IDEA

Innovations Deserving
Exploratory Analysis Programs

High-Speed Rail IDEA Program

Wireless Remote Structural Integrity Monitoring for Railway Bridges

Final Report for High-Speed Rail IDEA Project 54

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TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS MANAGED BY THE TRANSPORTATION RESEARCH BOARD

This investigation was performed as part of the High-Speed Rail IDEA program supports innovative methods and technology in support of the Federal Railroad Administration's (FRA) next-generation high-speed rail technology development program.

The High-Speed Rail IDEA program is one of four IDEA programs managed by TRB. The other IDEA programs are listed below.

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Wireless Remote Structural Integrity Monitoring System for Railroad Bridges

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ABSTRACT

The technical objective of this project was to develop a wireless acoustic emission system to monitor fatigue crack growth rates in steel bridges and to compare its performance with the hardwired technology currently used. The wireless prototype system performance compared favorably with the wired system during field tests on a CN steel railway bridge. A cost comparison that included estimated costs for hardware, installation, and interpretation/reporting by an NDT engineer revealed that the wireless system costs were about one-tenth of those for a comparable wired system.

Acoustic Emission testing is a mature nondestructive testing technology commonly used to detect fatigue cracks in pressure vessels, atmospheric storage tanks, and steel bridges. During an acoustic emission test, the tested structure must be stressed to stimulate fatigue crack growth. If a fatigue crack grows under stress, it will emit a sound wave, also known as an acoustic emission, that travels through the structure. Acoustic emission sensors and instrumentation are designed to detect sound waves emitted from active fatigue cracks while filtering out environmental noise. The rate and intensity of acoustic emission from fatigue cracks is used to characterize crack growth rate. The information may then be used by the bridge engineer to assess the requirement for maintenance action.

KEYWORDS

Acoustic emission, structural integrity monitoring, steel bridge, railroad bridge, wireless, remote monitoring, fatigue crack.

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EXECUTIVE SUMMARY

Acoustic Emission testing is a mature nondestructive testing technology commonly used to detect fatigue cracks in pressure vessels, storage tanks, and steel bridges. During an acoustic emission test, the tested structure must be stressed to stimulate fatigue crack growth. If a fatigue crack grows under stress, it will emit a sound wave, also known as an acoustic emission, that travels through the structure. Acoustic emission sensors and instrumentation are designed to detect sound waves emitted from active fatigue cracks while filtering out environmental noise. The rate and intensity of acoustic emission from fatigue cracks is used to characterize crack growth rate as inactive, active, or critically active. The information may then be used by bridge engineers to assess the requirement for maintenance action.

There are undetected cracks, detected and documented cracks, and repaired fatigue cracks in every steel bridge that Waves*in*Solids has inspected for their clients to date. Based on these inspected bridges and feedback from bridge engineers it is safe to assume that the majority of steel bridges in the U.S contain undetected fatigue cracks, known fatigue cracks with unknown crack propagation rates, and repaired/reinforced fatigue cracks that may or may not be dormant. The proposed technology will offer a cost-effective system to detect and monitor fatigue crack activity in real-time. The wireless device consists of a 4-sensor array and is installed on the fracture-critical bridge member of interest. As trains travel over the bridge the fracture-critical member is stressed. If a fatigue crack is active, it will emit acoustic emission when the structure is subjected to a maximum or near-maximum stress. The sensors detect the acoustic emission and the wireless instrument digitizes the information, analyzes, compresses, and then transmits the filtered information back, through a network of wireless sensors, to a central processing station for review by bridge engineers. Railroad engineers may use the information to load rate bridges and prioritize maintenance action.

The objective of this project was to develop the technology required to transition WavesinSolids' existing wired acoustic emission system to a low-cost wireless system. The wireless system was sought to accommodate the emerging requirement for long-term monitoring and to significantly reduce the overall cost for system implementation. The technology derived from this project may be used to monitor up to ten times more structures at comparable cost than was previously possible with the hardwired technology.

Baseline data was acquired on a steel railway bridge using the hardwired technology. The prototype wireless hardware and proposed sensors were designed and assembled. The performance of the wireless technology was compared with the wired technology in the laboratory. The results showed that the wireless instrumentation could perform the required signal processing at the sensor level and transmit the compressed data back to a remote laptop. Acoustic emission features extracted by the wireless system compared well with those extracted using the hardwired system during the same tests. The wireless system was installed on the same bridge location for evaluation. From a detection, acoustic emission measurement, and source location perspective, the wireless system performance compared favorably with the hardwired system. Waves*in*Solids is now moving ahead to use the wireless system for commercial inspection services.

FIGURE 1 Wired and wireless systems shown on CN's Victoria Bridge in Montreal. The wireless system is shown circled on the metal box that houses the wired system's PC. Shown on top of the metal box are the monitor and keyboard which are required to setup and run the wired system.

DESCRIPTION OF IDEA PRODUCT

BACKGROUND ON FRACTURE CRITICAL MEMBERS IN STEEL BRIDGES

Acoustic emission testing procedures are applied to a number of areas where in-service experience indicates that monitoring attention should be focused. These have been formalized into fracture-critical categories. The concept of fracture-critical members plays an important role in both the design and maintenance of steel bridges. The term fracture-critical is applied to both the bridge and the fracture-critical members on the bridge. A fracture-critical bridge is one that has one or more fracture critical members. A fracture-critical member is a tension member whose failure would result in collapse and catastrophic failure of the bridge. Fracture-critical analysis determines if a bridge is subject to catastrophic failure through fracture and identifies were the fracture-critical members are. This permits inspectors to focus attention on these critical locations during the service life of the bridge and to detect problems well ahead of failure.

The following (abridged from notes by Dr. John Fisher, Lehigh University) outlines some critical points on steel bridges where fatigue cracks are most likely to occur:

(1) At groove welds on flanges, webs, longitudinal stiffeners and between longitudinal stiffeners and intersecting members.

(2) At welded cover plates on flanges of beams and girders.

(3) At ends of various reinforcements or attachments plates welded on girder flanges, webs or truss members. This includes welded splices between parts; lateral gusset plates; repairs using welded doubler plates; attachments for signs, railings and light fixtures.

(4) At diaphragm connections on girder bridges. Cracks may occur at ends of both riveted or welded diaphragm connection plates on girder webs.

(5) At the end connections of floor beams or diaphragms.

(6) At floor beam bracket connections to girder webs and at tie plates between floor beams and outrigger brackets.

(7) At stringer to floor beam connections – **<u>connection angles</u>** for example.

(8) At lateral bracing connections to girders, including gusset plates welded to girder webs or flanges and at welds connecting gusset plates to diaphragms.

(9) At transverse stiffeners.

(10) At box girder diaphragms and connections.

(11) At truss bridge floor beams including connections to verticals and connections to lateral braces. At truss bridge verticals and diagonals especially at verticals near bridge ends and at vertical or diagonal eye bars.

(12) At pin connected links or hangers of multi span bridges. This includes cracks at the edge of pin holes, at the width transition or at the bar edge. Extra attention needs to be given to in-plane bending if the pins and links are frozen as a result of corrosion.

