Keynote Paper

New strategies for SHM based on a Multichannel Wireless AE Node

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ABSTRACT

This paper discusses the development of an Acoustic Emission (AE) wireless node and its application for SHM (Structural Health Monitoring). The instrument development was planned for applications monitoring steel and concrete bridges components. The final product, now commercially available, is a sensor node which includes multiple sensing elements, on board signal processing and analysis capabilities, signal conditioning electronics, power management circuits, wireless data transmission element and energy harvesting unit. The sensing elements are capable of functioning in both passive and active modes, while the multiple parametric inputs are available for connecting various sensor types to measure external characteristics affecting the performance of the structure under monitoring. The output of all these sensors are combined and analyzed at the node in order to minimize the data transmission rate, which consumes significant amount of power. Power management circuits are used to reduce the data collection intervals through selective data acquisition strategies and minimize the sensor node power consumption. This instrument, known as the 1284, is an excellent platform to deploy SHM in the original bridge applications, but initial prototypes has shown significant potential in monitoring composite wind turbine blades and composites mockups of Unmanned Autonomous Vehicles (UAV) components; currently we are working to extend the use of this system to fields such as coal flow, power transformer, and off-shore platform monitoring.

Keywords: Acoustic Emission, structural health monitoring,

1. INTRODUCTION

In 2007 the Federal Highway Administration (FHWA) National Bridge Inventory (NBI) classified 72,524 of the nation's bridges as structurally deficient [1]. At that time in the US, approximately 10,000 bridges were being constructed, replaced or rehabilitated annually. In 2011, 11.5 percent of the approximately 600,000 bridges nationwide are still classified structurally deficient; moreover, a number of bridges have exceeded their expected lifespan of 50 years and the average age of an American bridge is 42 years [2].

In an era of sever budget cuts and shrinking funds for rehabilitation, the resources assigned to inspection of these bridges are limited, which in turn results in a lack of data needed by bridge owners to make informed decisions for maintenance prioritization. One of the most comprehensive bridge testing methods today is based on acoustic emission (AE). Acoustic emission sensing has been constrained to hard-wired systems until now because the processing of high bandwidth sensor data on multiple channels requires significant power and in some cases rapid processing. The present project focused on the development of an AE system that utilizes a low-power\ Flash FPGA for signal processing and wireless communication to a base station.

As part of the national response to this critical national need of the aging civil infrastructure, in 2009 the National Institute of Standards and Technology (NIST) funded the project "Self Powered Wireless Sensor Network for Structural Health Prognosis" through its Technology Innovation Project (TIP) Grant #70NANB9H007. At the conclusion of the project in January 2013, the Joint Venture (JV) formed by Mistras Group Inc., Virginia Tech, University of South Carolina and University of Miami developed a commercially viable self-powered data fusion wireless sensor node powered by energy harvesters that transform unused ambient energy such as bridge vibrations and wind energy. The subsequent efforts by Mistras have been directed to modify the node for applications in other areas in need of Structural Health Monitoring such as wind turbines and aircraft.

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1.1 Instrument Description and Capabilities

The instrument platform envisioned in this project is a sensor node including multiple sensing elements, on board signal processing and analysis capabilities, signal conditioning electronics, power management circuits, wireless data transmission element and energy harvesting unit.

The instrument developed corresponds to a 4-channel wireless node, known by product designation as the 1284 node. This platform, includes inputs for four AE sensors; one strain gage with conditioning circuitry; and six parametric inputs, which can be used to connect different signals such as load, displacement, temperature, PH, humidity, corrosion potential, etc. The 1284 is equipped with rechargeable batteries and inputs for energy harvesting units that can provide power to recharge the instrument. The 1284 has the capability for waveform recording. The raw waveforms are not part of the data package transmitted wirelessly but rather stored in the SD card for later retrieval for post-processing. The node is also equipped with a “watch mode” which allows the user the user to connect and disconnect the node from the computer with the wireless receiver module without the need to turn the acquisition on or off.

The acoustic sensing elements are capable of functioning in both passive and active modes (i.e. Acoustic Emission and Acousto-Ultrasonic mode) while the multiple parametric inputs are used to connect various sensor types to measure external characteristics affecting the performance of the structure under study. The output of all these sensors is combined and analyzed at the sensor node in order to minimize the data transmission rate which consumes significant amount of power. Power management circuits were planned to reduce the data collection intervals through selective data acquisition strategies and minimize the sensor node power consumption.

