A robust signal processing method for quantitative high-cycle fatigue crack monitoring using soft elastomeric capacitor sensors

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A robust signal processing method for quantitative high-cycle fatigue crack monitoring using soft elastomeric capacitor sensors

Abstract
A large-area electronics (LAE) strain sensor, termed soft elastomeric capacitor (SEC), has shown great promise in fatigue crack monitoring. The SEC is able to monitor strain changes over a mesoscale structural surface and endure large deformations without being damaged under cracking. Previous tests verified that the SEC is able to detect, localize, and monitor fatigue crack activities under low-cycle fatigue loading. In this paper, to examine the SEC's capability of monitoring high-cycle fatigue cracks, a compact specimen is tested under cyclic tension, designed to ensure realistic crack opening sizes representative of those in real steel bridges. To overcome the difficulty of low signal amplitude and relatively high noise level under high-cycle fatigue loading, a robust signal processing method is proposed to convert the measured capacitance time history from the SEC sensor to power spectral densities (PSD) in the frequency domain, such that signal's peak-to-peak amplitude can be extracted at the dominant loading frequency. A crack damage indicator is proposed as the ratio between the square root of the amplitude of PSD and load range. Results show that the crack damage indicator offers consistent indication of crack growth.

Keywords
Fatigue crack detection; capacitive sensor; structural health monitoring; compact specimen; power spectral density; crack growth

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

Comments

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A robust signal processing method for quantitative high-cycle fatigue crack monitoring using soft elastomeric capacitor sensors

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ABSTRACT

A large-area electronics (LAE) strain sensor, termed soft elastomeric capacitor (SEC), has shown great promise in fatigue crack monitoring. The SEC is capable to monitor strain changes over a large structural surface and undergo large deformations under cracking. Previous tests verified that the SEC can detect and localize fatigue cracks under low-cycle fatigue loading. In this paper, we further investigate the SEC’s capability for monitoring high-cycle fatigue cracks, which are commonly seen in steel bridges. The peak-to-peak amplitude (pk-pk amplitude) of the SEC measurement is proposed as an indicator of crack growth. This technique is robust and insensitive to long-term capacitance drift. To overcome the difficulty of identifying the pk-pk amplitude in time series due to high signal-to-noise ratio, a signal processing method is established. This method converts the measured SEC capacitance and applied load to power spectral densities (PSD) in the frequency domain, such that the pk-pk amplitudes of the measurements can be accurately extracted. Finally, the performance of this method is validated using a fatigue test of a compact steel specimen equipped with a SEC. Results show that the crack growth under high-cycle fatigue loading can be successfully monitored using the proposed signal processing method.

Keywords: Fatigue crack detection; capacitive sensor; structural health monitoring; compact specimen; power spectral density; crack growth.

1. INTRODUCTION

Many existing highway bridges carry significant magnitude of loads over their long service periods, making them potentially prone to structural damages. Specifically, fatigue cracks occurring in steel bridges are critical structural concerns. These cracks are usually small in size at their initiations, leading to a challenging identification task. However, depending on the structural boundary conditions and bridge layouts, they may grow rapidly and cause catastrophic structural failures\textsuperscript{[1]}.

Fatigue cracks monitoring is critical for steel bridge such that warning messages can be sent before cracks reach critical sizes. To date, the most common crack detection approach is visual inspection\textsuperscript{[2]}. However, this approach is labor intensive, high cost, and prone to error. Nondestructive evaluation (NDE) techniques such as dye penetration, eddy current\textsuperscript{[3]}, magnetic particles\textsuperscript{[4]}, and ultrasonic testing\textsuperscript{[5]} can improve the accuracy of crack detection. Nevertheless, human operations are needed as opposed to automatic and continuous fatigue crack monitoring. Other advanced technologies like acoustic emission\textsuperscript{[6]} and piezoelectric sensor\textsuperscript{[7]} also show potentials for crack detection; but as tradeoffs, they require complex test setup and the accuracy of the detection result may depend on the noise level. Computer vision based crack detection algorithms have also been applied to detect certain types of cracks\textsuperscript{[8]}. 

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Recently, novel sensing technologies have received great attentions for structural health monitoring over mesoscale civil structures [9, 10]. Among them, large-size strain sensors show promises to monitor strain over large structural areas. Examples include nanotube-based sensors [11], resistive sensor sheets [12], patch antenna sensors [13], and soft elastomeric capacitor (SEC) sensors [14]. In particular, the SEC is a highly stretchable sensor, and is able to monitor a large strain change up to 20% [14]. In addition, it can be fabricated into large sizes (e.g. 3 in. by 3 in.). Past studies verified that the SECs can monitor strains of civil structures [15] and be used to reconstruct strain maps under in-plane stress conditions [16].