The fracture-critical member monitored during this project was a connection angle with an existing fatigue crack. The role of the connection angle is to connect the stringer to a vertical member. The stringer runs parallel to train traffic. The connection angle is a single unit with perpendicular flanges. The inside corner of the connection angle is filleted. Each connection angle flange has a series of fastener holes through which it is connected to a vertical or horizontal bridge member. The fatigue crack ran down the fillet of the connection angle as shown in Figure 2.

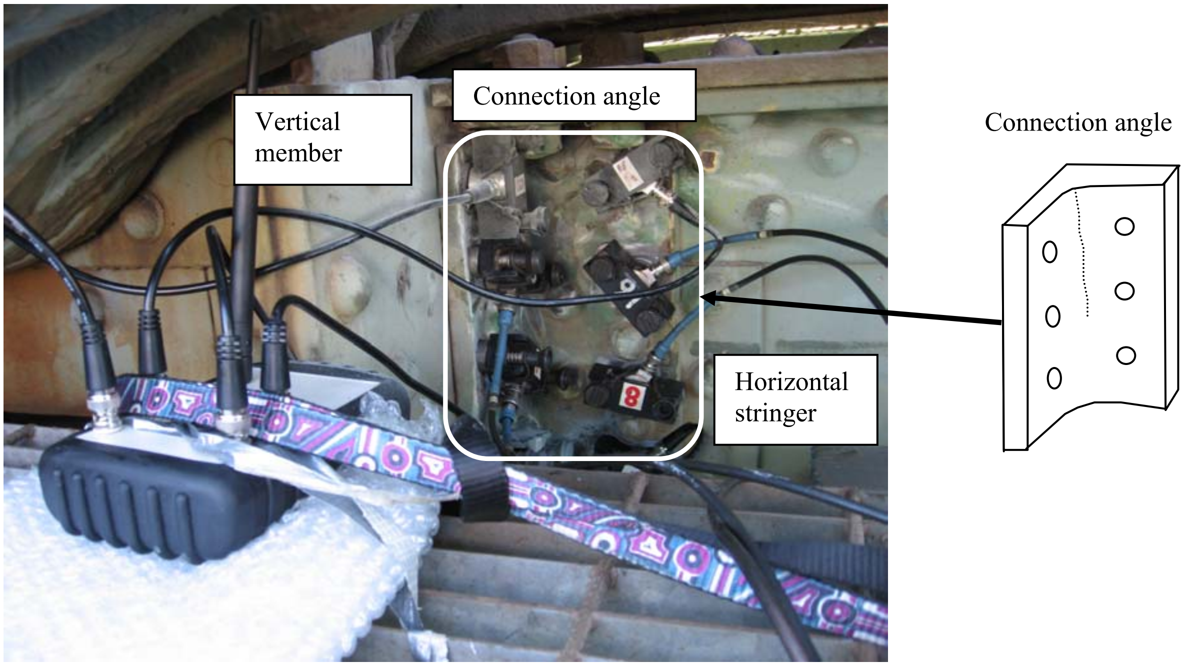


FIGURE 2 The connection angle monitored and a simplified schematic showing that the structure is a 90^o angle with filleted inside corner. The fatigue crack ran vertically down the filleted mid-section.

BACKGROUND ON ACOUSTIC EMISSION

Although fatigue cracks develop in most bridges, in many cases they propagate only a certain distance and become dormant due to stress relaxation. However, when propagation continues, advanced inspection methods can provide the bridge engineer with the additional information required to decide at a specific fracture-critical location whether no further action is required, the location should be monitored more frequently than scheduled inspections, or how soon funds should be allocated for repair or replacement. In such a case, acoustic emission may be used to classify the severity of fatigue cracks in fracture-critical members. It also includes a technique for classifying fatigue crack activity. Acoustic emission results are particularly useful for determining if cracks are stable or growing and whether repairs may be delayed or may not be required. It is a key source of engineering data to enhance safety and ensure ongoing availability, while reducing repair/refurbishment costs.

When a load is applied is to a fracture-critical member with an existing fatigue crack, stress concentration around the crack tip (leading edge of crack) can cause extensive plastic deformation, followed by work hardening, and, eventually, brittle fracture through this hardened area into a more ductile zone beyond the plastic deformation zone. This process repeats itself as the fatigue crack propagates through the member. This is called subcritical crack growth and is a source of acoustic emission. The basic acoustic emission principles are shown in Figures 3 through 5. In Figure 3, acoustic emission is generated from growing fatigue cracks when a fracture critical member is stressed. The growing fatigue crack generates a stress wave, or acoustic emission, that travels through the member. The stress wave is detected by an acoustic emission sensor which converts the mechanical displacement to an electrical voltage which may be displayed using standard data acquisition hardware. In Figure 4, the standard acoustic emission waveform characteristics are displayed. Sensors only detect acoustic emission that exceed the voltage threshold which is displayed as a horizontal line in Figure 4. Acoustic emission from a fatigue crack has a fast rise time (the time between the first voltage crossing and the maximum amplitude). The "duration" is the time elapsed between the first and last threshold crossing, and "counts" are how many times the threshold is crossed. These features are used to characterize crack growth activity. Finally, if the fatigue crack is detected by three or more sensors, it is located using a triangulation technique. The arrival time of fatigue crack acoustic emission will differ based on sensor location. This arrival time difference may be used with the speed of sound in the fracture critical member to calculate the approximate location of the source as shown in Figure 5.

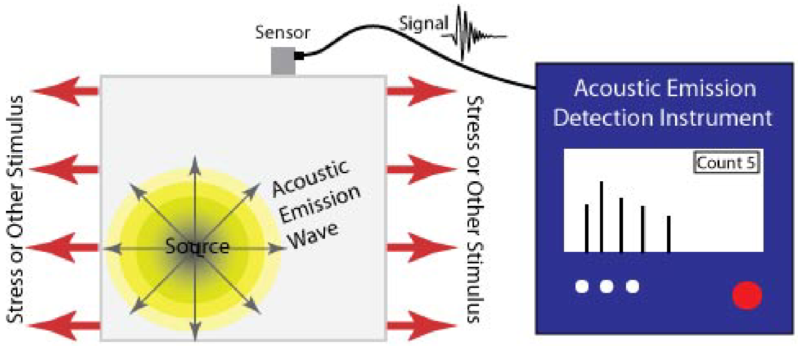


FIGURE 3 Acoustic emission starts off as mechanical energy in the material. The sensors detect and convert the acoustic emission to an electrical voltage which may be displayed using standard data acquisition hardware (www.ndt-ed.org).

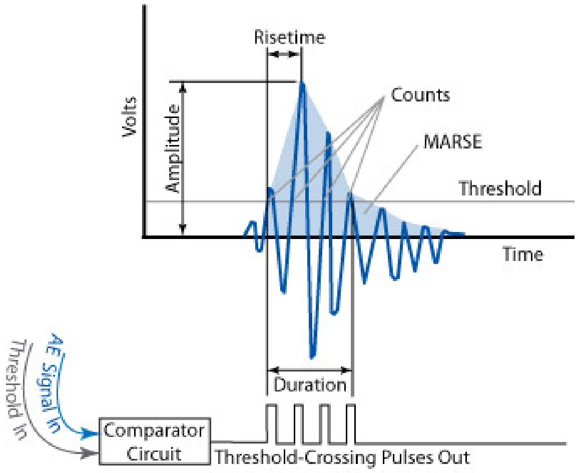


FIGURE 4   Acoustic emission waveforms have common characteristics that may be used to assess crack activity. For instance, an emission with a high number of counts, fast rise time, and long duration suggests higher growth rates as compared to an emission with lower/fewer of these parameters (www.ndt-ed.org).