The wireless transmission protocol for the 1284 was selected based on considerations such as maximum AE data set rate, interface data rate, maximum range of communication, and energy consumption. The interface selected was XBee at 900 kHzA, with a range of 600 m, an interface data rate of 57.6Kbps with a maximum AE data set rate of 250 AE hits per second among all channels in the instrument.

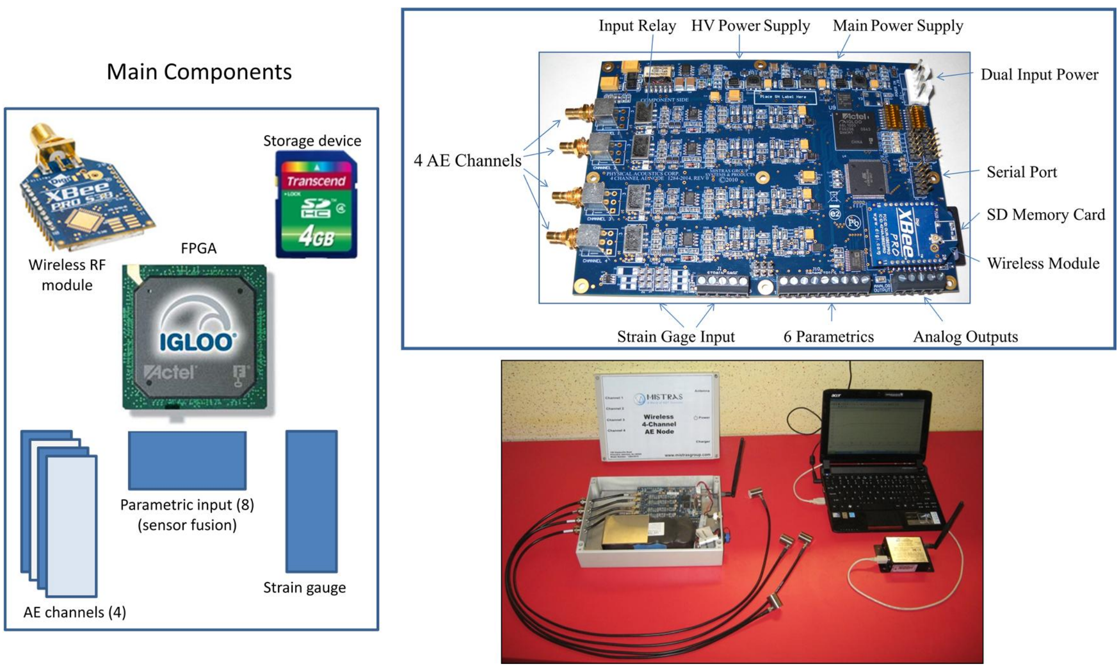


Figure 1. Components of the 1284 (4-channel wireless node), picture of the board (Rev 1.0) designed at Mistras, and the whole system connected to a laptop computer via a base station.

The 1284 has the capability to turn the AE sensors from a passive mode into an active mode. This means use the AE sensors as pulsers turning them from a passive detection mode to an active pulsing mode. This capability, known as Auto Sensor Test (AST), allows to sequentially pulse each one the four sensors at any desired time interval. This utility is critical to increase the 1284 node capability to monitor damage growth and evaluate damage severity once it has been detected using the passive AE capability. In terms of data management during long periods of monitoring, the 1284 has the capability to close files once they reach a predetermined size and open a new consecutive one.

The 1284 is designed to work with a special version of Mistras AE data acquisition and analysis software AEWin. This special version, AEWinWireless, allows to setup the 1284 by programming AST user on demand, program the sleep-wake up mode based on parametric value input, define remote alarms based on AE characteristics, define a particular parametric input for measuring rechargeable battery voltage, program auto resetting, setup the waveform capture capability for the SD card. The software also allows time ordering the AE signals received to calculate the differences in signal arrival time between the four AE sensors, which is critical to calculate the position of a potential AE source.

The 1284 node is designed to work with a variety of traditional piezoelectric low power AE sensors such as PK6 sensors, resonant at 60kHz, for concrete samples, PK15 sensors, resonant at 150kHz, for steel samples, and PKWD, wide band 100-1000 kHz, for general applications. These sensors are manufactured by Mistras Group Inc. and they are regularly used in commercial AE installations.

