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

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Lead Agency Project ID:	**Other Project ID (i.e., contract #):**	**Project Start Date:**
RE-0699-01		**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
$405,000	**$ 276,370**	**72 %**

Quarterly Project Statistics:

Total Project Expenses This Quarter	Total Amount of Funds Expended This Quarter	Percentage of Work Completed This Quarter
$ 34,338	**$ 34,338**	**6 %**

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.):

ISU Progress: 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 range of capacitance is 800-1000 pF. The anticipated number of sensors is 150 to 200 for the duration of the project.
During this quarter, 45 sensors of dimensions 1'' x 1'' have been fabricated. Technical support (Task 3) is being provided to KU on a continuous basis, as well as discussion and feedback (Task 4).

KU Progress: The work done by the KU team has three components: 1) validating the SEC arrays on a new large-scale bridge girder to cross frame connection model; 2) performing a preliminary field deployment of SEC sensors to a highway steel bridge for gaining experience and collecting data; 3) testing the capacitance sensor board developed by the UA team and realizing a low-power accelerometer-based triggering mechanism of the wireless sensor nodes for long-term monitoring.

UA Progress: UA team has been providing technical support to the KU team regarding the capacitance sensor board. UA team has also been developing a user manual for the sensor board.

Anticipated work next quarter:

ISU: Sensor production will continue in the next quarter. Technical support is being provided to KU on a continuous basis, as well as discussion and feedback.

KU: Ku team will continue to complete the large-scale bridge model test, investigate the preliminary data collected during the field visit, complete the sensor board testing and low-power triggering mechanism, and develop a plan for the next field deployment of a long-term wireless SEC sensor network to the bridge.

UA: In the next quarter, Arizona team will continue to provide assistance to the KU team in terms of evaluating the sensor board at KU test setup.

Significant Results:

The KU team was focused on two tasks in this quarter including: experimental investigation on a new bridge girder to cross frame connection model; and preliminary results from a field test on a highway steel bridge. The progress is summarized as follows:

1. Validatoin test on a new large-scale bridge model

In the last quarterly report, we validated the ability of the soft elastomeric capacitor (SEC) through a large-scale skewed bridge girder to cross frame model with existing fatigue cracks. In this quarter, a new large-scale bridge girder to cross frame connection model was tested, as shown in Fig. 1. Compared with the previous mode, the new model has the cross frame perpendicular to the girder, as opposed to skewed. In addition, no fatigue cracks existed in the model when the SECs were deployed, which allowed for validating the ability of the SECs to detect newly-developed fatigue cracks.

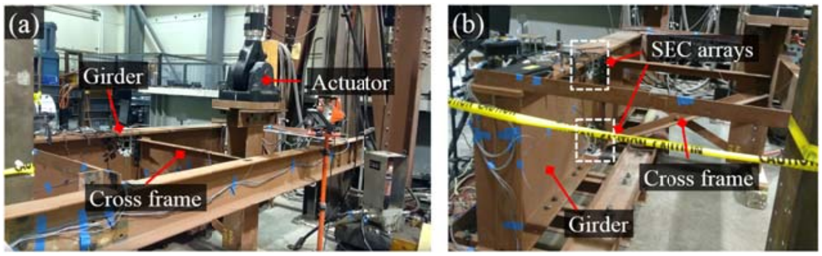


Figure 1. The tested model is a bridge girder to cross frame connection in which the cross frame is perpendicular to the girder.

Fig.1 illustrates the test setup, where the actuator was attached to the far end of the cross frame. SEC arrays were deployed at the interior side of the girder, along one side of the cross frame only. Detailed configurations of the SEC arrays are shown in Fig.2. At the top of the connection, 7 SECs were deployed at the stiffener and girder web as shown in Fig.2b. One large (2.5” × 2.5”) SEC was attached on the girder web while ther SECs are small (1”×1”) ones. At the bottom of the connection (Fig.2c), 5 large SECs were deployed and SEC b1, b3, and b5 were folded in order to sense the newly-developed fatigue cracks along the weld toes. Finally, a strain gauge was attached to the top chord of the cross frame in order to obtain strain data for normalizing the SEC measurements.

