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Abstract
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Keywords
structural health monitoring, strain gauge, Dynamic Characterization, Bio-inspired sensing, Soft elastomeric capacitor, smart sensors, thin-film sensors

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Dynamic Characterization of a Soft Elastomeric Capacitor for Structural Health Monitoring Applications

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ABSTRACT

A novel thin film sensor consisting of a soft elastomeric capacitor (SEC) for meso-scale monitoring has been developed by the authors. Each SEC transduces surface strain into a measurable change in capacitance. In previous work, the authors have shown that the performance of the SEC compares well with conventional resistive strain gauges, providing a resolution of 25 με using an inexpensive off-the-shelf data acquisition system for capacitance measurements. Here, we further the understanding of the thin film sensor by characterizing its dynamic behavior. The SEC is subjected to dynamic loads in bending mode. The study of Fourier and wavelet transforms indicates that the sensor can be used to identify dynamic inputs. Overall results demonstrate the promising capabilities of the thin film sensor at dynamic monitoring of civil structures.

Keywords: structural health monitoring, strain gauge, Dynamic Characterization, Bio-inspired sensing, Soft elastomeric capacitor, smart sensors, thin-film sensors.

1. INTRODUCTION

Structural health monitoring (SHM) is a vital process to maintain structural integrity and human safety. Implementing SHM requires building an integrated system to record, process and interpret data to assess a condition and estimate remaining life of the structure[1]. Recently, the authors have presented a sensor for large-scale strain measurements, termed Soft Elastomeric Capacitor (SEC)[2-4], intended to be used in a network configuration. Each SEC is a capacitive-based sensor, which transduces changes in its geometry caused by surface strains into changes in capacitance, allowing detection of deformations and/or cracks on the monitored surface. An SEC is fabricated by mixing a poly-styrene-co-ethylene-co-butylene-co-styrene (SEBS) polymer with titania (TiO_2) to form the dielectric, which is sandwiched between two electrode plates fabricated by mixing SEBS with carbon black (CB) nanoparticles.

Skin or thin-film sensing technology have previously been proposed by many researchers[5-8]. For instance, resistance-based thin-film sensors were fabricated utilizing carbon nanotubes[6, 7]. Others used capacitive-based thin films to measure pressure[8], strain[9, 10] and humidity[11, 12]. Several benefits can be attained from using capacitive-based sensors, including low power consumption, linear dependence on humidity, and high electrical robustness for particular geometries.

The SEC discussed in this paper differs from most other thin-film sensors by providing a scalability for meso-scale applications, including bridges, dams, aircraft wings, wind turbines, etc. [13]. Such scalability arises from the combination of cost effectiveness, mechanical robustness, low power usage, and ease of installation.

In this paper, a preliminary study on the dynamic behavior of the SEC is conducted. The objective is to further the understanding of the behavior of the sensor at monitoring structural vibrations. The study is conducted experimentally by subjecting a cantilever beam to a harmonic load sweeping from 1 to 40 Hz. A Fourier analysis is conducted on data recorded from the SEC, and the frequency response function of the sensor is evaluated.

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The paper is organized as follows. Section 2 presents the background information for fabrication process and the sensing principle of the SEC. Section 3 discusses the characterization process, and presents and discusses the results. Section 4 concludes the paper.

2. BACKGROUND:

2.1 Fabrication process:

The sensor preparation is done through a solution cast process. The first step is to dissolve the polymer (SEBS) in an organic solvent to create a homogenous polymeric solution. Secondly, the solution is mixed with 15 vol% titania nanoparticles (TiO_2 rutile, Sachtleben R 320 D). Thirdly, a sonic dismembrator (Fisher Scientific D100) is used to disperse the nanoparticles throughout the polymer matrix by producing high concentrated energy through the sonic tip during vibration. Fourthly, the mix is casted onto an 3.15 x 3.15 in^2 glass plate and left to let the solvent evaporate for 2 days. The produced film will constitute the dielectric of the capacitor. The conductive plates are fabricated by mixing the SEBS solution with 10 vol% carbon black nanoparticles (Printex XE 2-B). The nanoparticles are dispersed using a sonic bath (Branson ultrasonic cleaner 1510) for 24 hours. The conductive mix is then sprayed or painted layer-by-layer on the top and bottom of the SEBS-titania film. Finally, copper connections are attached to each side before applying the last layer of the CB solution. Those will serve as the electrical connection to the data acquisition system (DAQ). Figure 1. shows the picture of the produced SEC.

