The 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure
Vancouver, British Columbia, Canada
November 13-16, 2007

ACOUSTIC EMISSION TECHNOLOGY FOR INTELLIGENT INFRASTRUCTURE

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Abstract

Acoustic emission is a well-established nondestructive testing technique commonly used to monitor active fatigue cracks in metals, leaks in pressurized lines and tanks, impact damage, and matrix and fiber damage in composites. The AE testing marketplace is currently dominated by big, bulky and expensive piezoelectric transducers that are wired to massive multi-channel data acquisition systems. Embedding existing AE technology on structures requires significant capital investment. A single sensor costs between $300 to $900 (based on quotes from commercial vendors) and multi-channel instrumentation from $20,000 to $100,000. Based on the published prices of conventional AE sensors and instrumentation, and the sensor volumes for smart transportation infrastructure, new AE technology is required. The technology must be deliverable with comparable performance at one or two orders of magnitude lower cost, size and weight.

AE BRIDGE TESTING

Structure-generated strain and acoustic emission data contain valuable information on the integrity of materials of construction. In addition to an inherently high sensitivity, the correlation of acoustic data to load-induced strain, enables monitoring of inaccessible areas and the ability to monitor with a minimum of sensors. This is in contrast to most other nondestructive testing methods that require point-by-point inspection of only accessible areas of interest on a structure.

Acoustic emission was developed as a nondestructive testing method in the latter half of the 20th century. It is an accepted method subject to North American, European, Japanese and international standards. The standardized methods use controlled stimulation where the structure is isolated from its environment and systematically loaded mechanically or thermally (such as with a monotonically increasing pressure or a thermally decreasing load on cool-down of high-temperature equipment). The emissions from the activation of defects during this controlled stimulation are monitored.

In another very large group of applications, controlled stimulation is not feasible, the need is equally if not more pressing. In railway bridge monitoring, the load is provided by the passing of trains. In these uncontrolled stimulation applications, ambient operating and parasitic noises compete with valid flaw signals and require labor-intensive interpretation by highly specialized inspectors. Acoustic emission - strain correlation methods provide a sound basis for separating relevant signals from noise and to help identify the source of emission. They are very cost-effective to carry out and provide data of substantial economic value to the owner/operator of the structure and the military, domestic and industrial communities they serve.

The bridge engineer has a mandate to maintain the safety and capacity of the existing bridge infrastructure to ensure uninterrupted train operations while controlling or reducing repair and refurbishment costs. To maintain this balancing act, in an infrastructure of bridges that may have exceeded their expected life and be carrying loads greater than originally designed for, the bridge engineer relies on other engineering data from structural analysis, load history, strain measurement and inspection, to determine effective repair and replacement schedules. Railways have depended primarily on visual inspection to assess structural integrity. CN North America for the past 15 years has complemented structural analysis, strain measurement and visual inspection with acoustic emission and strain (AES) monitoring of specific fracture critical members on selected bridges. During this 15-year period AES monitoring has been used on over 215 bridges to assess the state of existing fatigue cracks, to locate hidden cracks and to assess the effectiveness of crack repairs. It is used on a periodic basis; data on one bridge takes up to two weeks of analysis of scanning a large signal database, and on-line monitoring that is increasingly in demand is not as yet feasible. Both the data analysis and continuous monitoring can be addressed by applying intelligent systems technologies.

Data is presented for a single train pass at the location shown in Figure 1 strain and acoustic emission (AE). The bridge is located in Stevens Point, WI, and owned and operated by CN North America. The test was undertaken from July 13 to 15, 2003 by WinS PIs as part of their on going AES bridge monitoring contract with CN North America. The purpose of this exercise is to show the correlation between load cycles (strain data) and AE from the fatigue cracking process as typically observed on steel railway bridges. A fracture critical member with a pre-existing crack was selected for monitoring as designated by the client. The location had previously experienced fatigue cracking and had its crack tips drilled. This location was found to be currently active.

WinS uses a digital strain – acoustic emission monitoring system with transient recording capabilities and an operating bandwidth from 220 – 850 kHz. 375 kHz resonant transducers, with integral preamp providing 34 dB gain are used, exclusively. All channels on the data acquisition system have a fixed (calculated) gain set to the total gain in the measurement chain. The instrument is capable of handling relatively high parametric acquisition rates without detrimental effects on AE data acquisition. All data are time stamped so exact correlation of AE hits to current parametric levels is possible. A load curve is acquired for all monitoring locations using conventional foil gauges. A parametric sampling rate of roughly 200 Hz is more than adequate for obtaining the primary loading curve. Acoustic emission data are analyzed using planar source location, load correlation, and time and frequency domain analysis. Planar location arrays are typically small (on the order of a few feet in both dimensions) due to high noise levels and constraints posed by location geometry experienced on many bridges.