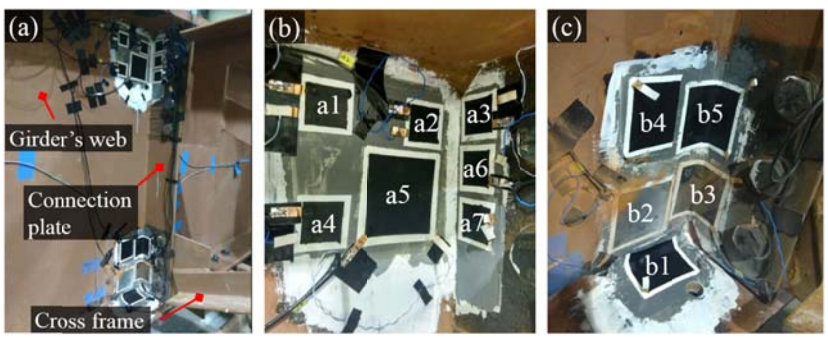


Figure 2. (a) A overview of the SEC arrays; (b) detailed view of the SEC arrays at the top of the connection; and (c) detailed view of the SEC arrays at the bottom of the connection.

In total 11,250 load cycles were applied to the test model through the actuator. The load range was selected as 0.5 kip to 5.8 kip for propagating the crack. When the load cycles reached 2100, 5800, 7000, 8550, 10000, and 11250 cycles, measurements were collected under the same load range (denoted as the full load range). In addition, two reduced load ranges, namely 50% load range (0.3 kip to 2.9 kip) and 25% load range (0.13 kip to 1.45 kip), were applied when the load cycles reached 7000, 8550, 10000, and 11250 cycles. As a result, 6 datasets were collected under the full load range and 4 datasets under the reduced load range.

Fig.3 briefly summarizes the fatigue crack growth observed under the fluorescent penetrant (Zyglo ZL-27A) during the test. Since the SEC arrays covered the fatigue-susceptible regions on one side of the connection plate, it would be difficult to identify the fatigue crack growth beneath the SECs. Here, our focus was placed on the other side of the connection plate to identify the crack activity. Since the bridge girder to cross frame model is symmetric about the cross frame, the crack activity on both sides of the cross frame could be similar.

As shown in Fig.3a, at 5,800 cycles, an L-shaped fatigue crack can be found on the interior side of the girder at the bottom of the connection. A ruler was placed next to the crack in order to measure the length of the crack. The vertical component of the crack is about 0.375 in., while the horizontal component is about 0.2 in. Once the load cycle reached

7,000 cycles, a horizontal fatigue crack was identified on the fascia side of the girder, as shown in Fig.3b. On the interior side of the girder, the horizontal component of the existing fatigue crack propagated longer as shown in Fig.3c, and continuously grew further when the load cycles reached 10,000 cycles and 11,250 cycles, as shown in Fig.3d and e. No fatigue crack was observed at the top region of the connection.