The above features of the SEC make it suitable for monitoring crack activities. The concept is to deploy the SEC over fatigue-susceptible regions on structural surfaces, so that it can sense the abrupt strain change caused by cracking beneath the sensing skin. Preliminary experimental results verified that the SEC can localize and detect low-cycle fatigue cracks [17]. Later, under similar test configurations and loading protocols, quantitative relations between the crack geometries and the sensor’s measurements were investigated [18, 19]. Furthermore, a numerical approach was investigated through finite element analysis, aiming to numerically predict the SEC’s response under crack growth [20, 21].

In this paper, we further the investigation of the SEC for monitoring high-cycle fatigue cracks. Compared to low-cycles fatigue, one important feature of high-cycle fatigue is that the crack growth is provoked by fatigue loading with much lower load ranges, which leads to smaller crack openings hence smaller sensor response, making it possibly challenging to monitor these cracks using the SEC. In addition, a long-term monitoring strategy must be considered for ensuring the functionality of the SEC over the long fatigue life of structures.

To address the challenges, we propose to use the peak-to-peak amplitude (pk-pk amplitude) of the sensor’s measurement as an indicator of crack growth. Frequency analysis is applied to robustly identify the pk-pk amplitude in the time series measurement with significant noise. The proposed method is validated experimentally through fatigue testing of a compact, C(T), specimen equipped a SEC. Results demonstrate that the proposed signal processing method can accurately and robustly identify the fatigue crack growth.

### 2. SOFT ELECTROMETRIC CAPACITOR

As shown in Fig. 1, the SEC is a large-area capacitor with a sandwiched structure. Its middle layer is a nonconductive plate made by styrene-ethylene/butylene-styrene (SEBS) block co-polymer filled with titania, while the top and bottom layers are two conductive plates consisting of SEBS filled with carbon black. Two copper tapes are deployed on top and bottom plates to connect the sensor to the data acquisition (DAQ) system. Details on the fabrication process of the SEC can be found in [13].

Fig. 1b shows the dimensions of the SEC, where \( w \) and \( l \) are the width and length of its effective sensing area, respectively, and \( h \) is the thickness of the sensor. The SEC can be deployed on structure surface using bi-component epoxy. The strain change beneath the SEC provokes geometrical change of the sensing area \( A \) and thickness \( h \), causing change of the capacitance \( C \) of the sensor, as shown in the following equation:

\[
C = \frac{e_0 e_r A}{h}
\]

where \( e_0 \) is the permittivity of air, \( e_r \) is the permittivity of the dielectric, and \( A = w l \) is the sensing area. The dimension of the SEC in this study is 3 in by 3 in, with an effective sensing area of 2.5 in by 2.5 in (Fig. 1c).
3. SIGNAL PROCESSING METHOD

The principle of the SEC for strain sensing can be further extended for crack monitoring, which is illustrated in Fig. 2. The SEC is deployed on a steel plate subjected to a fatigue load \( F \). For demonstration purpose, the load range of \( F \) is assumed to be constant during the crack growth. Under the fatigue load \( F \), a crack is generated from the right end of the specimen and propagates to the left. When the crack tip is outside the sensing area (Fig. 2a), the SEC can be treated as a large area strain gauge, producing a change in capacitance \( C \) caused by change in geometry (i.e., strain). Fig. 2b shows a later stage of the crack growth when the crack propagates into the sensing area. Larger mean capacitance and pk-pk amplitude can be observed. When the crack grows further (Fig. 2c), both mean capacitance and pk-pk amplitude are further increased. This is due to the fact that the stiffness of the steel plate is weakened by the crack growth, so that the crack opens more under the same range of load \( F \), provoking larger deformations of the sensing skin.

Previously, the mean capacitance of the SEC (as illustrated in Fig. 2) has been proposed for monitoring the crack growth under low-cycle fatigue loading. However, monitoring the mean capacitance is insufficient for identifying the crack growth under high-cycle fatigue loading because the SEC is subject to capacitance drift \([22]\) during long-term monitoring. The capacitance drift may be attributed to temperature and humidity change, or an intrinsic electrical behavior, which can be found in many smart materials \([23, 24]\).

In this paper, we propose to use the pk-pk amplitude (as illustrated in Fig. 2) of the SEC’s capacitance measurement to monitor high-cycle fatigue crack growth. The pk-pk amplitude is insensitive to the capacitance drift hence more...
robust for long-term crack monitoring. Nevertheless, the pk-pk amplitude is difficult to be accurately identified in time series, due to high signal-to-noise ratio under lower load ranges associated with high-cycle fatigue loading. To robustly capture the pk-pk amplitude, a signal processing method based on frequency analysis is proposed and is illustrated in Fig. 3. The method contains three steps: data collection, frequency analysis, and computation of the crack growth index (CGI).