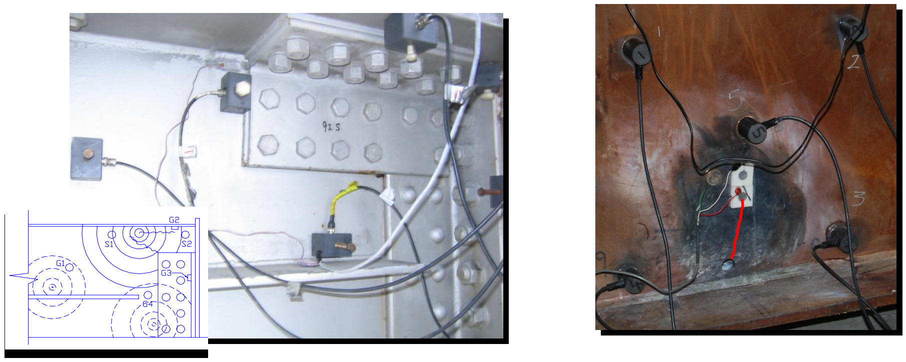
2. MONITORING APPLICATIONS

2.1 Civil Infrastructure Monitoring

The node was designed having in mind the need of an easily deployable system for small and critical area monitoring; particularly the objective was to monitor evolution of a crack discovered during routine inspection; to assess the behavior of a critical bridge member, such as a girder. The figure below (figure 2) shows two options where the 4-channel wireless node can be used to monitor critical areas. The applications showcased are:

1) Floor Beam to Girder Connection (linear location)
    - one sensor used for detection of AE sources from known discontinuity (e.g. crack)
    - 3 sensors used as “guard” sensors.
    - The purpose of the guard sensor is to graphically filter out AE noises sources that occur outside the area of interest.
    - If the AE source passes the “guard” sensor before passing the AE sensor (S1 or S2), the data is still collected but graphically ignored by the location algorithm.

2) Crack in girder web (2D planar location)
    - Set the four sensors in a distribution to monitor the crack
    - Strain gauge or displacement sensor can be connected to the parametric input
    - Calculate speed of the medium and set up location filters or linear or 2d location.
    - Track AE signals from the source over time.



(1) Floor Beam to Girder (2) Crack in girder

Figure 2: Examples of possible applications of critical area monitoring using the 4-channel wireless node.

Regarding field deployment, the University of South Carolina used the node in three load tests on medium and full scale specimens tested inside and outside the laboratory, and the University of Miami, deployed the 1284 node in two tests, one performed in the laboratory and one in the field; a summary of the tests is shown in Table 1. This document presents a brief summary of the data collected by the 1284 node as compared to wired AE system, Sensor Highway II.

Table 1: Summary of wireless node (1284) deployment

Location	Description of the test	Number of specimens
Outside laboratory test	Simulated seismic loading – 3-pile specimen	One
Laboratory test	Cyclic load test – Flexure specimens	Two
Laboratory test	Cyclic load test – Shear specimens	Six
Laboratory test	Cyclic load test – RC slabs built to experience flexural failure	Two
Filed testing	Three-story apartment building built in 1947 and scheduled for demolition	One

2.2 Aerospace Structures

Laboratory studies in the detection of delamination and crack initiation and propagation in aerospace composites using acoustic emission has been documented extensively [3-8]. However, its implementation in flying aircraft has been limited because of the size and weight of the equipment commercially available and its power demand. Because of its small size, weight, low power consumption and powerful data processing capabilities, the 1284 is the first viable AE instrument to be used in real SHM of aircraft. In order to demonstrate the feasibility, a 3 point bending test on a carbon composite bonded joint was monitored using both the 1284 and a regular AE system. The composite joint was similar to the ones found in the wing box of a particular model of Unmanned Aerial Vehicle (UAV). The experimental setup is shown in Figure 3.

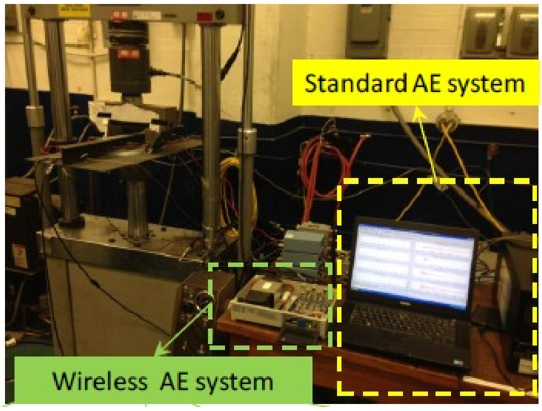


Figure 3. Three point bending AE test comparing the 1284 and a standard AE system.