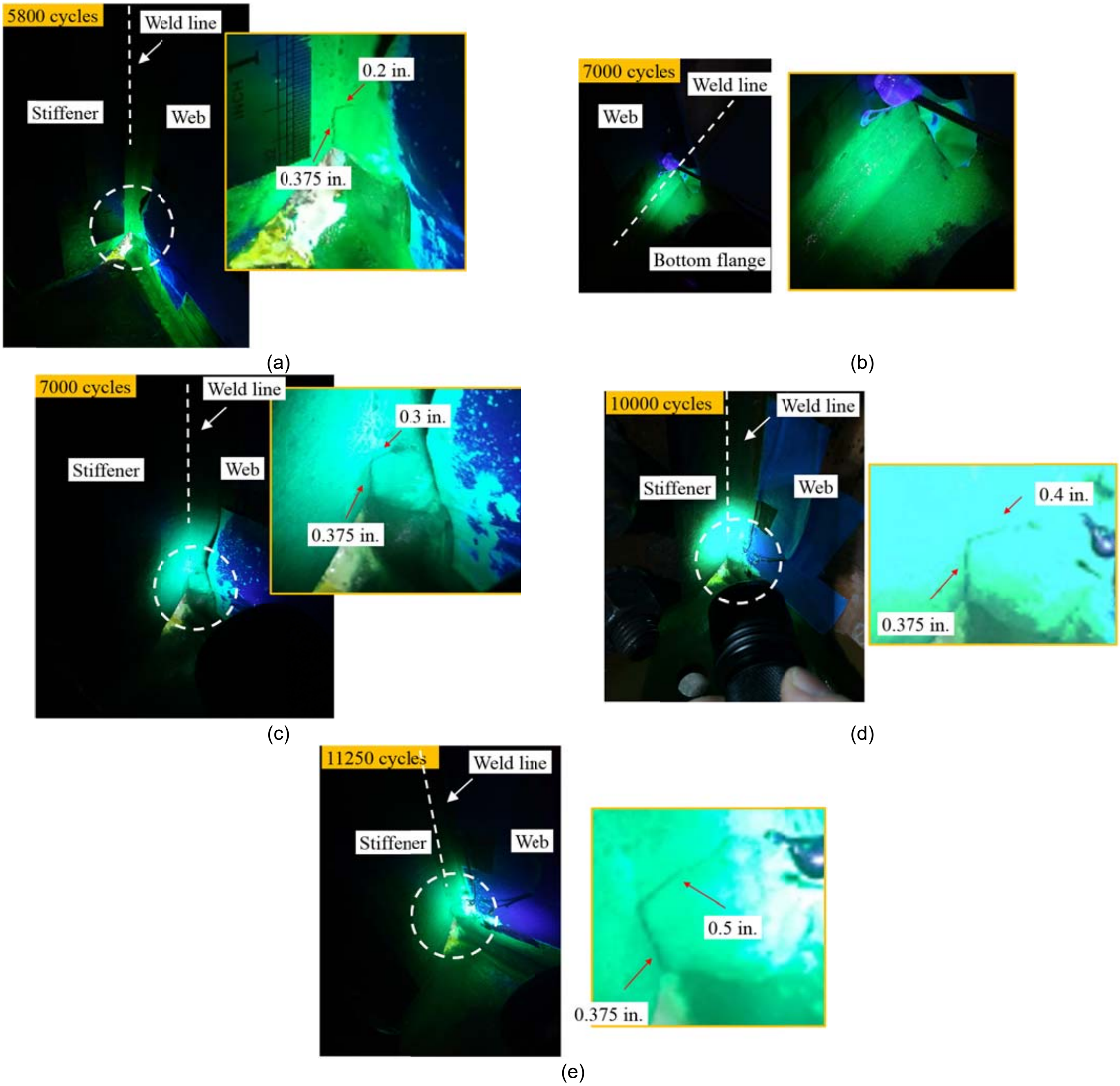


Figure 3. Fatigue crack growth during the test under different load cycles. Numbers of load cycles are marked on the top-left corner of each figure.

The collected measurements of the SEC arrays were processed based on our previously established algorithm in order to compute the crack growth index (CGI). The strain gauge measurement was adopted for normalizing the SEC's capacitance response. Fig.4 illustrates the CGI responses of the SEC arrays at the top region of the connection under different load ranges. As can be seen in Fig.4, all SECs produce constant CGIs during the test under the full load range, while fluctuation can be found under 50% load range and 25% load range. This might be due to the fact that the SEC arrays produce less capacitance responses under lower load ranges, making them prone to noise. Nevertheless, no fatigue crack was found at the top region of the connection in the test.

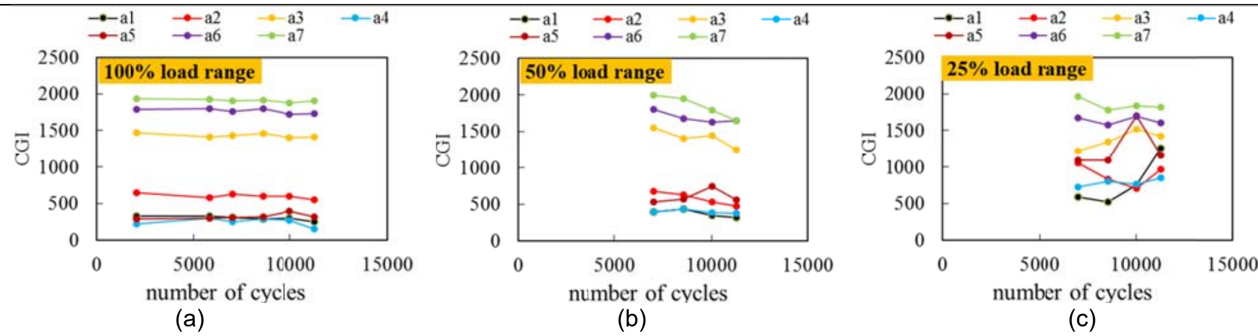


Figure 4. CGI responses at the top region of the connection under different load ranges.

