TRANSPORTATION POOLED FUND PROGRAM
QUARTERLY PROGRESS REPORT

Lead Agency (FHWA or State DOT): ____Kansas DOT______________________________

INSTRUCTIONS:
Project Managers and/or research project investigators should complete a quarterly progress report for each calendar quarter during which the projects are active. Please provide a project schedule status of the research activities tied to each task that is defined in the proposal; a percentage completion of each task; a concise discussion (2 or 3 sentences) of the current status, including accomplishments and problems encountered, if any. List all tasks, even if no work was done during this period.

Transportation Pooled Fund Program Project # **TPF-5(328)**	**Transportation Pooled Fund Program - Report Period:** ☒Quarter 1 (January 1 – March 31) ☐Quarter 2 (April 1 – June 30) ☐Quarter 3 (July 1 – September 30) ☐Quarter 4 (October 1 – December 31)
Project Title: Strain-based Fatigue Crack Monitoring of Steel Bridges using Wireless Elastomeric Skin Sensors	
Project Manager: **Susan Barker, P.E.** **Phone:** **(785) 291-3847** **E-mail: SusanB@ksdot.org**	
Project Investigator: **Li Jian** **Phone:** **785-864-6850** **E-mail: jianli@ku.edu**	

Lead Agency Project ID: **RE-0699-01**	**Other Project ID (i.e., contract #):**	**Project Start Date:** **9/2015**
Original Project End Date: **Multi-year project**	**Current Project End Date:** **8/31/2018**	**Number of Extensions:** **N.A.**

Project schedule status:

☒ On schedule ☐ On revised schedule ☐ Ahead of schedule ☐ Behind schedule

Overall Project Statistics:

Total Project Budget	Total Cost to Date for Project	Total Percentage of Work Completed
$405,000	**$ 15699.31**	**15%**

Quarterly Project Statistics:

Total Project Expenses This Quarter	Total Amount of Funds Expended This Quarter	Percentage of Work Completed This Quarter
$ 6811.64	**$ 6811.64**	**10%**

Project Description:
The main objective of this proposed research is to *provide state DOTs a practical and cost-effective long-term fatigue crack monitoring methodology using **a wireless elastomeric skin sensor network***. This research is intended to demonstrate the value-added of fatigue crack monitoring of steel bridges using wireless skin sensors over the traditional bridge inspection.

Progress this Quarter (includes meetings, work plan status, contract status, significant progress, etc.):

1. ISU progress:

Task 1 (ISU): Crack sensor fabrication.

Under this task, fatigue crack sensors are to be produced with an approximate thickness of 100-200 μm to enhance the mechanical robustness under harsh environment. Acceptable ranges of capacitance are 800-1000 pF. The anticipated number of sensors is 150 to 200 for the duration of the project.

The sensor's production schedule was set to 15 sensors per month starting November 2015. The objective of 75 sensors by March 31st was changed to 60 given the lag in testing. Fabricated sensors are listed in Table 1. Note: the data sheet for sensors 31-45 was accidentally discarded by a student.

Table 1 – produced sensors

Sensor	Date cast:	Capacitance (pF)	Dielectric Thickness (mm)	std dev	Resistance (kOhm)
31-45		Info not available			
46	3/10/2016	836	0.201	0.0110	15.4
47	3/10/2016	837	0.193	0.0118	15.8
48	3/12/2016	850	0.183	0.0058	16.0
49	3/12/2016	850	0.183	0.0108	15.7
50	3/12/2016	872	0.185	0.0081	16.0
51	3/12/2016	800	0.191	0.0110	16.6
52	3/12/2016	901	0.178	0.0137	14.9
53	3/12/2016	870	0.183	0.0112	16.2
54	3/12/2016	892	0.187	0.0162	15.1
55	3/12/2016	803	0.212	0.0079	16.2
56	3/12/2016	896	0.188	0.0075	14.9
57	3/12/2016	873	0.197	0.0082	14.5
58	3/12/2016	851	0.206	0.0070	15.7
59	3/12/2016	865	0.200	0.0105	15.3
60	3/12/2016	822	0.153	0.0149	16.4

2. KU progress:

In this quarter, the KU team conducted two experimental tests on compact tension specimens. The first test is to evaluate the SEC sensor's performance in detecting fatigue crack generated under a constant load range. Similar tests were performed prior to this project; however, the previous tests did not capture the quantitative relation between the measured sensor response and crack growth due to the limitations of the measurement method. In this new test, a high-resolution crack opening displacement (COD) gage is used to measure continuously the crack propagation during the test. The test shows that the SEC is able to detect crack growth by showing a steady increase of ΔC when crack length is larger than 0.5 in. Meanwhile, the COD gage provided accurate measurement of crack length during the whole test period.