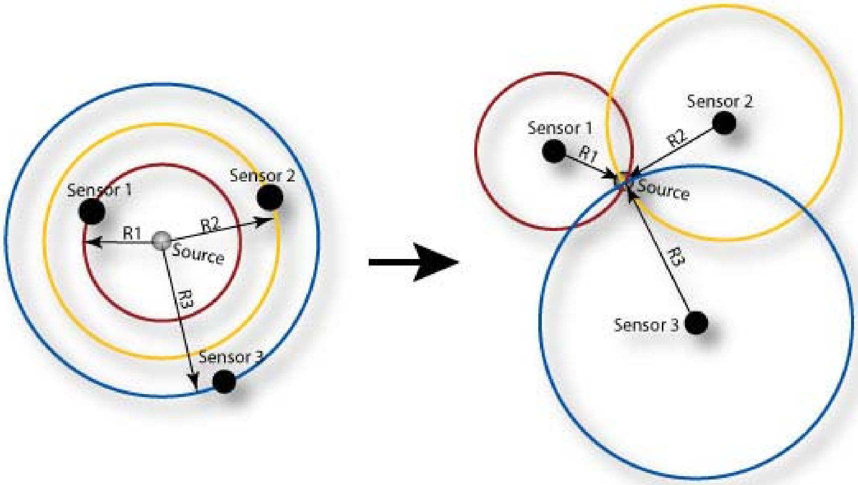


FIGURE 5   The location of a fatigue crack is determined through triangulation techniques. Sensor 1, for instance, detects the emission first followed by sensor 2 and 3. The difference in arrival times may be used to locate the tip of the fatigue crack (www.ndt-ed.org).

BACKGROUND ON THE INSPECTION SERVICE

Before this project began, commercial bridge inspection services were being supplied using WavesinSolids' proprietary hardwired acoustic emission technology. The technology is used to assess the crack growth rates of flaws in steel bridge structures. Inspection results are commonly used to make multi-million dollar maintenance decisions.

The wired version of the technology is currently used to inspect up to about 15 bridges per year per railroad client. Bridges have been monitored from one to thirty days depending on the requirement. Over the last few years, there has been increased demand for long-term, and even permanent installation, of the monitoring technology. Long-term monitoring with the current hardwired technology is cost prohibitive and ties up expensive capital equipment on bridges for extended time periods. The IDEA product was conceived to offer long-term monitoring services at one-tenth the cost through innovations in sensors, hardware, and wireless networks.

The product derived from this project will be marketed under the μSABRE$^{\mathrm{TM}}$ trade name. SABRE$^{\mathrm{TM}}$ is an acronym for **S**tructural **A**coustics for **B**ridge **R**eliability **E**ngineering which is the product name for the hardwired inspection service. μSABRE$^{\mathrm{TM}}$ is the wireless version of the technology designed for long deployments.

μSABRE$^{\mathrm{TM}}$ will be marketed to:

- Major railroads
- Shortline railroads
- Commuter railroads
- State departments of transportation
- Maintainers of federally-owned steel bridges
- International bridge owner/operators

Using this IDEA product, it is forecast that steel bridge maintenance engineers will be able to monitor up to ten times more fracture-critical bridge structures on existing maintenance budgets. This added capability will have a positive impact on transportation practice via improved bridge safety and reliability. The product marketing literature shown in the next two pages is currently being forwarded to existing and potential customers.

Structural Acoustics for Bridge Reliability Engineering

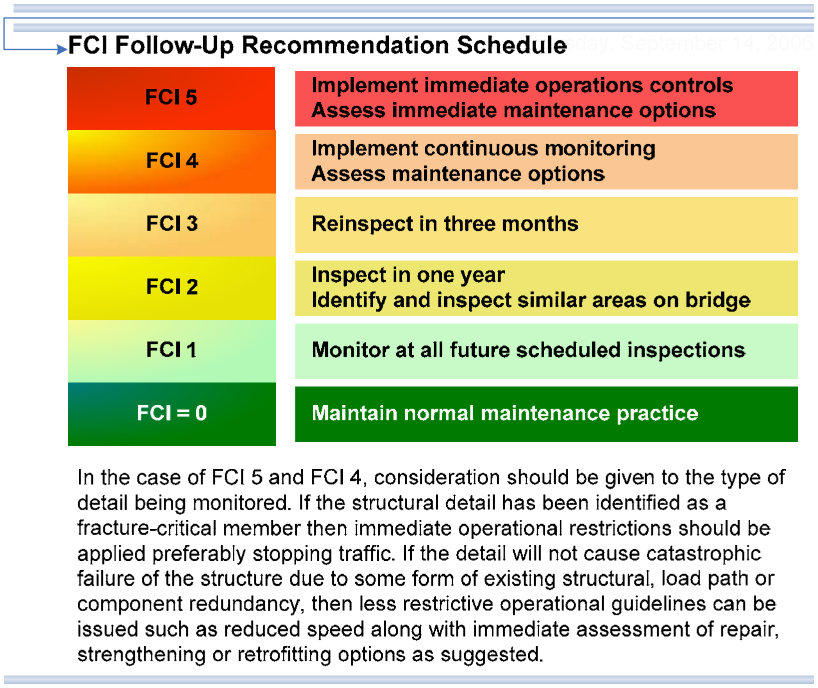
The vast majority of steel bridges currently in use are:

- *well beyond their original design life,*
- *loaded significantly above their original design values,*
- *experiencing premature structural problems from component fatigue.*

Safely extending the life while maximizing load ratings of such railway bridges, and maintaining ongoing, uninterrupted traffic operations, are great economic benefits to the bridge owner. Achieving such goals depends to a large extent on developing and maintaining an effective bridge inspection program.

Active, or growing, flaws in safety critical structures emit acoustic emission (AE) under load while dormant flaws do not emit AE.

SABRE^{TM} ranks active flaws according to activity and intensity and outputs a ***Fatigue Crack Index*** (FCI) between 1 and 5. An FCI 0 recommends maintaining normal maintenance practices. An FCI 5 recommends immediate operations control and maintenance assessment.



FCI Follow-Up Recommendation Schedule

day, September 14, 2006

FCI 5	**Implement immediate operations controls** **Assess immediate maintenance options**
FCI 4	**Implement continuous monitoring** **Assess maintenance options**
FCI 3	**Reinspect in three months**
FCI 2	**Inspect in one year** **Identify and inspect similar areas on bridge**
FCI 1	**Monitor at all future scheduled inspections**
FCI = 0	**Maintain normal maintenance practice**

In the case of FCI 5 and FCI 4, consideration should be given to the type of detail being monitored. If the structural detail has been identified as a fracture-critical member then immediate operational restrictions should be applied preferably stopping traffic. If the detail will not cause catastrophic failure of the structure due to some form of existing structural, load path or component redundancy, then less restrictive operational guidelines can be issued such as reduced speed along with immediate assessment of repair, strengthening or retrofitting options as suggested.