Fig. 5 illustrates the CGI Reponses of the SEC arrays at the bottom region of the connection under different load ranges. As can be seen in Fig.5a, the CGI of SEC b3 (denoted in Fig.2c) increases from 1000 to 5000 during the test, indicating SEC b3 detected the crack growth. In addition, SEC b1 also demonstrates an increment. This may be attributed a potential initiation and growth of a horizontal fatigue crack between the flange and the web, even though it could not be identified during the test. Compared with the full load range, CGI responses of the SEC arrays show similar trends under 50% load range. Nevertheless, relatively stable CGIs can be found under the 25% load range, as shown in Fig.5c.

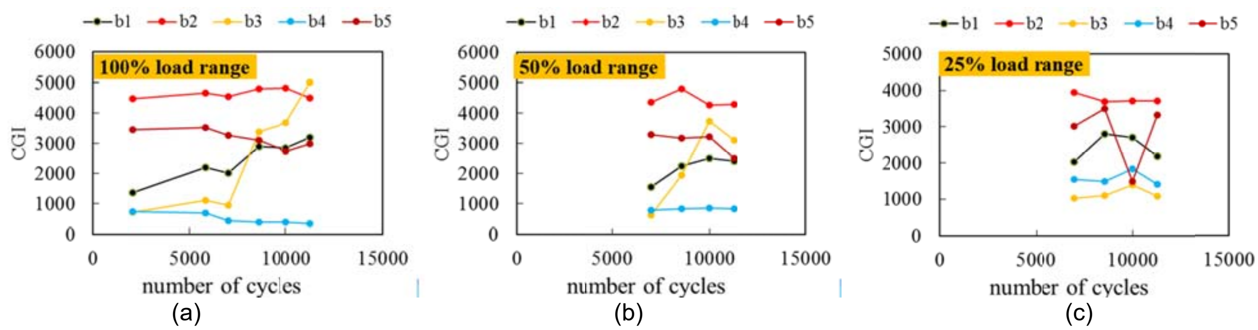


Figure 5. CGI responses at the bottom region of the connection under different load ranges.

2. Field deployment

The KU team also performed a field deployment of the SECs on a steel highway bridge in this quarter. The tested bridge was a part of the I-70 highway near Kansas City, Kansas. The bridge was named 70-105-41731-(127) and 70-105-417.32(128) according to the inspection report provided by the Kansas department of transportation (KDOT). The KU team visited the tested bridge twice on 01/23/2018 and 01/25/2018. Fig. 6 shows some photos taken from the field.

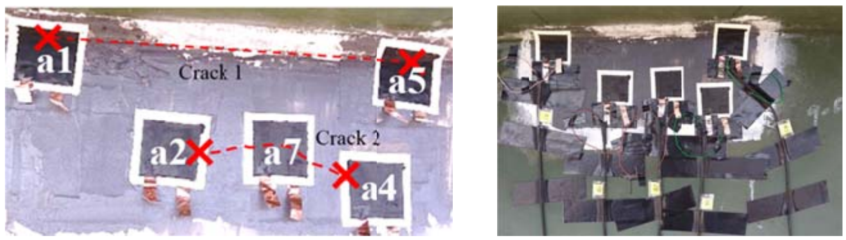
Figure 6. Field visit to the I-70 highway steel bridge.

The main purpose of this field deployment is to install SECs to a steel bridge and take preliminary data under traffic loading. The preliminary data and experience would serve as the basis for developing a plan for deploying a full wireless SEC sensor network in the near future.

As shown in Fig.7, the web gap region at the fascia side of an external steel girder was selected for installing the SECs. This bridge was inspected in 2013 and 2017, respectively. Based on the inspection reports and the marks of fatigue cracks on the structural surface, two fatigue cracks can be found in this region including: 1) a horizontal crack developed between the top flange and the web; and 2) a horizontal crack in the web. Both cracks propagated during the past 4-year inspection interval.