The AE desktop system was equipped with four AE sensors resonant at 300 kHz, while the 1284 wireless AE system used four AE sensors resonant at 150 kHz and both systems captured the load applied by the MTS system. In the wireless AE system, waveforms, AE feature and load data were collected and stored in the SD card, while the AE feature and load data were simultaneously transmitted to the base station in real time. The three point bending test consisted of two periods of fifty cycles each. Figure 4 shows the data collected during the test.

In Figure 4, the red points on the graphs represent the changing value of the load during the test. It is clear that the data from the standard AE system, Figure 4(a) is denser than that collected with the 1284, Figure 4(b). This is due to the fact that the 1284 has built-in limitations in the hit rate that in order to save power. However, a zoom of the 1284 data plot shows that the data describes very well the loading cycles and the AE burst of energy at the top load in the cycles. This shows that when collecting data with the 1284, the user has to be very smart in setting up the system to collect relevant data. To further demonstrate the capabilities of the wireless system, Figure 5 shows the cumulative energy and amplitude distributions of the recorded AE signals from both systems. Notice the jumps in the two curves marked by the blue arrows, clearly indicating points in the test where there was a sudden growth in damage inflicted to the composite.

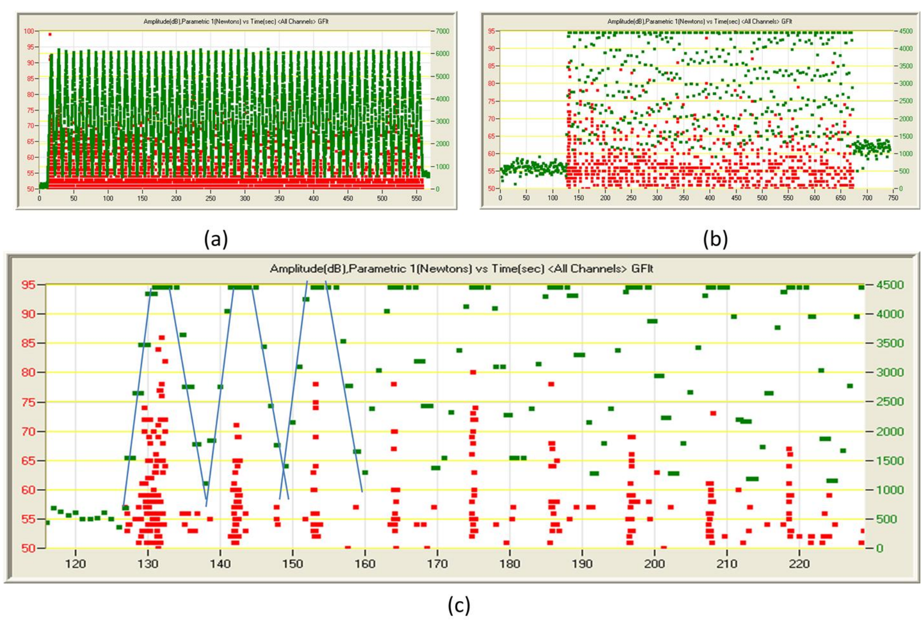


Figure 4. Data collected during the three point bending test, (a) Data collected with the standard AE system, (b) Data collected with the 1284 node, (c) Zoon of data collected with the 1284 node.

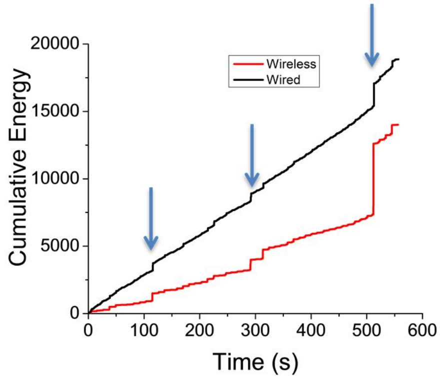


Figure 5. Cumulative AE energy as measured by the standard AE system (black) and the 1284 node (red) during the three point bending test. Notice the jumps (arrows) indicative of damage growth at different points during the test.

2.3 Wind Turbine Monitoring

Blade failures are currently the second most critical concern for wind turbine reliability. Delamination and cracking during operation due to in service stresses produced by manufacturing defects is an important issue in these structures. Continuous monitoring during service is desirable because the turbine blades are highly stressed by the constant wind contact, and continuous monitoring will reduce the need for regular inspections.

In order to deploy a SHM system in a wind turbine to assess the reliability of the blades, we designed a system consisting in three low power single channel wireless AE nodes, to be installed in each one of the blades of a wind turbine, and a base station placed at the wind turbine nacelle controlling the acquisition of each AE wireless node and compiling their inputs. This system was also furbished with a cellular modem to be able to communicate with the base station by remote desktop. The base station was installed at the back of the nacelle; a diagram of the system is shown in Fig. 6.