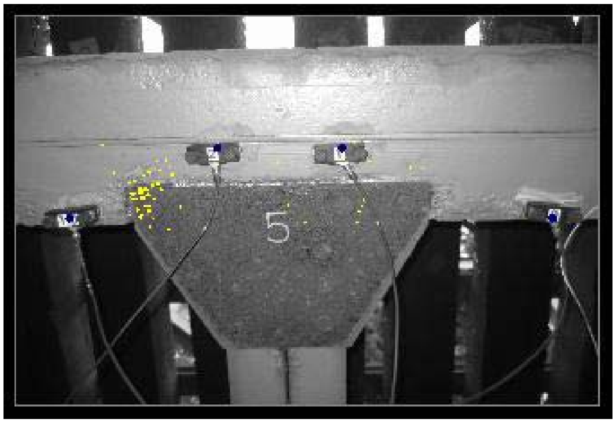
FCIs factor in AE activity, AE intensity, stress correlation, prior test results, and results from back-up visual and ultrasonic nondestructive testing.

μSABRE$^{\text{TM}}$ may be deployed remotely for hours or months depending on the application. For longer monitoring periods, the client can login to μSABRE$^{\text{TM}}$ through a secure on-line connection to observe real-time inspection results. Sensors are rapidly deployed on target structures. Bridge configurations most often monitored include:

- Hanger connections
- Link pin connection
- Copes and stringers
- Stiffener-to-weld connections
- Connection angles
- Repairs to known fatigue cracks

Economic Impact of μSABRE$^{\text{TM}}$ Inspection

In a case study of a 1000-foot long open deck bridge built in 1910 with roughly 33 million gross tons of annual traffic, which is approximately a 115% increase in MGT since its construction, cracks were observed at the bottom of intermediate stiffeners where they connect to the transverse brace frames. The replacement of these spans, estimated at approximately $10 M appeared to be the inevitable recourse. AE monitoring carried out by SABRE$^{\text{TM}}$ assessed the crack activity levels of critical areas. It was possible to delay replacement and adopt a manageable risk strategy to maintain existing and projected levels of safe train operations.



CONCEPT AND INNOVATION

In North America, there are two main suppliers of acoustic emission steel bridge monitoring services; Waves*in*Solids and Physical Acoustics Corporation. Both companies offer “remote” monitoring capabilities which are based on locally mounted sensors wired back to a compact PC. Communication with the “remote” system is accomplished via a modem or WLAN using a centralized PC. While the technology is referred to as “remote”, hundreds of feet of wiring and significant installation labor are still required to interface the sensor to the remote PC. The basic remote monitoring hardware is shown in Figure 6. On the left are the 4-channel acoustic emission data acquisition PCI cards. The boards are mounted in the remote PC shown on the right to which the sensors are hardwired. In many cases, 30 to 100 feet of cable is required to link the AE sensor to the remote PC as shown in Figure 7. In this figure, four 100 foot BNC cable bundles (top left), the cable bundles along the bridge deck up to the railroad ties where they are fed underneath the bridge (middle), and the same cabling to a 4 sensor array installed around a repair on a known fatigue crack (bottom middle) are shown.

- ***WinS estimates that wired sensor installation including the wires and technician labor required to install the wired sensors accounts for 30 to 40% of total bridge direct labor inspection cost.***

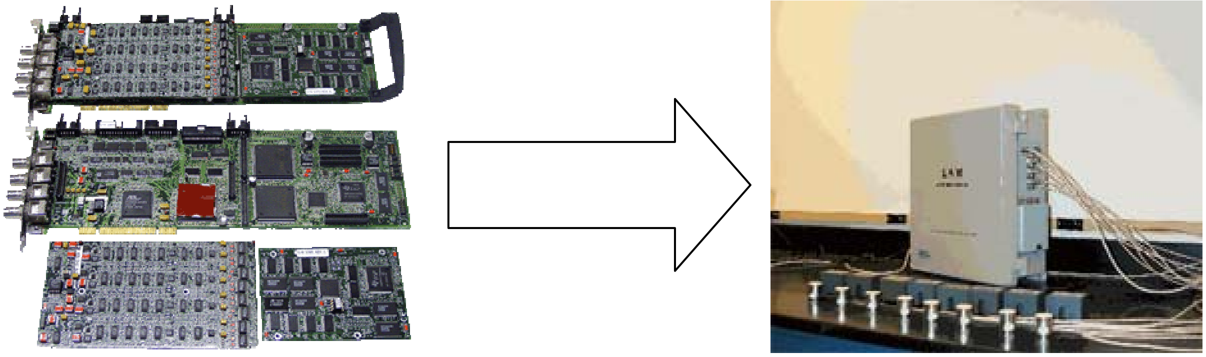


FIGURE 6 Current remote acoustic emission monitoring technology requires sensors to be hardwired into a local instrument installed on the bridge. The instrument houses PCI BUS based acoustic emission data acquisition cards. A local CPU is also required increasing power consumption. This configuration is what is currently being referred to as “remote” or as a wireless acoustic emission solution.

FIGURE 7 An example of cabling required for bridge testing with commercial acoustic emission technology. Left – Four 100-foot BNC cable bundles; middle – multi-channel BNC cable along bridge deck and sub-deck; right – continuation of cable sub-deck with required cable harnessing. It is estimated that wired sensor installation including the wires and technician labor required to install the wired sensors accounts for 30 to 40% of total bridge inspection cost.

As shown above, the acoustic emission testing marketplace is dominated by big, bulky and expensive instrumentation. Embedding existing acoustic emission technology on structures requires significant capital investment. A single sensor costs between \$300 to \$900 (based on quotes from Physical Acoustics Corporation, Inc.) and multi-channel instrumentation from \$20,000 to \$100,000 depending on the number of channels. Based on the published prices of conventional acoustic emission sensors and instrumentation, and the sensor volumes for smart infrastructure, new acoustic emission technology is required. To be accepted by clients, and ultimately integrated into routine maintenance practice, the technology must be deliverable with comparable performance at one tenth the cost, size and weight.

The objective of this TRB project, therefore, was to develop and demonstrate the core technology required to monitor steel bridges affordably using wireless sensor communication, new acoustic emission instrumentation, and by transferring the burden of inspection interpretation from the trained human inspector to embedded hardware intelligence at the sensor level.

INVESTIGATION

The project was divided into the following three stages:

STAGE I

Baseline Data Acquisition

Initial field testing was carried out on a railroad steel bridge using a conventional PC-based acoustic emission system to gather baseline data from known flaws. The sensors were mounted on fracture-critical areas for detection of acoustic signals emitted by active flaws. Baseline data was acquired on the Victoria Jubilee Bridge owned and operated by CN Rail. The bridge is located in Montreal, Canada. Acoustic emission data was acquired with WinS' existing PC-based instrumentation at locations selected by CN's Bridge Engineer. Baseline data was kept on file for benchmarking the performance of the wireless system developed during Stage II and tested during Stage III.

