Self Powered Wireless Sensor Network for Structural Bridge Health Prognosis: Achievements in the First Two Years


ABSTRACT

In this paper, recent advances achieved on the development of a new system capable of continuously monitoring the structural health of steel and concrete bridges using wireless sensors are presented. This system will be able to harvest its own power from structural vibration and wind energy and, based on the data collected and on embedded algorithms, assess and predict the health of the structure. In order to reach this objective, this five-year project includes a series of tasks that encompass a variety of developments such as developing an ultra low power AE system, energy harvester hardware and especial sensors for passive and active acoustic wave detection. Thorough studies on acoustic emission produced by corrosion on reinforced concrete and by crack propagation on steel components, and the development of models that correlate AE data with component remaining life are also part of the project activities. This project is funded by the National Institute of Standards and Technology (NIST) through its Technology Innovation Program (TIP) under grant # 70NANB9H007.

INTRODUCTION

In 2007 the Federal Highway Administration (FHWA) National Bridge Inventory (NBI) classified 72,524 of the nation’s bridges as structurally deficient. This, in addition to the fact that about 10,000 bridges are being constructed, replaced or rehabilitated annually in the United States, put a large strain on the resources assigned to inspection of these bridges.
In turn, the result is a lack of data that bridge owners need to make informed decisions for maintenance prioritization [1]. As part of the national response to this critical national need of the aging civil infrastructure, NIST funded the project “Self Powered Wireless Sensor Network for Structural Health Prognosis.”

For this project, Mistras Group Inc. (MG), Virginia Tech (VT), University of South Carolina (USC) and University of Miami (UM) proposed an ambitious plan with two major goals: (a) transforming unused ambient structural energy into power using energy harvesters for powering a newly developed data fusion wireless sensor node, and (b) interpretation of fused sensor data for identifying structural damage and deterioration though specially developed models and algorithms [2]. At the conclusion of the project, the group will deliver a commercially ready self-powered data fusion wireless sensor node with built-in predictive models and decision algorithms for bridge component health prognosis.

During the first two years of this five-year project, the advances have been substantial in several of the project tasks and can be summarized as follows:

- Development and test of an ultra-low power 4-channel AE wireless node with capability for eight additional parametric inputs including strain gages.
- Development and test of a windmill with a power output of 166 mW at 7 mph wind speed with a cut-in wind speed of 3.8 mph.
- Successfully developed field-deployable prototype to interface with low power 4-channel AE wireless node.
- Test of novel piezoelectric wafers as AE sensors in passive and active modes.
- Test of several steel specimens for crack growth during fatigue test.
- Investigation and development of preliminary relationships between AE and crack growth parameters.
- Development and implementation of a prognosis model to determine the stress intensity range based on acoustic emission data.
- AE data collected and preliminary data analysis conducted in two bridges using the prototype AE wireless nodes.

As the project goes into the third year, a series of preliminary field tests are planned for the prototype wireless node integrated with the energy harvester. It is expected this integrated prototype will be deployed in several bridges before the end of 2011. Also, several prototype energy harvesters that combine nonlinear vibration of piezoelectric elements and electromagnetic induction will be tested and eventually integrated with the wireless nodes. As the fatigue and corrosion tests progresses and the data are used to improve the prognosis models, these will provide a series of algorithms that eventually will be embedded in the wireless node.

**WIRELESS SENSOR NODE**

The data acquisition platform being developed is a wireless node with Acoustic Emission (AE) sensors, inputs parametric sensors and strain gages. The node also includes on board signal processing and analysis capabilities, signal conditioning electronics, power management circuits, wireless data transmission element and inputs for energy harvesting units. The sensing elements act in passive (AE) and active modes (Acousto-Ultrasonics).
The multiple parametric inputs are used to connect different sensors such as temperature, strain, PH, etc. The outputs of all these sensors will be combined and analyzed at the sensor node in order to minimize the data transmission rate which consumes significant amount of power. Power management circuits are planned to reduce the data collection intervals through selective data acquisition strategies in order to minimize the power consumption of the wireless node.