In the first step, both capacitance $C^{(i)}$ of the SEC and force $F^{(i)}$ of the applied fatigue load are collected when the crack propagates to different lengths $l^{(i)}$. The pk-pk amplitude of the SEC is provoked by the crack opening, which is further governed by the applied load. Therefore, in order to monitor the crack growth, the capacitance measurements $C^{(i)}$ need to be normalized by the applied fatigue load $F^{(i)}$. The applied force can either be directly measured through the actuator in laboratory setting or indirectly via appropriate strain measurements in field test.

The next step is to calculate the power spectral densities (PSDs) of the capacitance $C^{(i)}$ and force $F^{(i)}$ measurements. Peaks of the PSD curves ($\text{peak}_{C}^{(i)}$ and $\text{peak}_{F}^{(i)}$) indicate the magnitudes of the pk-pk amplitude in time series measurements of the capacitance $C^{(i)}$ and force $F^{(i)}$. Averaging can be applied to reduce the noise effects. Compared with directly obtaining the pk-pk amplitude in the time series, the proposed method produces more robust results with high noise content present in the measurements. Once $\text{peak}_{C}^{(i)}$ and $\text{peak}_{F}^{(i)}$ are obtained, $\text{CGI}^{(i)}$ is computed as the square root of the ratio of $\text{peak}_{C}^{(i)}$ to $\text{peak}_{F}^{(i)}$. The $\text{CGI}^{(i)}$ is essentially a normalized strain indicator. Finally, the crack growth can be consistently monitored by the increasing CGIs.

Figure 3. Proposed signal processing method where the SEC is shown as transparent for the demonstration purpose

4. EXPERIMENTAL VALIDATION

4.1 Test configuration

Fig. 4 shows the test configuration. A C(T) specimen was used in the fatigue testing. The specimen was made of A36 steel with a thickness of 0.25 in. The dimensions of the C(T) specimen is shown in Fig. 4e. A notch was prefabricated on the C(T) specimen for generating the fatigue crack. The specimen was mounted on the Instron load frame (model 1334) through two clevises. Two adhesive measuring tapes were attached on the front side of the specimen to measure the crack length during the test, while an SEC was installed on the backside using epoxy (JB-weld) as shown in Fig. 4d. To monitor the opening of the crack, a clip-on displacement gage (Epsilon model 3541)
was installed at the front face of the specimen. An off-the-shelf DAQ system (ACAM PCAP02) was adopted for measuring the capacitance of the SEC (Fig. 4c).

During the test, a 10-Hz sinusoidal load was applied to generate and propagate the fatigue crack. Each time the crack propagated 1/16 in, the load rate was reduced to 0.5 Hz for data collection. Collected data included the applied fatigue load, clip-on gage reading, and capacitance of the SEC at a sampling rate of 50 Hz. Approximately 100 load cycles were taken during each data collection. After data collection, the load rate was resumed to 10 Hz for continuing the crack propagation.

![Test setup; (b) front view of the specimen; (c) DAQ system; (d) back view of the specimen; and (e) dimensions of the specimen](image)

Figure 4. (a) Test setup; (b) front view of the specimen; (c) DAQ system; (d) back view of the specimen; and (e) dimensions of the specimen

![Loading protocol](image)

Figure 5. Loading protocol

![Illustration of the effective sensing area](image)

Figure 6. Illustration of the effective sensing area

To ensure realistic high-cycle fatigue crack was generated in the test, a loading protocol is designed to achieve a constant range of stress intensity factor $\Delta K$ throughout the crack propagation. The designed loading protocol would produce much smaller load ranges, limiting the plastic deformation at the crack tip and producing a realistic fatigue crack on would see in bridges. Fig. 5 illustrates the newly-designed loading protocol. The range of stress intensity factor $\Delta K$ is limited within 20 to 25 ksi in $^3$. The corresponding upper limit $F_{\text{max}}$ and lower limit $F_{\text{min}}$ of the fatigue load can be computed based on ASTM E1820-15 $^{[25]}$. The stress intensity ratio $R = F_{\text{min}}/F_{\text{max}}$ is set as 0.1, which is also required in this loading protocol design. A detailed design procedure of the loading protocol can be found in reference $^{[26]}$. The crack length on the horizontal axis of Fig. 5 is measured from the notch of the C(T) specimen as shown in Fig. 6. Therefore, the crack would first reach the sensing area when it grows to 5/16 in.
Fig. 7 shows a picture of the fatigue crack during the test. The plastic deformation at the crack tip is limited by the new-designed loading protocol. At the end of the test, a total of 1,810,000 load cycles were applied to the C(T) specimen and the test was terminated when the crack reached 29/16 in.