System Specification

A detailed performance specification was developed for the μSABRE^{TM} system including overall system functional requirements and specifications for the data acquisition, data processing and communications hardware, the system software and the data interpretation procedures. This task included identification of a suitable microelectronics hardware platform for the wireless AE (Acoustic Emission) sensing unit.

Preliminary System Costing Analysis

A preliminary costing analysis comparing the cost of a conventional system (SABRE^{TM}) with the prototype system (μSABRE^{TM}) defined in the system specification section was performed. Costing analysis comprising capital investment for instrumentation procurement was undertaken. System costing was based on the microelectronics specification developed. Suppliers for the individual microelectronics components were identified and pricing of the various components was obtained for large quantity orders.

STAGE II

Package and Characterize Sensors

The MEMS transducers were bonded to packages selected for good acoustic coupling to structures, and were characterized electrically in their unloaded state. The transducers were then integrated with custom preamplifiers, within housings that provide electrical shielding and the means of mechanical mounting to structures.

The packaged and housed transducers were then characterized for sensing performance using simulated acoustic emissions.

Develop Dedicated System Hardware

This task included the following:

- Software development: The software required to manipulate the acoustic emission data from the acoustic emission MEMS sensor unit was developed.
- System components integration: The MEMS acoustic emission sensors, sensor microelectronics, and software were integrated into a single sensing unit called a MOTE. The MOTE consists of the MOTE sensors, a tiny microcomputer with a CPU, memory, power source, and radio transmitter.
- Demonstration of system in laboratory: The integrated system's ability to acquire, digitize, store, and transmit data wirelessly was confirmed in the laboratory environment.

STAGE III

Optimize and Ruggedize System

The integrated system developed in Stage II was packaged in rugged and shielded housing for bridge testing.

Install Prototype and Conventional System on Bridge

The integrated prototype and conventional systems were installed on the selected bridge to acquire data.

Monitor Systems

Both systems monitored acoustic emission activity on the bridge and standard acoustic emission data features were compared. These features included sensitivity, signal-to-noise, ruggedness, susceptibility to EMF noise, etc.

Update Costing Analysis

Costing analysis of the prototype system was updated based on feedback from the field tests.

SUMMARY OF PROJECT FINDINGS

The project may largely be summarized by the Stage III field test results. The objective of this stage was to benchmark the wireless system against the wired system. This was accomplished by comparing acoustic data acquired by both systems in terms of *activity* and *intensity*. Activity is defined in terms of acoustic events that are detected inside the sensor array by all four sensors. Intensity is defined as the average signal strength of the acoustic events in dB. The activity and intensity values are combined to assign an AE Index between 1 and 4 which is one of the input parameters used to determine the Fatigue Crack Index which is described on page 12. Wireless data transmission over 25 meters was the benchmark wireless distance.

TESTED STRUCTURE

The tested connection angle is shown in Figure 8. The location reference point was towards the top right of the connection angle. The wireless MOTE sensors were located as shown below. The wired system sensors are shown inside the wireless MOTE sensors. A comparison of the wireless and wired monitoring systems installed on the bridge is shown in Figures 8 and 9.

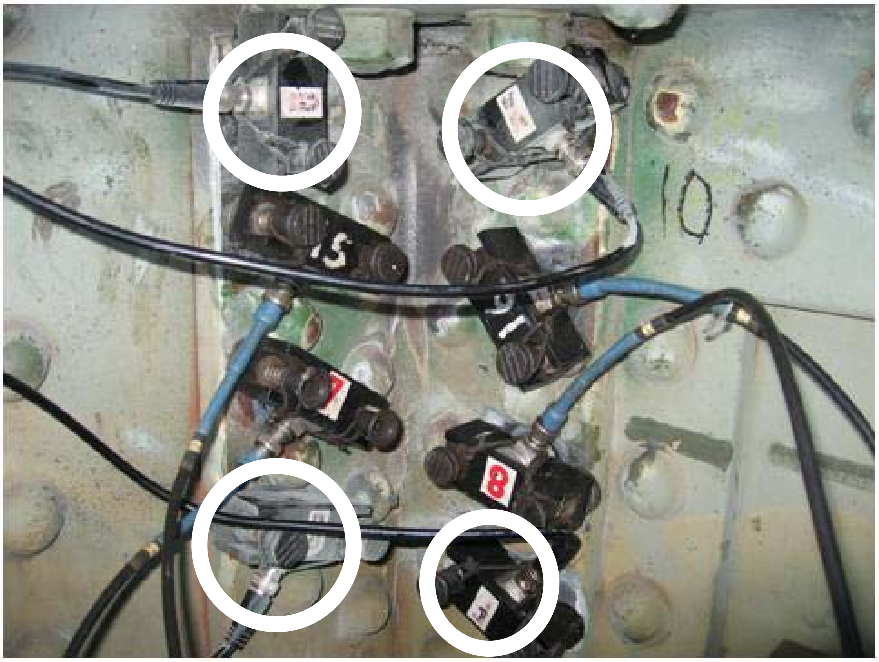


FIGURE 8 Instrumented connection angle with the wireless MOTE sensors circled. The wired system's sensors are inside the wireless array.

FIGURE 9 Wired and wireless systems shown in CN's Victoria Bridge. The wireless system is shown circled on the metal box that houses the wired system's PC. Shown on top of the metal box are the monitor and keyboard which are required to setup and run the wired system. The wireless MOTE is activated via a remote laptop.

FIGURE 10 Wireless MOTE secured adjacent to the connection angle monitored.

INSPECTION RESULTS AND INTERPRETATION

Inspection results are summarized for the wireless and wired monitoring system in this section. The wireless system results are compared to the wired system results that were recorded concurrently. The wireless results are also compared to the results from the original wired tests undertaken during Stage I. It should be noted here that SABRE's ability to detect and characterize acoustic emission from fatigue cracks was validated in the late 1990s through an internally funded research and development project. During this project, notches were introduced into fracture critical bridge members at stress concentration zones. These components were cyclically loaded to initiate fatigue crack growth at the notches then further loaded until failure. The structures were instrumented with acoustic emission sensors during these tests. These tests showed clearly that SABRE could reliably detect acoustic emission from growing fatigue cracks, could locate fatigue cracks, and discriminate between acoustic/electrical noise and acoustic emission from fatigue cracks.

The results are compared in terms of:

- **Activity:** The number of events that occur within the sensing array. For an acoustic source to be classified as an event, it must be picked up by all four sensors and originate from inside the array. Activity may be classified as ***Critically Active*** if events are observed consistently at peak load, ***Active*** if randomly observed over the load spectrum, and ***Inactive***.

- **Intensity:** The average amplitude, in dB, of the events. Acoustic emission may be classified as ***Low Intensity*** (< 50 dB), ***Intense*** (50 - 75 dB), and ***Critically Intense*** (> 75 dB).

A Fatigue Crack Index (FCI) is assigned to the structure for each test based on the measured activity, intensity levels, and correlation with back-up nondestructive methods. The objective of the interpretation was to compare the FCIs generated by the wired and wireless systems. The interpretation procedure is proprietary and, for this reason, is not presented in detail in this report.

