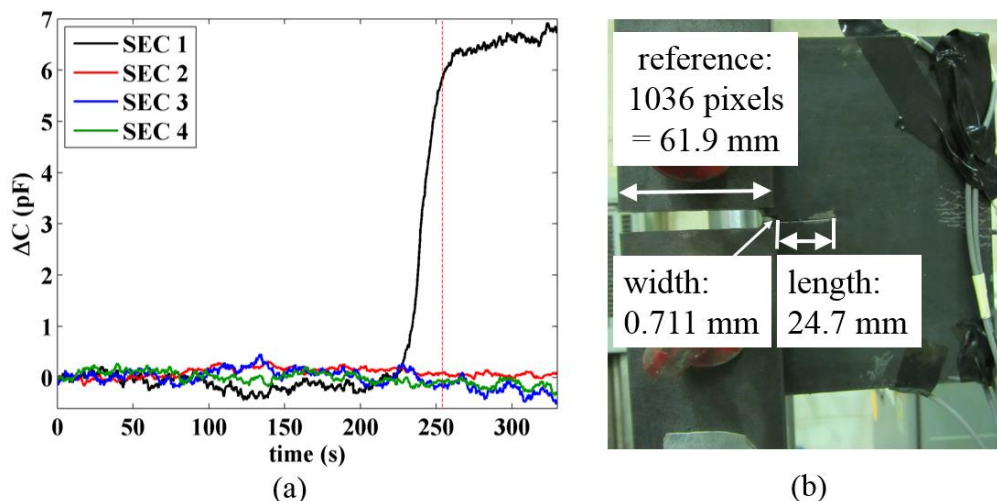


Fig. 3: typical test result: (a) time series of capacitance measurements; and (b) picture of the cracked specimen

Measurement Method

The envisioned measurement method for very dense array applications is schematized in Fig. 4. Each SEC will be equipped with an ROC directly integrated on the sensing material layer. A microprocessor, an MSP430 for instance, will be programmed to sequentially record measurements of each SEC's change in capacitance at a very fast rate. The microprocessor will pre-process the information into useful features, and transmit these features wirelessly. The next section presents recent work conducted on the design of the ROC.

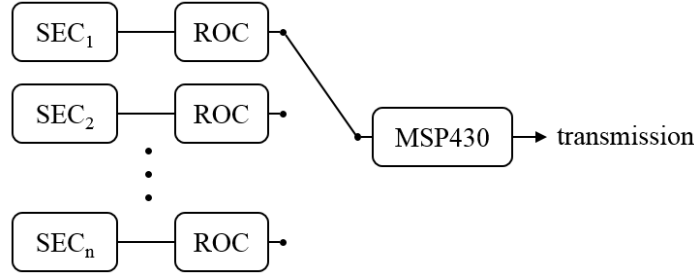


Fig. 4: schematic of the measurement method for very dense array applications

READOUT CIRCUIT

The proposed ROC is shown in Fig. 5. It measures changes in capacitance by computing the difference between the measured capacitance and a known capacitance value. This difference is then used as the capacitance of a relaxation oscillator circuit which produces a square wave, the period of which is linearly related to the measured capacitance. The known capacitor value is settable through the use of an eight-bit digital potentiometer to calibrate the system to a specific sensor.

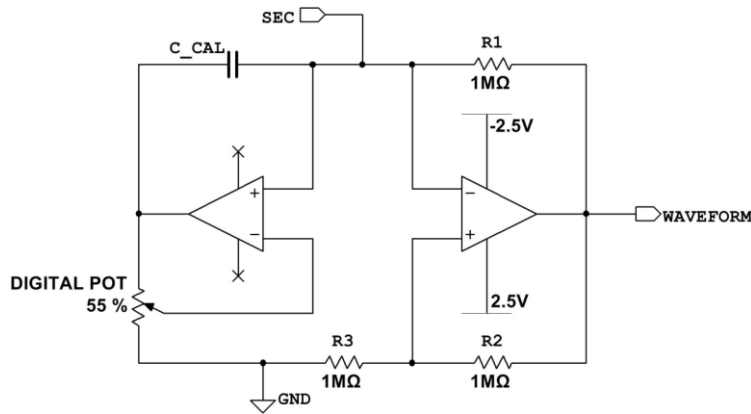


Fig. 5: schematic of the readout circuit

The known capacitor is set to have a capacitance C_1 . This capacitance is determined by a calibration capacitor C_{cal} and the tuning of the digital potentiometer k . For convenience, a change of variable is used such that $x = 1/k$. The capacitance value of C_1 is calculated using

$$C_1 = (1 - 256x)C_{cal} \quad (3)$$

The oscillator used is a relaxation oscillator. This type of oscillator was selected due to its high stability over a wide operating range of passive component values and easy to measure square wave output. The periodicity of a relaxation oscillator is selected by tuning the R and C values of the passive components. By selecting all resistors to have the same value, a duty cycle of 50% is achieved. For a basic relaxation oscillator the period of the output waveform is

$$T = 2 \ln(3) RC \quad (4)$$

and the period of the output waveform resulting from a change in capacitance ΔC is