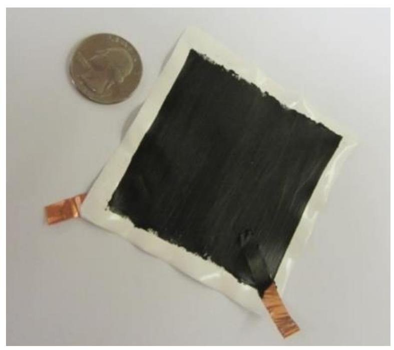


Figure 1. An SEC (3 x 3 in^2)

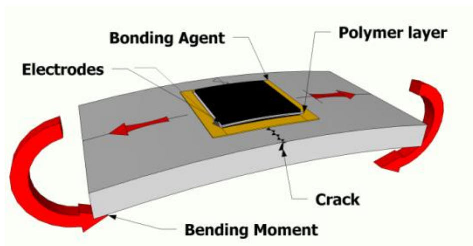
2.2 Electromechanical Model

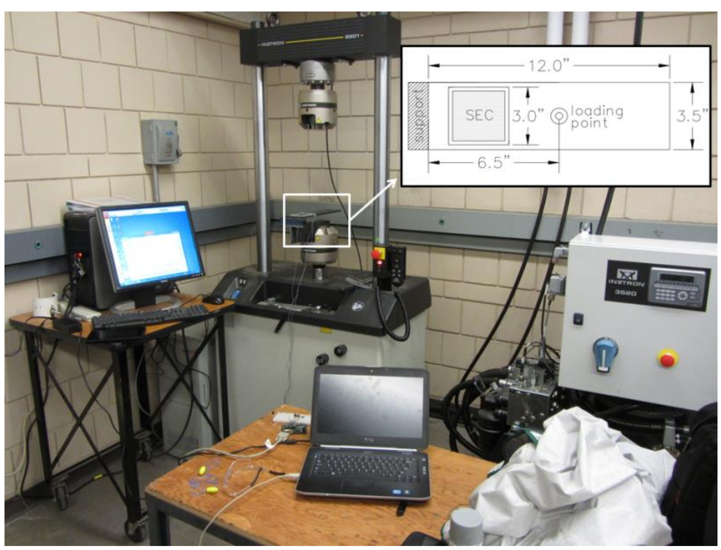
The capacitance C of an SEC can be modeled as a non-lossy parallel plate capacitor,

$$C = \epsilon_0 \epsilon_r \frac{A_0}{h_0} \quad (1)$$

where $\epsilon_0 = 8.854$ pF/m the vacuum permittivity, ϵ_r is the polymer relative permittivity, $A_0 = w_0 \cdot l_0$ is the area of the electrodes of width w_0 and length l_0, h_0 is the thickness of the dielectric, and subscript 0 denotes a nominal quantity. A change in the geometry of the SEC is transduced into a change in capacitance, providing a direct measurement of the monitored strain. The sensing principle is illustrated in Figure 2. The sensor is adhered onto the monitored surface using an epoxy. A strain provoked by a crack or bending can be directly measured as a change in capacitance ΔC. Given the nominal capacitance C from Eqn. (1) and a unidirectional strain along the length ($\Delta w = 0$ due to the epoxy), one can derive the relationship between ΔC and C after taking the derivative of Eqn. (1)[14]:

$$\Delta C = \left(\frac{\Delta l}{l} - \frac{\Delta t}{t}\right) C \quad (2)$$


Bonding Agent
Polymer layer
Electrodes
Crack
Bending Moment


12.0"
support
SEC
3.0"
loading point
3.5"
6.5"
INSTRON

3.1 RESULTS AND DISCUSSION:

Using Euler-Bernoulli beam theory, the analytical strain at the sensor level is given by:

$$\kappa = \frac{1}{\rho} \approx \frac{d^2\delta}{dx^2} \qquad (5)$$
$$\varepsilon_x = -z\kappa$$

where, κ is the curvature of the beam, ρ is the radius of curvature, ε and δ are the strain and the displacement along the x axis of the beam (horizontally in the schematic of Figure 3), respectively. This analytical input strain is compared with the strain calculated from the SEC response using Eqn. 4. Figure 4 shows 3 segments of the input strain signal as well as the sensor response at a) 1Hz; b) 10 Hz; and c) 20 Hz, after a high pass filter was applied to eliminate a linear drift in the signal. The figures show a good match between the two signals (input and SEC) in terms of strain values at 1Hz. However, the discrepancy between both signals tends to increase with increasing frequency due to lower signal-to-noise ratio (SNR) in the SEC signal. This can be attributed to the viscoelastic behavior of the materials[15], and the presence of parasitic noise.