The events recorded by the wireless system are shown in Figure 11. In this figure, five different train passes are observed. The events recorded inside the array are superimposed upon the Train 1, 2-3, and 5 strain curves. Note that there was some overlapping of trains 2 and 3 as they passed over opposite tracks. For this analysis they were treated as a single train. No events were recorded for train 4 by either the wired or wireless systems. These events are considered randomly distributed over the load spectrum since they are not consistently observed at peak load for all trains. These events were further analyzed for intensity levels.

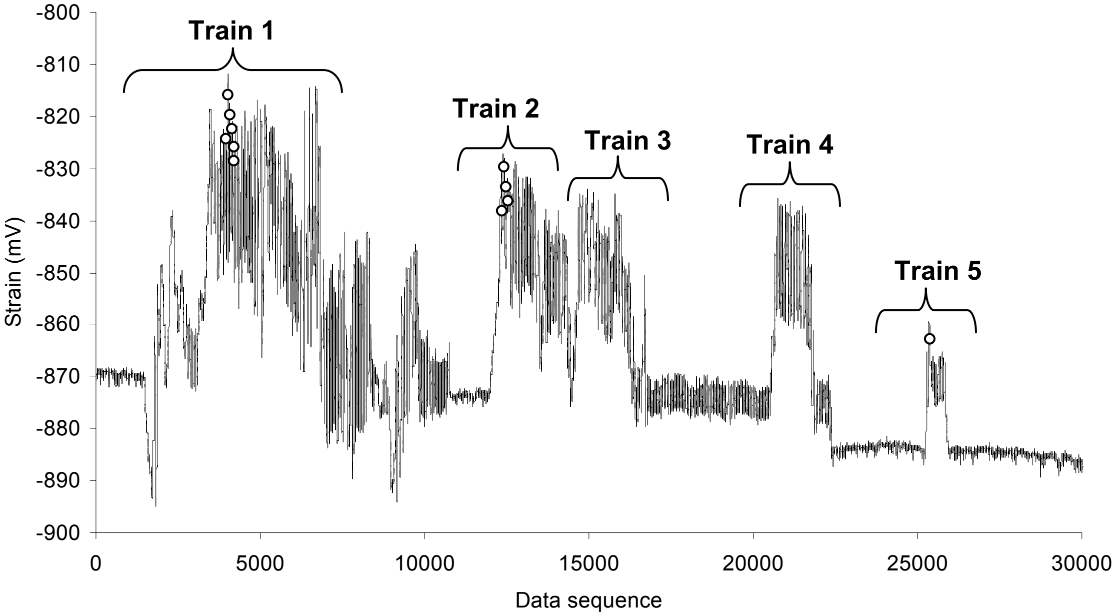


FIGURE 11 Strain measurements showing the 11 superimposed acoustic emission events at peak load for trains 1, 2 and 3, 4 and 5. In this instance, the events are considered randomly distributed over the load spectrum and are assigned an *Active* ranking. The average intensity of the events is over 50 dB which ranks as Intense. Based on these rankings and the observed fatigue crack by back up NDT, the structure was assigned an FCI of 3.

A summary of the Activity, Intensity, and Fatigue Crack Index for the wireless test and the 2 wired tests (2007 and 2006) is shown in Table 1. The wireless system detected a total of 11 events over 5 train passes at an average intensity of 52 dB. For the same 5 trains, the wired system detected 9 events at an average intensity of 54 dB. The acoustic emission Index for both monitoring systems was 2 ~ *Intense*. The activity was rated as *Active* for both systems as well since events were not consistently observed at peak load. Based on these rankings, the structure was assigned an FCI of 3. The 2006 wired test gave the same ranking for intensity but events were observed consistently at peak load. The activity was ranked as critically active which corresponds to a FCI of 4.

Table 1 demonstrates that the wireless system detects acoustic emission from active flaws on bridges with comparable sensitivity to the wired system. For train 1, the wireless and wired systems detected 6 and 5 events from within the array. These numbers are close enough to suggest that the two systems are performing comparably since a missed event may be attributed to sensor location, surface preparation, and sensor coupling to the structure. Similarly, the average intensities are comparable. The 4 dB difference, again, is well within the realm of the practical considerations cited above.

The results from trains 2-3 also indicate that the wireless system is detecting the same events the wireless system is detecting. Both systems detected 4 events inside the array at comparable intensities ~ 51 dB (wireless) and 58 dB (wired).

Train 4 results suggest further that the wired and wireless systems are performing comparably since neither array detected any events.

Finally, the train 5 result shows that the wireless system detected one event while the wired system did not pick up anything. The result is not indicative of sensitivity differences between the two instruments. It is again suggestive that sensor location, surface preparation, and acoustic coupling will have minor influences on activity and intensity.

TABLE 1 Summary of wireless and wired system tests.

	Nov. 2007 Microsabre Test (wireless)	Nov. 2007 Sabre Test (wired)	2006 Sabre Test 10 days of testing
	Train 1		
Events	6	5	
Avg Intensity (db)	50	54	
AE Index	AE Index 2	AE Index 2	
	Train 2-3		
Events	4	4	545
Avg Intensity (db)	51	58	58 dB
AE Index	AE Index 2	AE Index 2	AE Index 2
	Train 4		
Events	0	None 0	
Avg Intensity (db)	N/A	N/A	
AE Index	N/A	N/A	
	Train 5		
Events	1	None 0	
Avg Intensity (db)	54	N/A	
AE Index	AE Index 2	N/A	
NDT Detects Cracks	**YES**		**YES**
Fatigue Crack Index (FCI)	FCI 3	FCI 3	FCI 4

The only discrepancy in test results is found by comparing the activity of the 2006 wired test with that from the wireless test. In the 2006 wired test, there were 545 events over 10 days, which was considered consistently active at peak load. An AE Index of 3 was therefore assigned which translated to an FCI of 4. The best available explanation for this observation is that a higher percentage of trains ran on the track adjacent to the connection angle tested during the 2006 wired test.

A location comparison of the events is shown in Figure 12 using yellow and white boxes for the wired and wireless systems, respectively. In the connection angle shown, there is commonly a 1-3" location error due the actual connection angle and multiple fasteners in the joint. These features affect line-of-sight between the sensor and acoustic source as well as the sound wave velocity, both of which, influence accurate source location. The events, however, are located in the vicinity of the crack tip (leading edge of crack) and are within the margin of location error associated with connection angles. Location error may be attributed to the fasteners that obstruct the direct propagation of acoustic emission from fatigue cracks to the sensors.