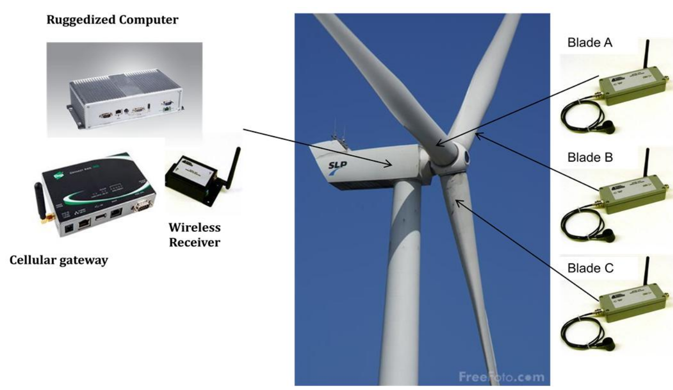


Figure 6. Components of a SHM system for turbine blade monitoring.

A single AE sensor, is connected to the wireless node via a coaxial cable and attached to the structure being tested. The single channel wireless node is rated for outdoor use, and wide temperature operation. The AE wireless node and battery pack installed on each blade of the turbine were placed inside of a Faraday change and installed at the torque plate of each blade (root of the blade).

Once the logistics and problems associated of system deployment and survivability where solved, the next step is to identify the critical areas for monitoring in a blade, which are turbine dependent, and identify necessary sensor spacing, for successful localization of sources. Two main issues can be monitored using AE in blades, localized ice formation, and crack initiation. The ability to perform location with the AE signals collected from the blade (as discussed in item 3 above), can be done by using a multichannel AE wireless node. Mistras has already developed such unit and it is in the process of deploying it for different monitoring applications where location or multiple sensor input of synchronized data is necessary.

3. INSTRUMENT CAPABILITIES AND LIMITATIONS

3.1 Instrument limitations

The limitations of the 1284 are the result of the wireless transmission protocol elected, which although optimized for low power (by using ZigBee), it has limited range and one has to carefully decide the type of ZigBee protocol used depending on data rate, RF signal attenuation and the need to either send data continuously wirelessly or transfer data files at programmed periods when the system is not acquiring. Data acquired (both AE and parametric data) can be transferred to the base station with minimum delay, and at high hit rates about 5% of the data is dropped (not send to the base station), as the first priority of the instrument is to save the data acquired into the SD card.

Once the issues associated to wireless communication are resolved, other limitations of the 1284 arise mainly from the need of low power consumption and extend battery life of the unit. For instance a 10mA/h battery can sustain the 1284 for 10 days processing with 1 hit per channel per second, whereas the same battery last 8 hours on the Pocket AE system under the same hit load.

3.2 Instrument capabilities

- Four AE channels, 8 parametric inputs and 1 strain gauge module.
- Waveform capture on SD card.
- Customizable (during manufacturing) low pass and high pass filters for AE acquisition, and frequency of RF wireless module (2.4GHz or 900MHz).
- AST on user demand that can be used to test the channels, or to perform tomography studies in a region of interest.
- User defined AE feature filtering, alarm definition capability, and waveform acquisition filter.
- Up to 10 hits/sec per channel, when waveform saving is enabled and data is transferred.
- Up to 80 hits/sec per channel, without waveform saving and with wireless transmission.
- User defined Sleep-Wake up mode based on parametric input values.
- Data file transmission when the node is not in acquisition mode.
- Full watch mode capability (connect and disconnect remotely without stopping acquisition).
- Dedicated output for measuring battery voltage and energy harvester performance.

4. CONCLUSIONS

During the four-year project “Self-powered Sensor Network for Bridge Health Prognosis”, sponsored by NIST through is TIP program, Mistras Group Inc. developed the smallest lowest power, full capability AE system with on-board signal processing capabilities comparable to those found in large commercially available AE multichannel boards.

The 1284 is designed to work in two different modes: as a unit transmitting processed data wirelessly to a remote location, which is accessible via internet gateway or cellular modem, or as a collector unit which saves data in the memory card for later retrieval.

The applications for the 1284 extend beyond the area of bridge health monitoring into the generalized structural health monitoring of very diverse structures. The data obtained in the three point bending test of a composite sample shows that the 1284 node has the capability for SHM of composite components in flying aircraft. The 1284 is ready for deployment on offshore oil platforms, composite ships, combat deployable bridges and wind turbines.

5. AKNOWLEDGEMENTS

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