The second test is to evaluate the SEC sensor's capability of detecting realistic fatigue cracks generated under cyclic loadings with decreasing load ranges, such that the stress intensity factor is kept within a realistic range to reflect real condition of fatigue cracks in bridges. Crack propagation is quantified by the magnitude of the power spectral density (PSD) of the measured capacitance change at the dominant loading frequency. The ratio between the PSD amplitude and load range gives a clear indication of crack propagation under the realistic fatigue loading.

3. UA progress:

The UA team continued to focus on the design and realization of the DAQ system, i.e., the capacitive strain sensor board (C-strain board). In this quarter, the C-strain board was modified with optimized AC bridge configuration for capacitance measurement. In addition, the excitation voltage of the bridge circuit was changed from square wave to sine wave to further reduce noise. The linearity of the DAQ circuit was tested using static testing with fixed-value capacitors. Dynamic tests were also performed. Results showed good linearity and the sensitivity was around 310mV/pF. Furthermore, noise test showed the noise level of the sensor board was around 3.9 mV with the SEC sensor, and 1.6mV without the SEC sensor.

Anticipated work next quarter:

ISU: The objective of the next quarter is to produce 45 additional sensors, for a total of 105 sensors. The production of sensors will continue until KU provides results from further testing, which could lead to additional optimization (Task 2). Technical support (Task 3) is being provided to KU on a continuous basis, as well as discussion and feedback (Task 4).

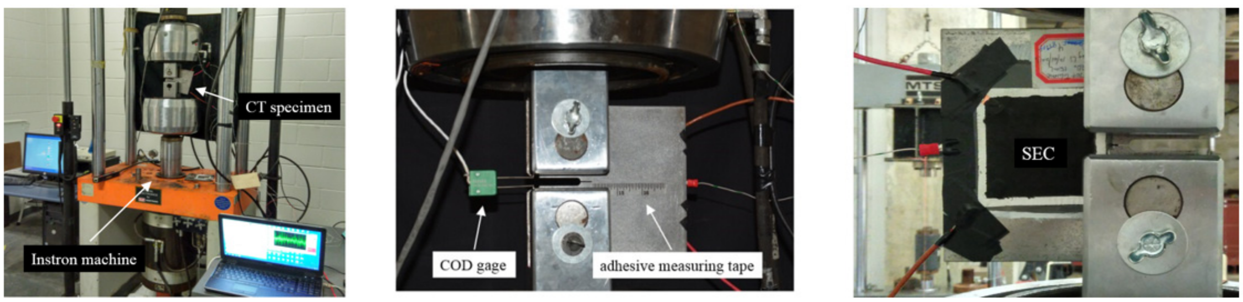
KU: The KU team will work with UA team to perform a series of calibration tests for the developed C-strain sensor board. In addition, further tests will be done with an array of sensors to detect realistic fatigue cracks.

UA: The UA team will implement onboard calibration capability for the sensor board. UA team will visit KU in next quarter to perform these calibration tests to finalize the sensor board design.

Significant Results:

Part one: Fatigue crack detection with the SEC sensor.

1. Test 1 with constant load range
   Fig. 1 shows the test setup. A new element to this test is the COD gage for measuring the crack length continuously during the test.



(a) (b) (c)

Fig. 1. Test setup

Fig. 2 shows the comparison between the crack length calculated from the COD gage measurement according to ASTM E1820 and that from human reading with the adhesive tape measure. Excellent agreement is achieved between the two. This test successfully verified the accuracy of the method based on COD gage, so future tests will continue to use the COD gage for providing crack length measurement.

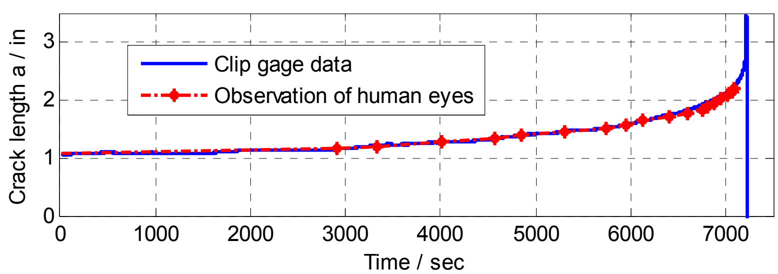


Fig. 2. Crack length vs. time

Fig.3 shows the test result of the CT specimen under a constant load range. The magnitude of the range of the capacitance measurement, ΔC, is chosen as the indicator of crack propagation. It can be seen from the figure that the sensor is able to detect crack growth by showing a steady increase of ΔC when crack length reaches more than 0.5 in.