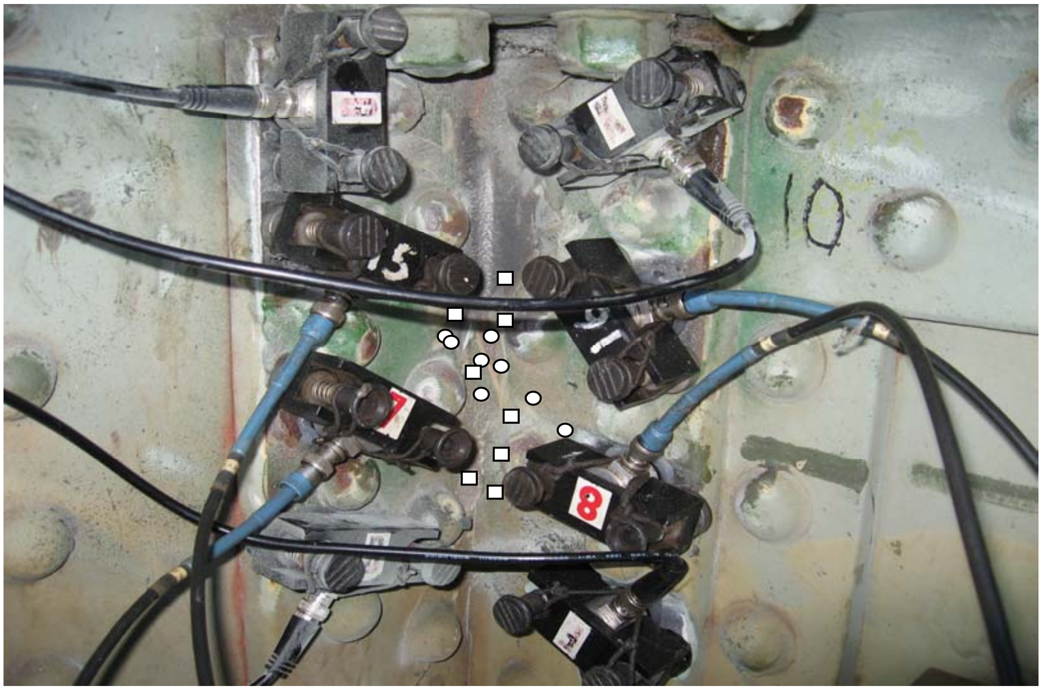


FIGURE 12 Estimated location of wired (circles) and wireless (squares) events showing that all the events are clustered in an approximate 3" x 2" area on the connection angle.

SYSTEM COSTING ANALYSIS – SABRE^{TM} VS. μSABRE^{TM}

In this section, a revised costing analysis for the commercial version of μSABRE^{TM} is presented. Costing is provided for the monitoring of the Victoria Bridge and compared with the documented costs for SABRE^{TM} installation. The analysis considers the following cost factors:

- Monitoring system installation direct labor
- Monitoring system direct materials
- Reporting and interpretation direct labor

Monitoring System Installation Costs

In many cases, 30 to 100 feet of cable is required to link the acoustic emission sensor to the remote PC as shown in Figure 7. In this figure we see four 100-foot BNC cable bundles (left), the cable bundles along the bridge deck up to the railroad ties where they are fed underneath the bridge (middle), and the same cabling to a 4 -sensor array installed around a repair on a known fatigue crack (right).

The installation costs are shown in Table 2 below. Setup of the wired system on the Victoria Bridge connection angle took approximately 3 hours. The majority of this time was dedicated to running cable under ties, rail, and sub-deck to access the desired fracture-critical member. Installation of the wireless system took approximately 0.5 hours.

The wireless system performs automated feature extraction at the sensor and transmits this information back to a remote laptop for review. The wired system transmits waveforms back to the field PC from which signal features need to be extracted by a technician using software tools. The interpretation and reporting of the wired system inspection data took approximately 8 hours. Interpretation and reporting of wireless inspection data took two hours for the same test.

The wired and wireless hardware costs for the Victoria Bridge connection angle are shown towards the bottom of Table 2. The wired cost estimate is $13,850. The majority of this cost is incurred by legacy hardware which includes the 4-channel PC card and ruggedized computer. Legacy hardware refers to the personal computer based acoustic instrumentation that has been used for the last two decades by the majority of the acoustic emission inspection service providers. The wireless equipment cost reflects the hardware required to support a full commercial version of the technology. The wireless hardware cost, which now includes 4 piezoelectric sensors, is estimated at $1,290 compared to $13,850 for the wired version. The customized hardware developed during the course of this project is up to one tenth cheaper than the conventional system being used.

TABLE 2 Wired and wireless bridge inspection cost estimates including setup/teardown, interpretation/reporting, and instrumentation costs for the Victoria bridge connection angle.

Wired Setup/Teardown						**Wireless Setup/Teardown**					
Technician	3	hrs	@	$ 59	$ 176	Technician	0.5	hrs	@	$ 59	$ 29
Helper	3	hrs	@	$ 52	$ 156	Helper	0.5	hrs	@	$ 52	$ 26
				Total	**$ 332**					**Total**	**$ 55**
Wired System Interpretation/Reporting						**Wireless System Interpretation/Reporting**					
NDT Engineer	8	hrs	@	$ 65	$ 520	NDT Engineer	2	hrs	@	$ 65	$ 130
				Total	**$ 520**					**Total**	**$ 130**
Revised Wired Hardware Cost						**Revised Wireless Hardware Cost**					
4-channel PC card	1	unit	@	$7,000	$7,000	Wireless OEM	1	unit	@	$ 50	$ 50
Rugged PC	1	unit	@	$5,000	$5,000	FPGA	1	unit	@	$ 80	$ 80
Sensor/pre-amp	4	unit	@	$500	$500	A/D channels	5	unit	@	$ 10	$ 50
Cabling	4	unit	@	$150	$150	Op-amps	5	unit	@	$ 2	$ 10
Wireless card	1	unit	@	$1,200	$1,200	PSRAM	1	unit	@	$ 10	$ 10
				Total	**$13,850**	SD Memory	1	unit	@	$ 5	$ 5
						USB Interface	1	unit	@	$ 10	$ 10
						Power circuits	1	unit	@	$ 15	$ 15
						BNCs	4	unit	@	$ 5	$ 20
						Antenna	1	unit	@	$ 20	$ 20
						Enclosure	1	unit	@	$ 20	$ 20
						PCB + Assembly	1	unit	@	$ 200	$ 200
						Sensor	4	unit		$ 200	$ 800
										Total	**$ 1,290**
Total Cost per Installation				**$ 14,702**		**Total Cost per Installation**				**$ 1,475**	

SUMMARY OF TEST RESULTS

In Stage III, the wireless acoustic emission MOTE developed and tested in Stage II was installed on CN's Victoria Bridge. Data were acquired on a previously-monitored connection angle (2006 tests). Test data that was acquired with the wireless system at distances up to 30 meters from the sensors compared well with that from the wired system. The wireless system detected a total of 11 acoustic events inside the sensor array for 5 train passes. The wired system detected 9 events for the same trains. The average intensity of the events detected by the wireless system was 52 dB compared to 56 dB for the wired system. Based on these *activity* and *intensity* levels, both the wireless and wired systems assigned the structure a Fatigue Crack Index (FCI) of 3. The results were also compared to the wired system baseline test undertaken in 2006. The wireless results matched in terms of intensity but a decrease in activity was observed. This was attributed to a higher percentage of trains passing on the track adjacent to the location monitored during the 2006 tests. From a detection, acoustic emission measurement, and source location perspective, the wireless system performed comparably to the hardwired system. This comparison is based upon analysis of the number or acoustic emission events detected and the average intensity of the events detected.

The sensor level feature extraction microelectronics performed as specified during the course of the test. The acoustic features required for analysis were successfully extracted at the sensor and cued for wireless transmission. The waveform features were successfully transmitted using the wireless MOTE to a laptop located approximately 30 meters from the sensors.