$$\begin{aligned} T(\Delta C) &= 2 \ln(3) R(C_0 + \Delta C + C_1) \\ &= 2 \ln(3) R(C_0 + (1 - 256x)C_{\text{cal}}) + 2 \ln(3) R\Delta C \\ &= T_0 + G\Delta C \end{aligned} \quad (5)$$

with

$$(6)$$

where T_0 is the nominal period of the output waveform when no additional capacitance is present from the sensor, and G is the gain multiplier of the change in measured capacitance. The sensitivity of the system is maximized when G becomes large, which is achieved by maximizing the value of R and when T_0 becomes minimized by selecting x and C_{cal} such that $C_0 + (1 - 256x)C_{\text{cal}}$ is minimized. Because x is related to the set point of an eight-bit digital potentiometer, it must be selected such that $x = 1/k, k \in \mathbb{Z}, 0 \leq k < 256$.

RESULTS AND DISCUSSIONS

The readout circuit presented above was mounted on a breadboard, along with a microcontroller, USB controller, digital potentiometer, and a virtual ground (Gnd) to create the DAQ. These components are shown in Fig. 6.

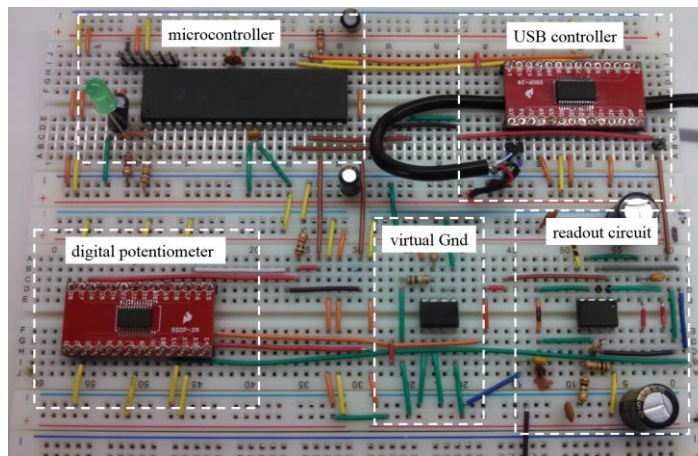


Fig. 6: data acquisition system

The circuit was tested with seven ceramic capacitors of 5, 10, 15, 22, 27, 32, and 37 pF values to simulate a change in capacitance (ΔC) from an initial 0 pF state. With the

nominal capacitance being 470 pF, which is similar to the nominal capacitance of an SEC, this is equivalent to 0.532, 1.06, 1.60, 2.34, 2.87, 3.40, and 3.94% strain using Eq (1). Fig. 7(a) is a plot of the experimental measurements as a function of ΔC . Each set of measurements contains 10,000 samples. It can be observed that the signal in Fig. 7(a) is stable for each level of ΔC , and that the measured period increases sequentially with ΔC . Fig. 7(b) is a plot of the measured period versus the simulated strain. The period for each level of strain was taken as the average value over the 10,000 samples for each ceramic capacitor. There is a linear trend between the period and the strain. The offsets can be explained by the presence of parasitic capacitance unaccounted for (e.g., from the breadboard). The theoretical fit from the model (Eq. (6)) is represented by the blue dashed line. The model is close to the experimental fit, showing the promise of the proposed readout circuit at measuring small changes in capacitance.

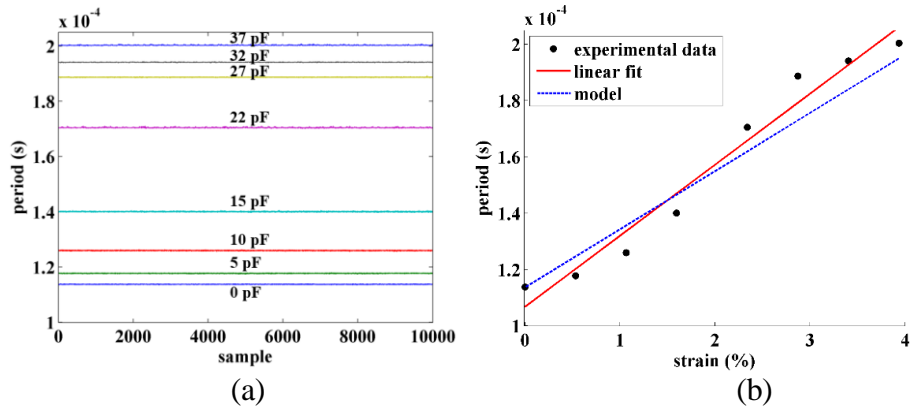


Fig. 7: (a) measured period as a function of ΔC ; and (b) measured period versus simulated strain

CONCLUSION

The SEC is a novel scalable sensing technology enabling very dense network applications of skin-type transducers. A particular network application of the SEC is for detection and localization of fatigue cracks, which has been demonstrated in prior work for a limited number of sensors. Dense network applications necessitate the development of dedicated electronics. This paper presented the design of a dedicated ROC, developed for that purpose. The circuit consists of a relaxation oscillator that produces a square wave based on a differential capacitance input. The period of the square wave is directly related to the change in capacitance, which in turn can be related to a change in strain, also linearly. Preliminary tests were conducted on ceramic capacitors, which simulated eight strain levels from 0% to 3.94% strain. Results show that the ROC was linear as a function of strain, stable as a function of time, and that the experimental data closely fit the electrical model. Future work includes tests using the SEC, and the investigation of stability versus time-varying strain input.