Figure 7. (a) A picture of the fatigue crack during the test; and (b) the detail of the crack

Fig. 8 shows the full record of the capacitance measurement $C^{(i)}$ of the SEC throughout the fatigue test as well as detailed plots of typical measurements in a shorter time duration of 10 sec. The crack length corresponding to each measurement $C^{(i)}$ is labeled on each figure. As illustrated in Fig. 8, the overall mean capacitance of the SEC is subject to drift in this long-term measurement, as the entire fatigue test lasted for about one month. Additionally, high signal-to-noise ratio can be found due to the low fatigue load range. Accurately identifying the pk-pk amplitude of the time series can be challenging. In the next subsection, the capacitance $C^{(i)}$ and applied force $F^{(i)}$ are processed using the proposed signal processing method to be able to identify the crack growth.

Figure 8. Top: a full record of capacitance measurement $C^{(i)}$ in the test, where individual measurement $C^{(i)}$ at different crack lengths are stitched together. Crack lengths are labeled in boxes. Bottom: detailed plots of typical capacitance measurement $C^{(i)}$ when the crack length is 0 in., 15/16 in., and 29/16 in.

4.2 Validation of CGI

To validate the performance of the proposed signal processing method, both capacitance $C^{(i)}$ and applied force $F^{(i)}$ are processed using the procedure described in section 3. First, $C^{(i)}$ and $F^{(i)}$ are detrended to have a zero mean with only the pk-pk amplitude information retained in the signals. Then, PSD of $C^{(i)}$ and $F^{(i)}$ are computed when the crack reaches different lengths. A NFFT (number of fast Fourier Transform points) of 1024 are used in the PSD computation. The PSD results for both SEC measurement and the applied load are shown in Fig. 9 and Fig. 10, respectively. The crack lengths on these figures are measured from the notch as illustrated in Fig. 6. Because the test adopts a periodic sinewave as the fatigue load, dominant peaks on the PSD curves ($\text{peak}^{(i)}_{C}$ and $\text{peak}^{(i)}_{F}$) can be found at the 0.5 Hz loading rate. These peaks provide more robust indication of the magnitudes of pk-pk amplitude.
in the time series measurements. The relations between the crack length and peak\(_c^{0}\) and peak\(_F^{0}\) are shown in Fig. 9s and Fig. 10s, respectively. A decreasing trend of peak\(_F^{0}\) reflects the fact that the applied fatigue load was reduced as the crack propagated further, while an increasing trend of peak\(_c^{0}\) indicates a larger pk-pk response of the SEC under a longer crack.

![Figure 9. (a) to (r): PSDs of SEC measurements when the crack propagates from 0 in. to 29/16 in. (s): PSD peaks of SEC measurements vs. crack length](image)

To monitor crack growth using the SEC, the capacitance measurement should be normalized by the applied force. The CGI is proposed as a normalized strain indicator of the SEC as shown in Fig. 3. Fig. 11 presents the CGIs at different crack lengths. A positive correlation between log(CGI) and crack length can be observed. The result verifies 1) the crack growth can be successfully monitored by the CGI which increases as the crack propagates, and 2) the proposed signal processing method is able to provide robust result for quantitative monitoring high-cycle fatigue cracks based on the SEC sensor.
Figure 10. (a) to (r): PSDs of the applied load when the crack propagates from 0 in. to 29/16 in. (s): PSD peaks of applied load vs. crack length

Figure 11. Established CGI vs. crack length
In this paper, we presented a novel strain sensing technology for monitoring high-cycle fatigue cracks in steel bridges. The SEC is adopted for its large sensing area, flexibility, and mechanical robustness. In particular, the pk-pk amplitude of the SEC’s capacitance response is proposed as a robust indicator of fatigue crack growth. To accurately identify the pk-pk amplitude, a signal processing method is established based on frequency analysis. The performance of the proposed method is then experimentally evaluated by fatigue testing a C(T) specimen equipped with a SEC. Results indicate that a positive correlation can be found between \( \log(CG) \) and crack growth. The proposed signal processing method greatly enhanced the SEC’s capability for monitoring high-cycle fatigue cracks. The findings of this investigation offer great potential for further applications of the SEC in steel bridge applications.

The proposed strategy was evaluated in a laboratory setting in the present study. The fatigue load was assumed to be a periodic sinusoidal wave with a single dominant frequency, which is adopted many other fatigue tests \cite{27, 28}. However, fatigue cracks in steel bridges are generated by traffic loads, which contain more complex features than the load applied in this study. In particular, traffic load cycles could contain different features in terms of amplitude and frequency, depending on the weight and speed of passing vehicles. Our future work will focus on updating the current signal processing method for steel bridge applications under complex traffic loads.

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