Figure1 shows typical strain - acoustic emission data obtained during bridge testing. In the top left, the loading cycle is shown. During maximum loading, 908 to 910 seconds for the safety critical structure shown, crack growth is present at numerous locations in member. This curve shows the strain profiles as a train load passes over the area being monitored. On it is superimposed acoustic emission data that, on this cycle is one emission. The location of the same emission is shown on the bridge. The strain and AE data are used as a Kaiser Effect validation of the emission as a deformation mechanism as opposed to noise and both strain and location correlations provide a basis for a sound evaluation of the use of strain and acoustic emission data for fitness-for service evaluation.

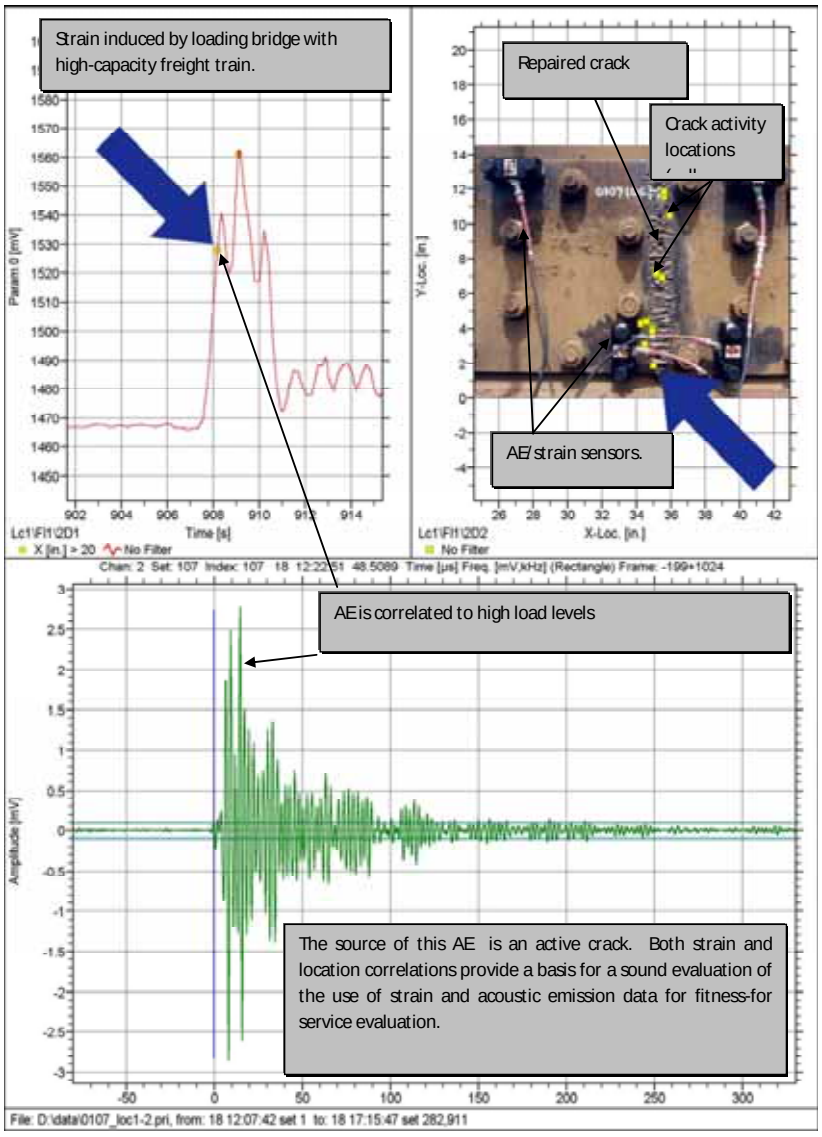

Figure 1. Crack growth detected at high bridge loading.

MEMS AE SENSORS

Conventional acoustic emission transducers contain piezoelectric sensing elements (Figure 2, left). Motion of the structure exerts a force on the bottom of the piezoelectric transducer. The piezoelectric element is strained due to the combined effects of the force exerted by the structure and the inertial effect of the damping layer, resulting in a time-dependent terminal voltage. These transducers are typically designed to exhibit a resonance in the range 100 kHz- 1 MHz. By using a resonant transducer one is able to reject signals from portions of the frequency range that have no relation to damage (for example, structural vibrations). Typically transducers respond to only a portion of the 100 kHz- 1 MHz that contains most of the energy emitted by a crack.

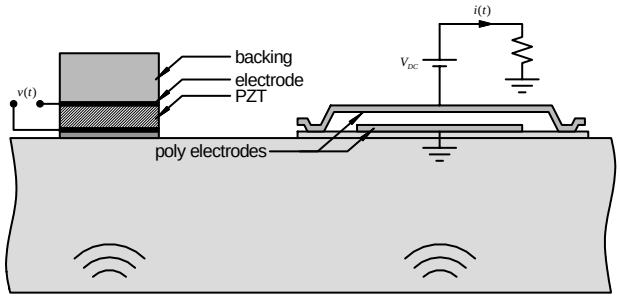

Figure 2. Schematic drawing of acoustic emission transducers: (left) conventional piezoelectric transducer and (right) MEMS transducer.