Figure 7. Detail views of the fatigue-susceptible region prior to sensor installation.

Fig. 8a shows the arrangement of the SEC arrays after installation. 5 small (1”×1”) SECs were deployed at this region, where two SECs (a1 and a5) were installed to cover Crack 1 and three SECs were attached to Crack 2. Fig.8b shows the SEC arrays after soldering the cables.



(a) (b)

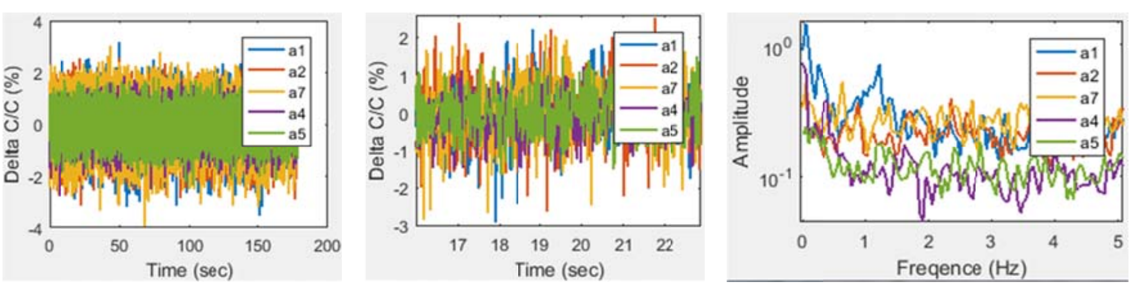
Figure 8. (a) Arrangement of the SEC arrays; and (b) the SEC arrays after soldering the cables.

Fig. 9 illustrates the SEC installation on the interior side of the girder, where two SECs were installed including one small (1”×1”) SEC and one large (2.5”×2.5”) SEC. In addition, a strain gauge was installed at the bottom chord of the cross frame. However, no photo was taken for the strain gauge after installation.

(a) (b)

Figure 9. SEC installation on the interior side of the girder.

A sample measurement was collected in the field using the SEC arrays on the exterior side of the girder, as shown in Fig.8b. The measurement was taken using the PCAP02 data acquisition (DAQ) board. The measurement had a 3-min duration and its time-series can be found in Fig.10a. Fig.10c shows the power spectral density response of the Sec arrays. The data is being analyzed to gain further insight from this field deployment.



(a) (b) (c)

Figure 10. (a) Time-series measurement of the SEC arrays; (b) a detailed view of the time-series measurement; and (c) power spectral density of the SEC measurements.

3. C-strain sensor board setup

In the last quarter, the KU team has been testing the capacitance sensor board developed by the UA team. The sensor board is designed to measure the capacitance of SEC sensors by converting the capacitance change to voltage change. At KU, we have been trying to balance the sensor board based on the instructions provided by Arizona team. For this purpose, there are two steps to be taken. Firstly, the potentiometers on the sensor board need to be adjusted to match the signals of different jumpers monitored by the oscilloscope. There are two types of balancing for the sensor board including coarse balance and fine balance. Coarse balance is easier to achieve; however, it causes more errors in the measurements of the sensor board. To achieve high quality data, fine balance is necessary for field tests. The second step is to perform shunt calibration to calculate the coefficient to convert the measured voltage to capacitance. To perform these steps, the Xnode is used as the power source for data acquisition. Fig. 11 presents the configuration of the connections between the sensor board, SEC sensor, and Xnode. We have succeeded to finish the balancing step. Fig. 12 shows different stages of the balancing step displayed on the oscilloscope. Our next step is to perform shunt calibration.