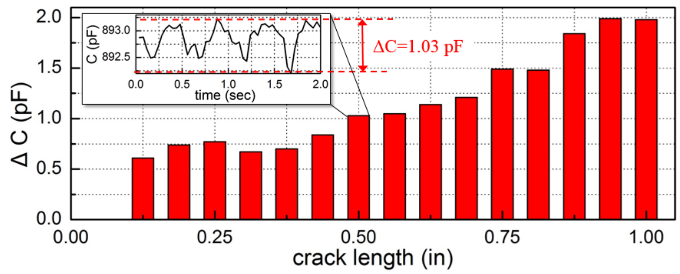


Fig. 3. Sensor's amplitude change vs. crack length

2. Test 2 with varying load range for realistic fatigue crack
   In order to assess the SEC sensor's performance under more realistic fatigue cracks, the loading protocol was changed to have multiple load ranges which decrease when the crack propagates. The load ranges were designed so that the stress intensity factor can be kept within a relatively constant range to simulate a realistic fatigue crack one would see in real bridges. The applied load ranges are shown in Fig. 4.

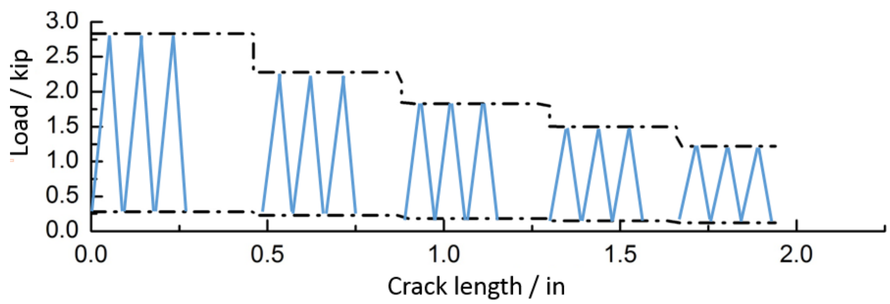


Fig. 4. Loading protocol in test 2

A crack damage indicator is proposed based on the amplitude of the power spectral density (PSD) of the measured capacitance change at the loading frequency, which is 0.5 Hz in the test. Compared with amplitude in time domain, assessment based on amplitude in frequency domain avoids filtering of the signal and provides consistent information for all measurements. Fig.5 shows the PSD curves of the SEC measurements at different crack lengths. Peaks at 0.5 Hz can be clearly identified in these curves. Figs. 6 – 8 show the PSD peaks around 0.5 Hz, with each figure associated with one load range. As can be seen in the figures, as the crack propagates the PSD amplitude at the dominant frequency consistently increases. When load range drops, the peak may drop but increases again with further crack growth. Finally, when the PSD peaks are normalized against the load range, as shown in Fig. 9, the normalized PSD peaks can provide consistent indication of crack growth throughout the entire fatigue life of the specimen.

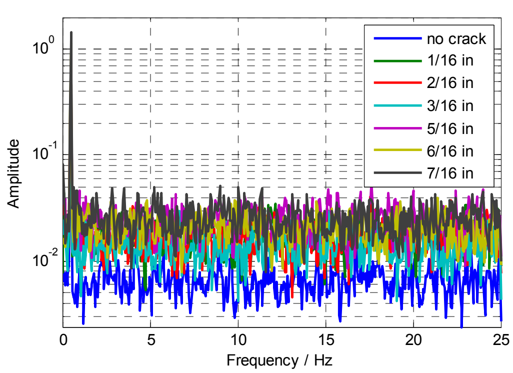


Fig. 5. PSD of the signal during the crack growth

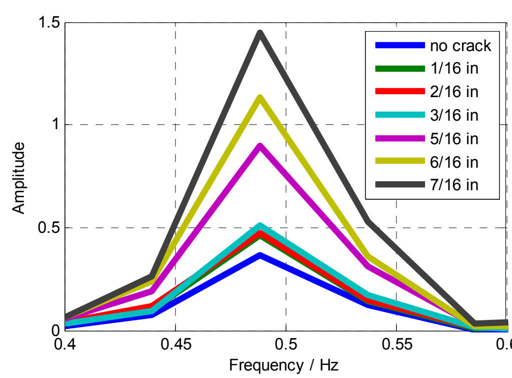


Fig. 6. PSD peaks (crack length from 0 to 1/16 in)