The MEMS sensor operates in a different way and is similar to the cMUT (capacitive MEMS ultrasonic transducer). Figure 2 (right) shows one element of a MEMS acoustic emission transducer. The transducer consists of an electrode fixed to the substrate and a flexible diaphragm suspended a distance g above. In operation, the substrate is acoustically coupled to the structure. Acoustic waves in the substrate move the bottom electrode with respect to the top diaphragm. When a DC voltage VDC is applied between the two electrodes, motion causes an electric current in the external circuit, In general, a high sensitivity for a given velocity is desired. Consequently for best results the gap should be small, and the bias voltage VDC should be large but below the diaphragm collapse condition. Various resonant frequencies are obtained by altering the effective mass and the span (for transducers suspended along edges) or the spring constants of supports (for piston-type designs). The quality factor Q, which is inversely related to the bandwidth, is determined by the damping and thus the spacing of etch release holes in the top diaphragm.

WIRELESS PLATFORM

The wireless MEMS AE sensing unit consists of 4 sensors and embedded microelectronics. Platform selection was based upon recent testing of a WinS AE piezoelectric sensor with Field Programmable Gate Array (FPGA) technology. The FPGA technology was originally designed by Vanderbilt University for sniper location counter-warfare applications. The application used an array of acoustic microphones to detect and locate snipers using time-of-flight and triangulation techniques. The device sampled acoustic data at 1 MHz which is fast enough for the bridge monitoring application. In 2006, W*in*S shipped a conventional piezoelectric sensor to Vanderbilt University's ISIS center for testing. Standard AE instrumentation calibration tests were undertaken successfully using a mechanical pencil. The pencil lead was pressed firmly against the surface of the steel plate to which the sensor was bonded. An acoustic event was created when the pencil lead broke. The new AEMOTE is shown in Figure 3.

Figure 3. WinS conventional AE sensor attached to wireless 4-channel AE MOTE.

BRIDGE MONITORING

Beyond the standard filtering through analog signal conditioning, the interpretation procedure is based on two AE signal metrics; activity and intensity. In this process, correlation to train loading on the bridge member being monitored plays a key role in the AE source ranking. These metrics are combined to provide an Acoustic Emission Source Index. The Fatigue Crack Index is derived from acoustic emission data in terms of the Acoustic Emission Source Ranking Index and complementary data. The output of the system is a scale of recommendations based on a ranking of the acoustic emission indications combined with other observations and inspections that are incorporated into the Fatigue Crack Index that consists of five levels. The output recommendations corresponding to these FCI levels are shown in **Error! Reference source not found.**.

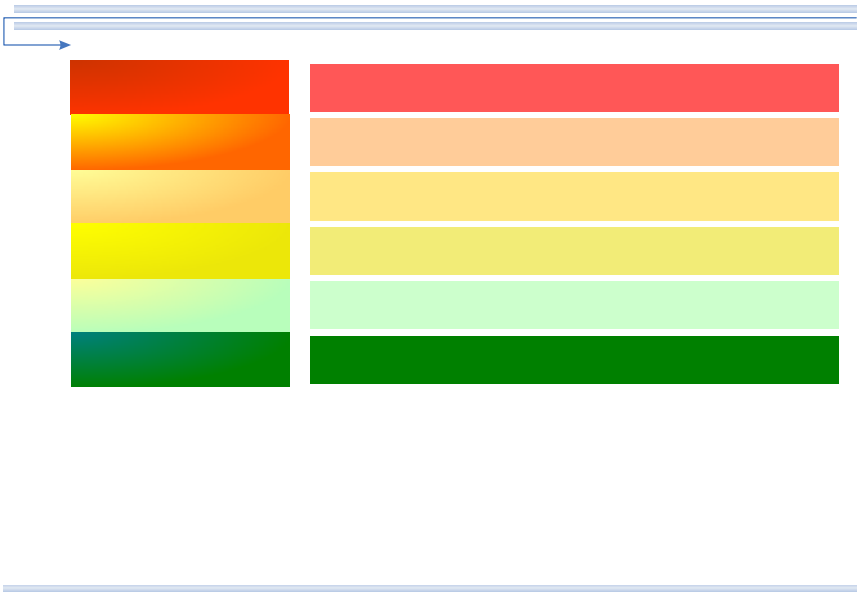

Figure 4. Recommendation schedule for acoustic emission testing.

SUMMARY

This paper describes a new AE platform suitable for intelligent infrastructure applications. The performance specifications for this current system in terms of such set up and data acquisition parameters as frequency range of interest, environmental operating conditions, and gains and thresholds provide a basis for the design of the proposed system are currently being defined. We have defined the output format for the data in terms of acoustic emission and structural integrity indices that will serve as a basis for providing recommendations for maintenance decisions. The system information content and its use in data interpretation and data flow for the system were also summarized. Prototype software has demonstrated the capability to perform data compression to meaningful data that has the potential for generating crack growth rate information. Costing analysis shows that the proposed system has the potential to achieve the targeted 2 order of magnitude reduction in system cost. This ensemble of information provides a basis for full scale development of the remote monitoring technology.

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