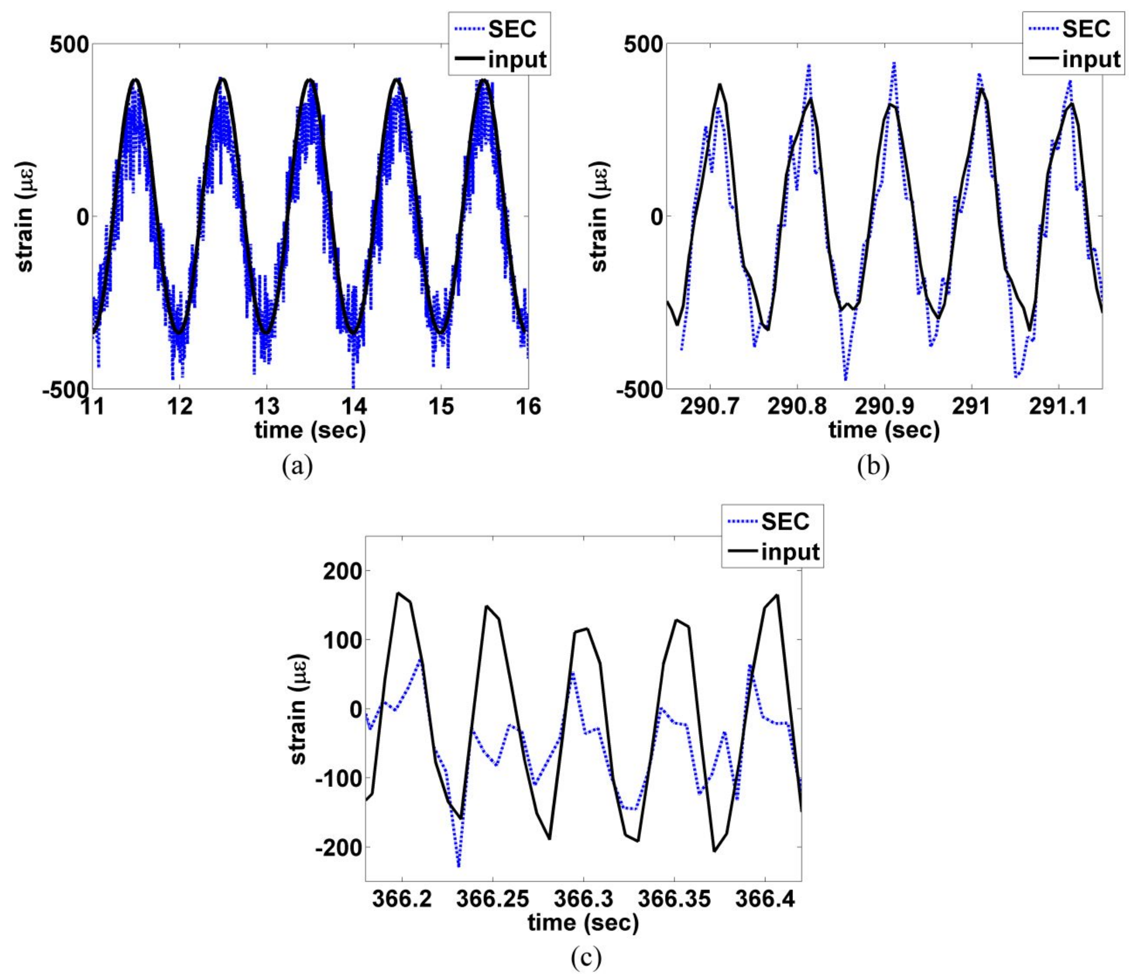


Figure. 4 comparison of strain time history between the input and SEC signals at a)1Hz; b)10 Hz; and c)20 Hz.

Figure 5 shows the wavelet transform of the SEC signal. The SEC can detect the input frequency content over the 1-40 Hz range, but there is an increasing level of noise with increasing frequency, consistent with results discussed above. Figure 6 (a) shows the Fourier transform of both signals, here we can observe the match in the frequency content in the input signal and what is detected by the SEC. Figure 6 (b) investigates the frequency response function (FRF) of the sensor and is evaluated using the Fourier transform of both signals. Results are shown only over the range 1-20 Hz due to high level of noise beyond that point and resulting inaccuracies in the FRF. The resulting FRF shows an approximate unit amplification for up to 15 Hz, after which the FRF decreases. This phenomenon can also be attributed to the viscoelastic behavior of the materials.