ACKNOWLEDGEMENTS

This work is supported by grant #494 TR672 from the Iowa Department of Transportation, and grant 1001062565 from the Iowa Alliance for Wind Innovation and Novel Development. Their support is gratefully acknowledged. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the sponsors.

REFERENCES

1. S. Kharroub, S. Laflamme, S. Madbouly, & F. Ubertini. Bio-based soft elastomeric capacitor for structural health monitoring applications. *Structural Health Monitoring*, 14(2), 158-167, 2014.
2. L. Yu, V. Giurgiutiu, P. Ziehl, D. Ozevin, and P. Pollock. Steel bridge fatigue crack detection with piezoelectric wafer active sensors. In *SPIE Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring*, 76471Y, 2010.
3. M. Gresil, L. Yu, Y. Shen, and V. Giurgiutiu. Predictive model of fatigue crack detection in thick bridge steel structures with piezoelectric wafer active sensors. *Smart Structures and Systems*, 12(2):097-119, 2013.
4. H. Tsuda, J.-R. Lee, Y. Guan, and J. Takatsubo. Investigation of fatigue crack in stainless steel using a mobile fiber bragg grating ultrasonic sensor. *Optical Fiber Technology*, 13(3):209-214, 2007.
5. D.C. Lee, J.J. Lee, I.B. Kwon, and D.C. Seo. Monitoring of fatigue damage of composite structures by using embedded intensity-based optical fiber sensors. *Smart materials and structures*, 10(2):285, 2001.
6. L. Gao, E.T. Thostenson, Z. Zhang, J.-H. Byun, and T.-W. Chou. Damage monitoring in fiber-reinforced composites under fatigue loading using carbon nanotube networks. *Philosophical Magazine*, 90(31-32):4085_4099, 2010.
7. D'Alessandro, A., Ubertini, F., Materazzi, A. L., Laflamme, S., & Porfiri, M. (2014). Electromechanical modelling of a new class of nanocomposite cement-based sensors for structural health monitoring. *Structural Health Monitoring*, 14(2), 137-147.
8. F. Ubertini, L. Materazzi, A. D'Alessandro, & S. Laflamme, Natural frequencies identification of a reinforced concrete beam using carbon nanotube cement-based sensors. *Engineering Structures*, 60, 265-275, 2014.
9. I. Kang, M.J. Schulz, J.H. Kim, V. Shanov, and D. Shi. A carbon nanotube strain sensor for structural health monitoring. *Smart Materials and Structures*, 15(3), 737, 2006.
10. K.J. Loh, T.C. Hou, J.P. Lynch, and N.A. Kotov. Carbon nanotube sensing skins for spatial strain and impact damage identification. *Journal of Nondestructive Evaluation*, 28(1):9-25, 2009.
11. R.K. Srivastava, V.S.M. Vemuru, Y. Zeng, R. Vajtai, S. Nagarajaiah, P.M. Ajayan, and A. Srivastava. The strain sensing and thermal mechanical behavior of flexible multi-walled carbon nanotube/polystyrene composite films. *Carbon*, 49(12):3928 _ 3936, 2011.
12. Y. Hu, W.S.A. Rieutort-Louis, J. Sanz-Robinson, L. Huang, B. Glisic, J.C. Sturm, S. Wagner, and N. Verma. Large-scale sensing system combining large-area electronics and CMOS ICS for structural health monitoring. *Solid-State Circuits, IEEE Journal of*, 49(2):513_523, 2014.
13. S.T. Tung, Y. Yao, and B. Glisic. Sensing sheet: the sensitivity of thin-film full-bridge strain sensors for crack detection and characterization. *Measurement Science and Technology*, 25(7):075602, 2014.
14. S. Laflamme, M. Kollosche, J.J. Connor, & G. Kofod, Robust flexible capacitive surface sensor for structural health monitoring applications. *Journal of Engineering Mechanics*, 139(7), 879-885, 2012.
15. S. Laflamme, H. Saleem, B. Vasan, R. Geiger, D. Chen, M. Kessler, & K. Rajan, K. Soft elastomeric capacitor network for strain sensing over large surfaces. *Mechatronics, IEEE/ASME Transactions on*, 18(6), 1647-1654, 2013.
16. S. Laflamme, F. Ubertini, H. Saleem, A. D'Alessandro, A. Downey, H. Ceylan, & A. Materazzi. Dynamic Characterization of a Soft Elastomeric Capacitor for Structural Health Monitoring. *Journal of Structural Engineering*, 2014.
17. S. Kharroub, S. Laflamme, C. Song, D. Qiao, B. Phares, & J. Li. Smart sensing skin for detection and localization of fatigue cracks. *Smart Materials and Structures*, 24(6), 065004, 2015.