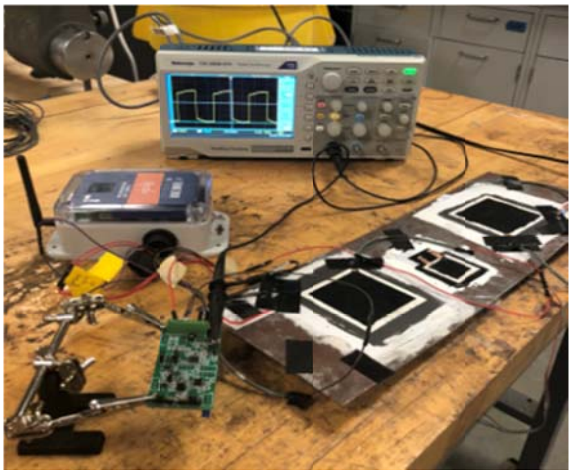


Figure 11. C-strain sensor board setup

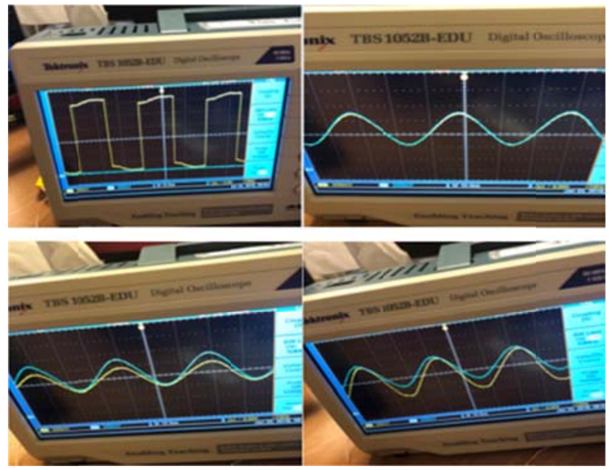


Figure 12. Balancing steps

4. Low-power triggering accelerometer to wake up the Xnode for long-term monitoring

To achieve long-term autonomous monitoring of fatigue cracks, our plan is to wake up each wireless sensor node when it is informed that a large vehicle is passing by to induce significant response of the SECs. These events are called triggering events. That happens when the vibration level due to the truck is larger than a predefined vibration threshold of the sensor node. To realize event-based wakeup of the sensor nodes, an additional low-power accelerometer (ADXL362) will be connected to each Xnode to wake up the node under large bridge acceleration. This functionality is being developed by the University of Illinois (UIUC). KU team has been working with UIUC to test the triggering mechanism. Based on the instructions from UIUC, the low-power accelerometer should be connected to the Xnode according to Fig. 13. At KU, we have been trying to figure out the connection between the ADXL362 and the Xnode. Fig. 4 presents a picture of test setup. The ADXL362 has been successfully connected to the Xnode, and is being evaluated to test the designed triggering functionality.

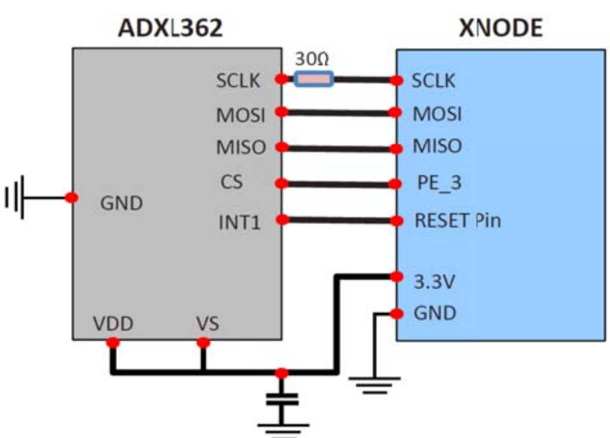


Figure 13. ADXL362 connection to Xnode

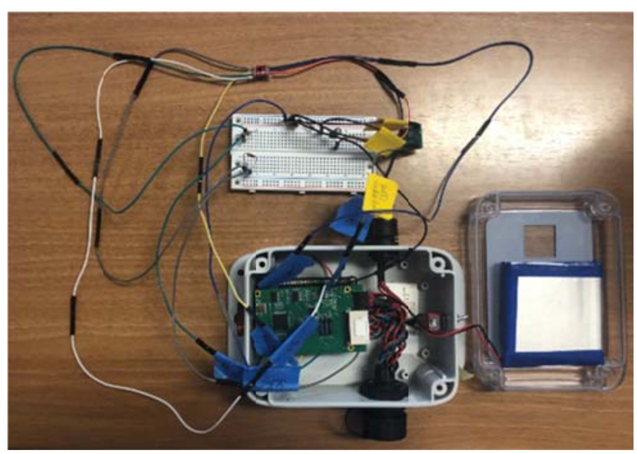


Figure 4. The circuit for ADXL362 connection at KU

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.