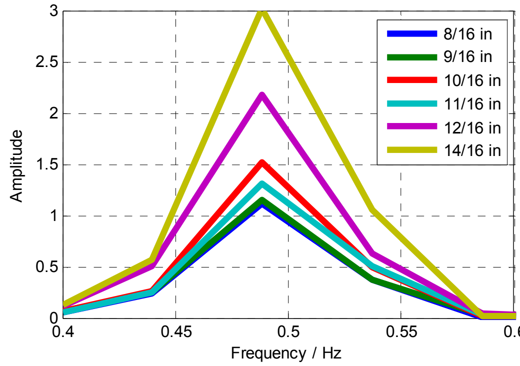


Fig. 7. PSD peaks (crack length from 8/16 to 14/16 in)

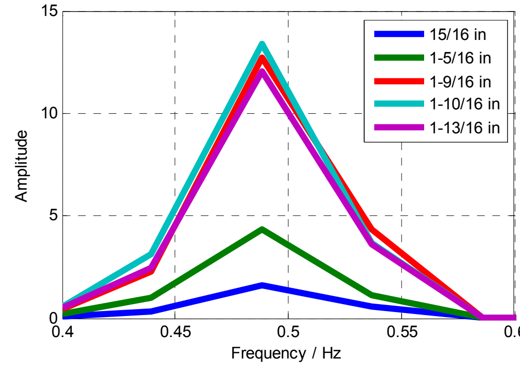


Fig. 8. PSDpeaks (crack length from 15/16 to 1-13/16 in)

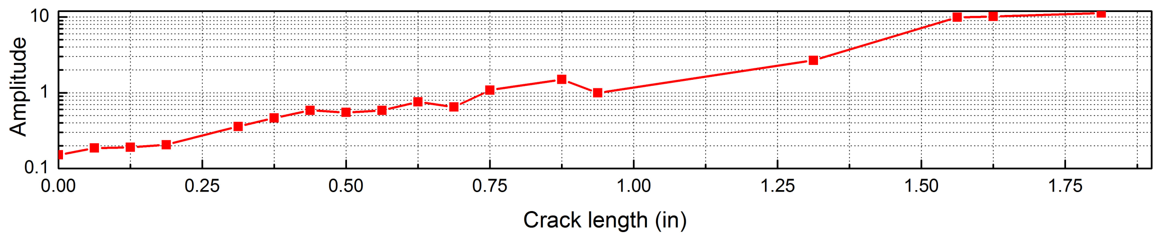


Fig. 9. Normalized PSD peaks of the capacitance measurement during the fatigue life

Part two: Data acquisition sensor board development for the SEC sensor.

1. Modification of the C-strain board.
   The updated schematic of the C-strain board is shown in Fig. 10. In this schematic, two types of AC bridge circuits with two capacitors were integrated into one sensor board. Meanwhile, a low-pass filter was employed to convert the square wave to sine wave as the external excitation to the AC bridge. Fig. 11 shows the realized prototype of the modified C-strain board.

2. Linearity of the C-strain board.
   Among several configurations of AC bridges, the one with two capacitors and two resistors showed the best performance for capacitance measurement. Static tests with several fixed-value capacitors as nominal capacitance change showed good linearity of this C-strain sensor board, as shown in Fig. 12. The sensitivity of the board was 310mV/pF.

3. Dynamic test with the SEC sensor.
   Dynamic tests have been carried out using an electrodynamic shaker at University of Arizona. The SEC sensor was attached to a metal plate mounted on the shaker. The shaker excited the plate and the dynamic strain changes were measured using the SEC sensor. Test results showed the C-strain sensor board clearly detected dynamic capacitance change with the SEC sensor. The test setup is shown in Fig. 13. One metal foil strain gauge was attached to the back side of the plate to measure the reference signal. Fig. 14 and Fig.15 show the measured strain change using the metal foil gage and the measured capacitance change using the SEC sensor, respectively.

4. Noise tests for the C-strain sensor board
   Two noise tests have been done to assess the noise levels of the C-strain board with and without the SEC sensor connected. Fig. 16 shows the noise level and its power spectral density (PSD) with a fixed-value capacitor. The RMS noise is about 1.6 mV. Fig.17 shows the noise level and its PSD with the SEC sensor attached. The RMS noise is about 3.9 mV.