4-Channel AE Node

Initially, a limited platform with one AE channel was developed, tested in the laboratory and demonstrated at the 1st year review meeting [3]. It was decided to use this one-channel node as a learning step to test the power consumption reduction strategies and the wireless transmission protocols, and then extend the capability of the node into a 4-AE channel node. In this way, the potential area covered by a single node was increased and location capabilities added. These increased the capability to track the evolution of defects in bridge components. The newly designed 4-AE channel wireless node was designed, built and laboratory tested [4]. The technical specifications of this node, designated by MG as the 1284 AE wireless node, are shown in Table 1. Figure 1 shows the 1284 node in a weather proof box with sensors and a notebook computer with the USB wireless receiver.

The prototype 1284 node was demonstrated in January 2011 during the project’s second year review meeting. The node was packed with a set of rechargeable batteries and it was installed on a small bridge undergoing repairs. The netbook computer, with the USB wireless receiver and running the acquisition program AEWin was located in a pier approximately 150 feet from the 1284 node position, was used to receive the data collected. The data was produced by several center punches done on one of the bridge girders where the sensors were located.

### Table I. 1284 Wireless Node Specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
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<tbody>
<tr>
<td>Board Size</td>
<td>4in x 5.5in</td>
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<tr>
<td>Weight</td>
<td>Less than 0.5 lbs</td>
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<tr>
<td>Power Requirements</td>
<td>5-18 volts (2 inputs, largest will power the node)</td>
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<tr>
<td>Power Consumption</td>
<td>170 mW at full power (at 10 or less hits/sec)</td>
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<td></td>
<td>50 mW in sleep mode with parametric wakeup</td>
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<tr>
<td></td>
<td>10 mW in sleep mode with timer wakeup</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-40°F to 158°F (-40° to 75°C)</td>
</tr>
<tr>
<td>AE bandwidth</td>
<td>1 kHz to 250 kHz</td>
</tr>
<tr>
<td>Acousto-Ultrasonic Pulser</td>
<td>Adjustable voltage, 5 to 40 volts, and toneburst (frequency, number of cycles) on each channel</td>
</tr>
<tr>
<td>Parametric Channels</td>
<td>6 (voltage &amp; current), 1 specific for strain gage</td>
</tr>
<tr>
<td>Memory Card</td>
<td>SD Memory card slot for mass storage</td>
</tr>
</tbody>
</table>
AE Sensors

Several AE sensors have been used in tests during the two first years of the project. These are low power piezoelectric PK6 sensors, resonant at 60kHz, for concrete samples, and PK15 sensors, resonant at 150kHz, for steel samples. These sensors are manufactured by MG and they are regularly used in AE installations. Even though they are proven in field installations, these sensors are more sensitive to signals that produce out-of-plane particle motion in the samples under monitoring. However, a large percentage of the energy released by propagating cracks in steel plates produces to in-plane particle motion. Thus a sensor with better sensitivity to this type of displacement is needed. Therefore a serious effort is underway to habilitate Piezo-Wafers Acoustic Sensors (PWAS) as AE sensors [5].

Preliminary results indicate that although PWAS show lower general sensitivity than regular PK sensors, they show better sensitivity to simulated in-plane displacements. Figure 2 shows RF signals produced by simulated cracking in a 0.25” thick steel plate, as detected by a PWAS and a PK15 sensor. The results are encouraging and show PWAS have the potential for becoming a good AE sensor. However, before PWAS can be used as commercial AE sensors, some limitations have to be resolved: vulnerability to electromagnetic interference (EMI), complex installation, decrease of sensitivity with sample thickness and packaging. Solutions to these limitations are currently being investigated and it is expected that a field deployable PWAS AE sensor will be ready at the end of the 3rd year of the project.

ENERGY HARVESTING

Energy harvesting is a very important component of the project and the advancement in this area during the first two years has been excellent.
Figure 2. Comparison of "in plane" RF signals detected by PWAS and PK15 sensor.

Two different approaches to energy harvesting were investigated: wind and a combination of electromagnetic-piezoelectric-vibration energy harvesting. In both cases several prototypes were designed built and tested. In the area of wind energy harvesting, two prototypes were built: the first one, a traditional horizontal axis design was demonstrated to produce 166mW of regulated power at a wind speed of 7 mph with a cut-in speed of 3.8 mph [6]. The second one, a vertical axis contactless type was able to produced 9 mW at 7mph [6]. Both prototypes are shown in Figure 3.