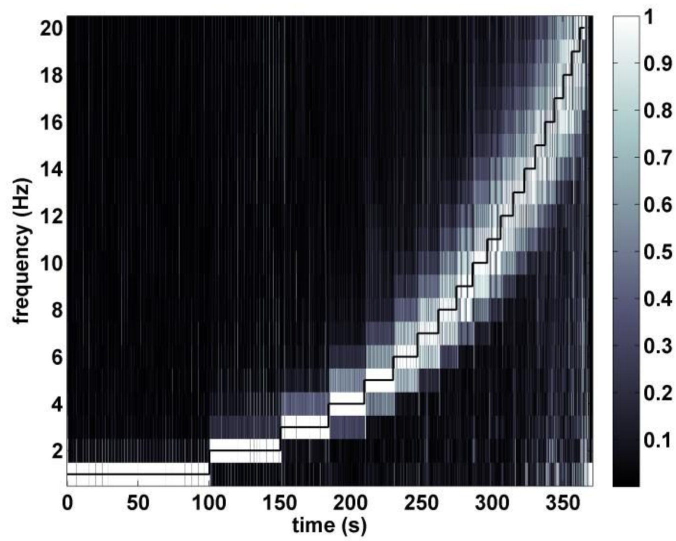


Figure. 5 Wavelet transform of the SEC signal

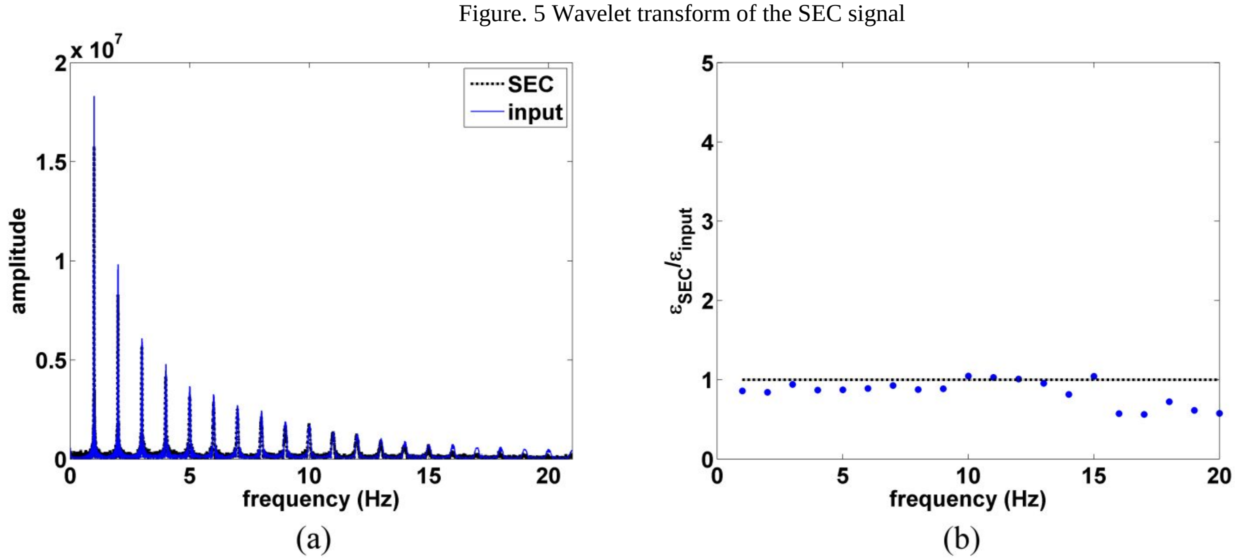


Figure. 6 a) the Fourier transform of the input and the SEC signal, and b) the FRF of the sensor

4. CONCLUSION

The dynamic characteristics of a novel sensor have been studied over the frequency range 1-40 Hz. The capacitive-based sensor is made of inexpensive elastomer and fillers for performance and durability enhancement. To conduct the study, a harmonic load with sweeping frequency of 1-40Hz was applied to a small cantilever beam and the response of an SEC adhered onto the top surface of the beam recorded. Results show the capability of the sensor to detect the frequency content over the 1-40 Hz range, but that the accuracy on the strain readings was maintained only up to 15 Hz. Future work will include reduction of noise in the SEC signal and modeling of the viscoelastic behavior.

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