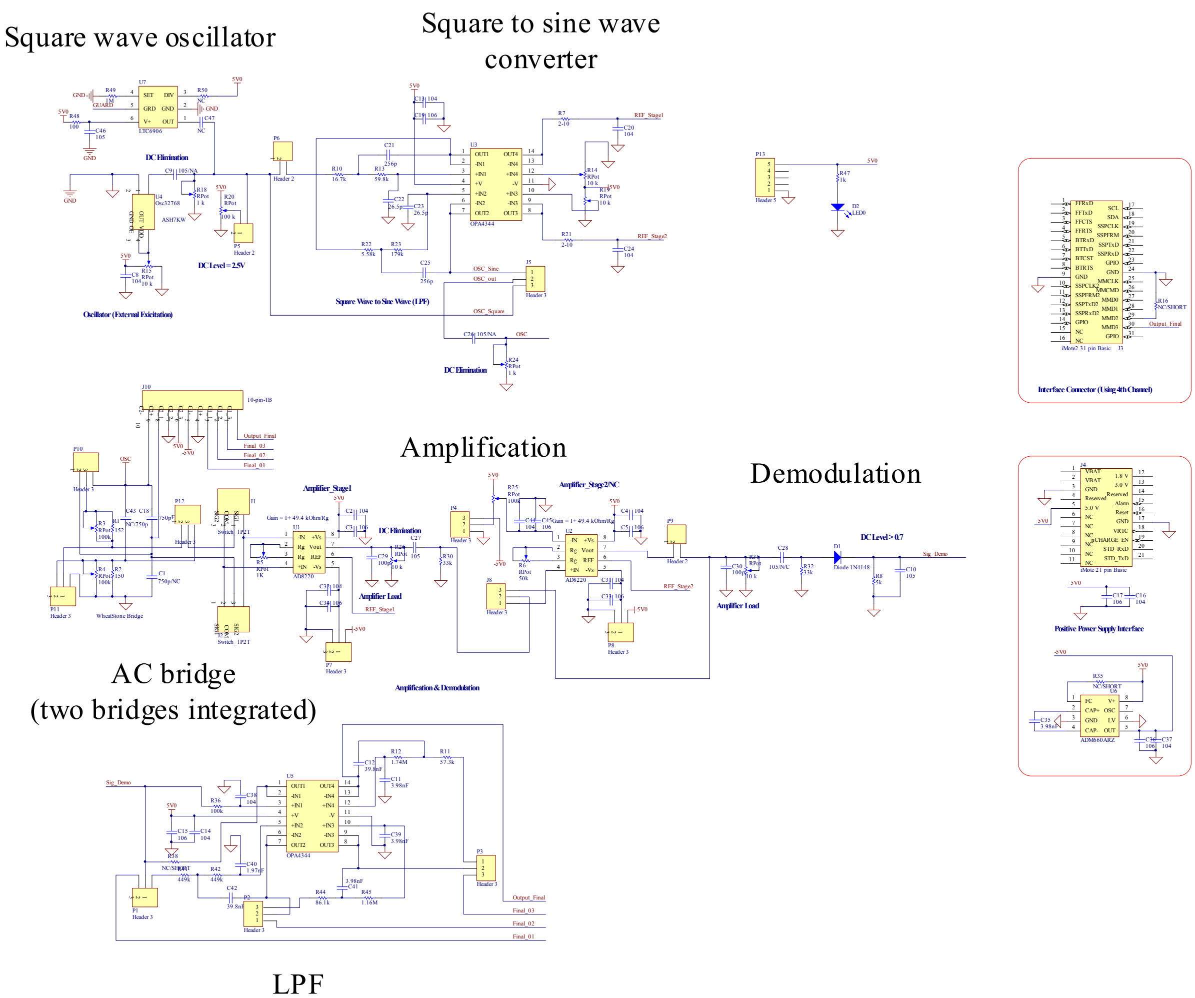


Fig. 10. The updated schematic of the C-strain board.

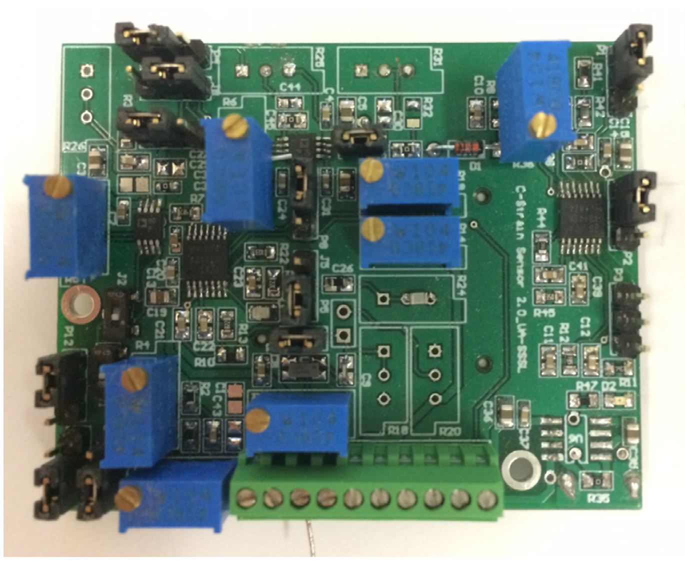


Fig. 11. The real product of the C-strain board.