Figure 3. Wind energy harvesters developed in the first two years of the project: (a) Horizontal axis windmill and (b) vertical axis windmill.
In the case of the electromagnetic-piezoelectric-vibration prototype harvester, over 10mW unregulated power was generated at accelerations of 0.1g and 7.2 Hz, typical vibration values for a concrete bridge.

According to Table I, the improved hardware platform will consume approximately 170mW, which could be provided by a combination of the horizontal axis windmill and the electromagnetic-piezoelectric-vibration prototype, provided there is a constant 7mph wind. This assumption is unrealistic in most of the sites considered for deployment of the system. Therefore, other energy harvesting alternatives need to be explored. That is why during the 3rd year of the project, the focus will be in investigating nonlinear effects on hybrid harvesters, which combine electromagnetic with piezoelectric energy harvesting through random vibration. It is expected that this type of harvester will increase energy generation by orders of magnitude compared to simple vibration harvesters.

**CRACK PROPAGATION AND CORROSION DETECTION WITH ACOUSTIC EMISSION**

As indicated in the introduction section, the wireless node under development will have built-in analysis and prognosis capabilities, based in a combination of AE and external parametric sensor signals. In order to develop those capabilities, correlations between the AE released by propagating damage such as cracking in steel and concrete bridges, or by corrosion of steel reinforcement, as in the case of concrete bridges, needed to be established. For this purpose extensive experimental work has been undertaken in these two areas.

**Crack Propagation in Steel Specimens**

A series of notched steel specimens were fabricated and submitted to fatigue cycling with the objective of growing cracks in a control manner and to monitor the growth by an array of AE sensors mounted on the specimens. The data obtained indicates that the increase of cyclic loads as well as the critical cracking level can cause a rapid increase in AE signals as shown in Figure 4.

The data collected during these early fatigue experiments was used to develop a model which associates absolute energy rate with crack growth parameters. This model is able to predict fatigue life in terms of stress intensity factor range versus load cycles as shown in Figure 5 [7]. It is expected that as more data is available from upcoming tests, the model will become more robust and will be able to predict remaining life of steel bridge components based on the AE activity detected while it is monitoring in service using the 1284 AE wireless node.

**Corrosion monitoring**

Over 20 steel-reinforced concrete samples, cracked and un-cracked, have been tested under accelerated corrosion tests and monitored with AE with the aim of detecting the early stages of corrosion before it produces cracking in the concrete.
The AE parameter of interest for the early detection of corrosion is signal strength, which correlates very well with the amount of impressed electric current passing through the corrosion cell.

In addition, other AE parameters such as signal amplitude and absolute AE energy are being observed for potential correlation with the different corrosion stages. Preliminary results show that AE monitoring does detect corrosion earlier than conventional electrochemical techniques, especially in un-cracked specimens. It is expected that correlations between AE and the presence and severity of active corrosion will be developed and incorporated into the 1284 node hardware calculation capabilities. In this way, the 1284 will be able to determine whether active corrosion is happening in reinforced concrete, and what is the severity of it.

Figure 4. AE activity as function of cycling load of steel specimens

Figure 5. Prognosis of Stress Intensity Range as a function of AE activity and number of fatigue cycles.
CONCLUSIONS

At the end of the project’s second year, significant advances have taken place in the development of the data acquisition platform for self-powered wireless node for structural health prognosis. A four AE channel system has been developed and demonstrated, and will be ready for field test during the second half of the project’s third year. The PWAS sensors show good potential to be implemented as AE sensors due their sensitivity to in-plane displacement produced by crack growth. However, several limitations of this type of sensor need to be overcome in order to substitute traditional AE sensors.

Extensive tests have been completed in the area of crack growth and accelerated corrosion monitoring with AE. The results indicate that good correlations between AE and damage occurrence have been found. It is expected that these correlations will evolve into solid models that will predict remaining life of concrete and steel bridge components. These models will be incorporated into the hardware of the AE wireless nodes.

It is important to mention that the impact of this project extends beyond the area of bridge health monitoring. Several wireless prototype nodes have been already requested for applications on offshore oil platforms, composite ships, combat deployable bridges and wind turbines. Also, a prototype rotational motion energy harvester for applications on turbine wind blades is being developed.

REFERENCES