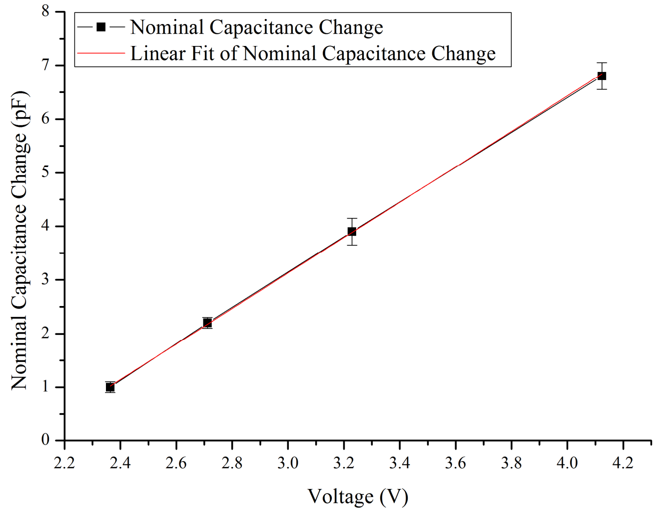


Fig. 12. Static test results with linear fit.

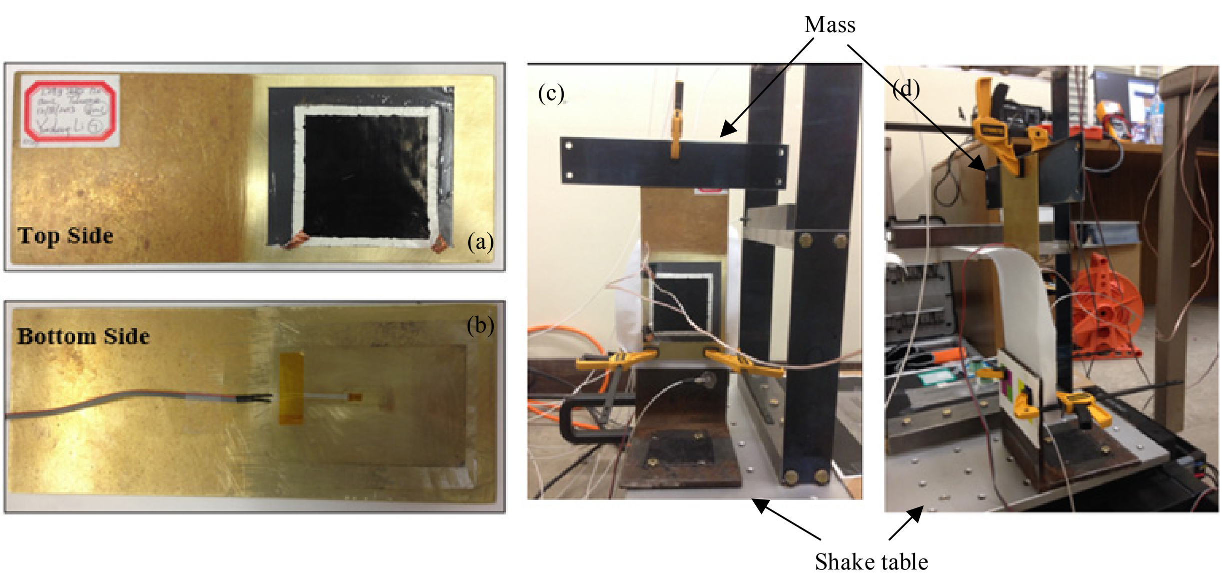


Fig. 13. Test specimen and experimental setup.

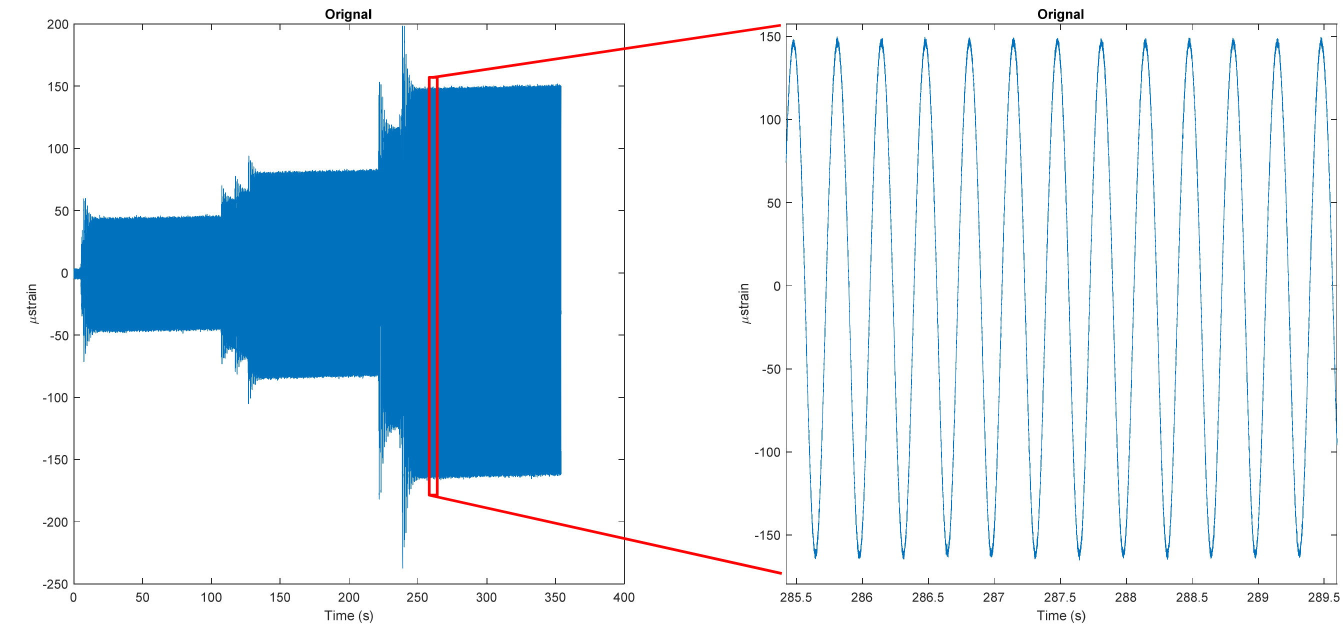


Fig. 14. Measured strain from the foil strain gauge on the specimen.

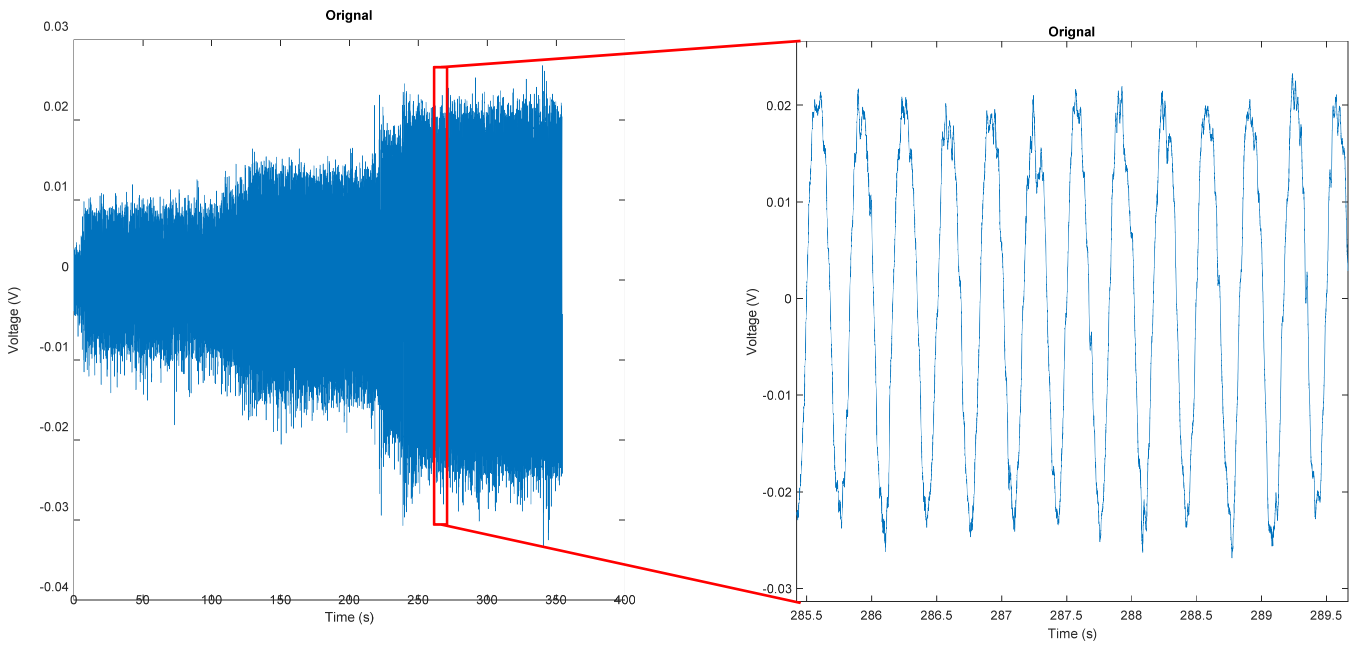


Fig. 15. Measured capacitance from the SEC sensor on the specimen.

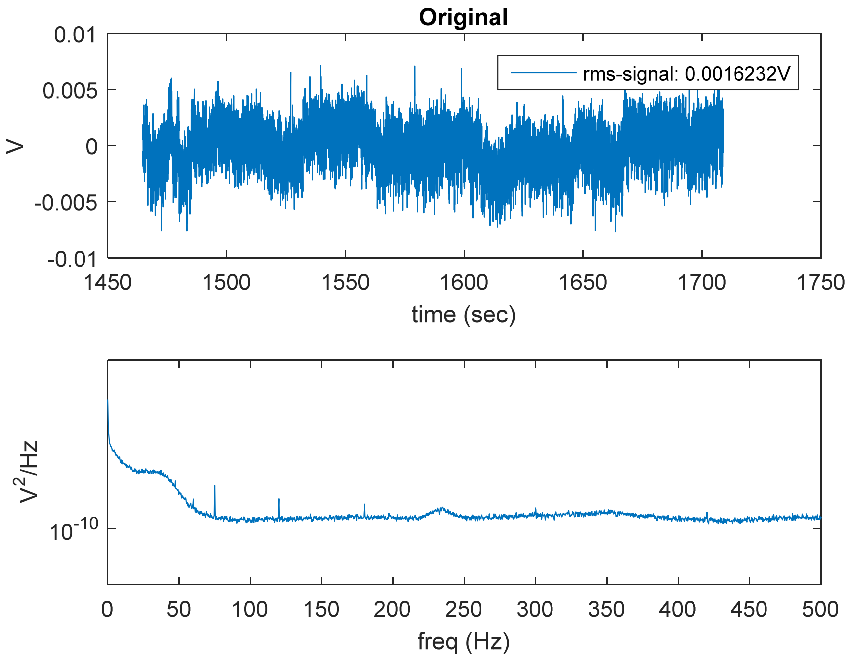


Fig.16. Noise test result and its PSD with a fixed value capacitor.

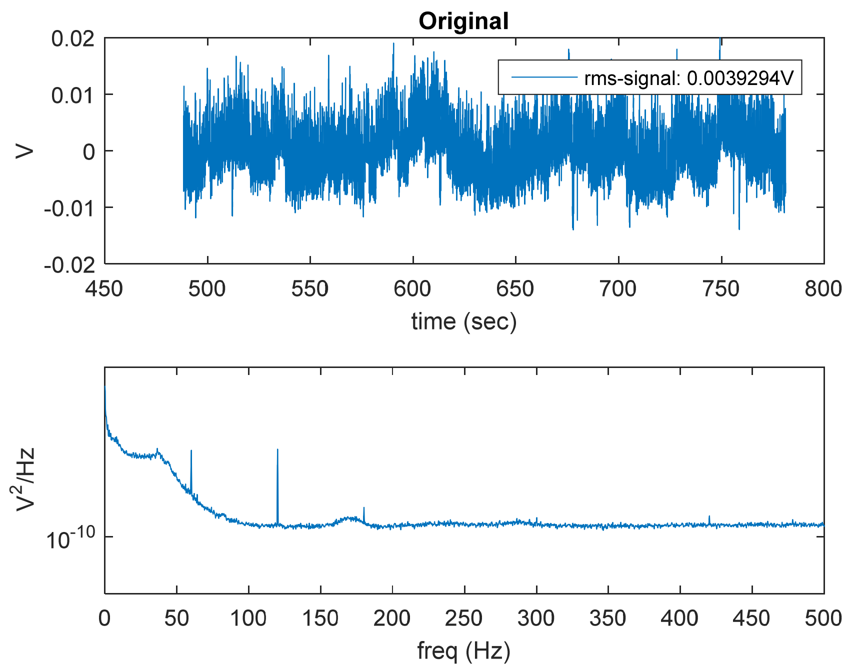


Fig. 17. Noise test result and its PSD with an SEC sensor.

Circumstance affecting project or budget. (Please describe any challenges encountered or anticipated that might the completion of the project within the time, scope and fiscal constraints set forth in the agreement, along with recommended solutions to those problems).

None.