The revised cost analysis showed that it cost approximately $15,000 to monitor the connection angle on the Victoria Bridge using the wired technology. The revised wireless estimate, using piezoelectric sensors, showed that the same test with the wireless system would cost approximately $1,500. The low-cost wireless technology developed during this project may permit bridge owners to monitor up to ten times as many critical areas at current bridge maintenance budgets.

TECHNOLOGY LIMITATIONS

An objective of this project was to develop and evaluate the feasibility of using capacitive MEMs acoustic emission sensors as an alternative to the piezoelectric sensors used currently. The MEMS sensors showed potential to be manufactured at one tenth the cost of the piezo sensors. Before this project, however, their sensitivity to acoustic emission generated from flaws in bridges was largely unknown. Two MEMS development cycles were undertaken by Carnegie Mellon University at significant cost.

In the first cycle, they fabricated an unsealed device. The MEMS sensor, manufactured using the PolyMUMPs process, is a capacitive device that consists of many tiny membranes. The membrane top and bottom plates are plated electrodes. Therefore, each tiny membrane behaves like a capacitor. During the fabrication process, a gap must be etched out from the polysilicon substrate using the etchant holes shown in Figure 13. It is desirable to not seal and evacuate the membrane cavity from a cost perspective due to the additional process steps. The unsealed – non-evacuated device, however, will have lower sensitivity compared to the sealed – evacuated device. Stage II tests showed that the unsealed – non-evacuated sensor did not detect acoustic emission from the steel test specimen. Greater sensitivity was sought in order to detect acoustic emission events coupled from a steel structure and to support the objectives of this project.

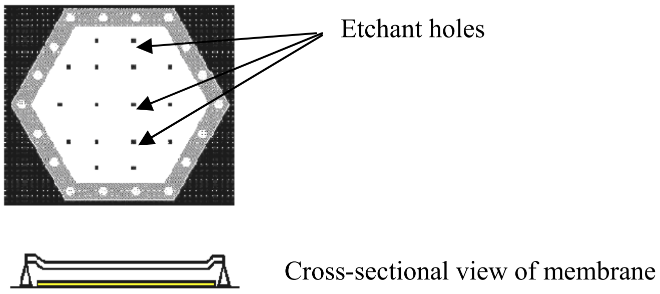


FIGURE 13. A close-up of a MEMS membrane showing the etchant holes used to access the polysilicon substrate. In the open membrane configuration, the membrane cavity is not evacuated and sealed in a vacuum. Membrane vibration, therefore, is damped by atmospheric pressure decreasing the overall sensitivity of the sensor.

In the second cycle, the MEMS sensor membranes were vacuum sealed to increase sensitivity. In this task, a hole is drilled in the solder seal lid, the perimeter of the lid is then soldered to the packaging, and a small amount of solder is dropped around the hole. The whole package is then moved to the vacuum chamber. A soldering iron, installed in the vacuum chamber, can move upwards and downwards.

After the vacuum chamber reaches the desired pressure, the soldering iron is turned on and the solder around the hole is melted, sealing the hole in the lid. After the solder cools, the package is removed from the vacuum chamber. Figure 14 shows the admittance measurements of a 500 kHz transducer, showing the sharper resonance obtained in vacuum as compared to atmospheric pressure. The sharper resonance remains unchanged after several weeks, indicating good hermeticity.

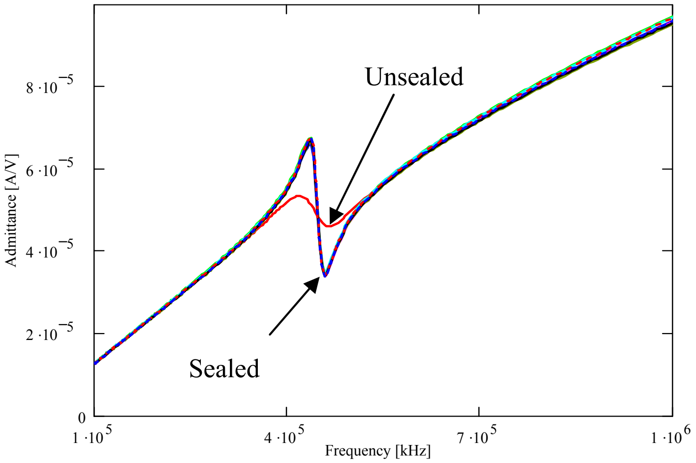


FIGURE 14 Measurements of the admittance magnitude as a function of frequency for 500 kHz transducer: atmosphere pressure in sealed and unsealed state.

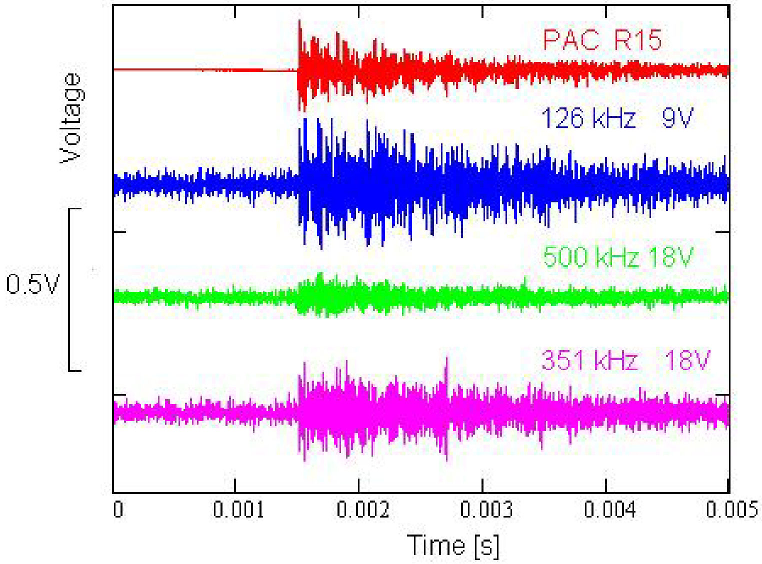


FIGURE 15 Waveforms generated from same simulated acoustic emission source for PAC R15 piezoceramic sensor (top), 126 kHz MEMS sensor (2nd down – 9V DC bias), 500 kHz MEMS sensor (3rd down – 18V DC bias), and 351 kHz MEMS sensor (bottom – 18V DC bias). The 126 kHz and 351 kHz MEMS sensors show comparable signal amplitude to the piezoceramic sensor. MEMS noise levels, however, are significantly higher.

The relative sensitivity of the MEMS sensor was calculated using the waveforms in Figure 11. From top to bottom, the waveforms were acquired using a PAC R15 piezoceramic sensor, 126 kHz MEMS sensor biased with 9 Volts, 500 kHz MEMS sensor biased with 18 Volts, and 351 kHz MEMS sensor biased with 18 Volts. All waveforms were acquired from the same simulated acoustic emission source. The maximum amplitude of the MEMS 126 and 351 kHz sensors, observed at approximately 0.0015 seconds, is comparable to that of the piezoceramic sensor. The baseline noise observed in the MEMS sensors, however, is approximately 4 times higher than that observed in the piezoceramic sensor. The signal-to-noise ratio (SNR) for all sensors is compared in Table 3. The SNR for the piezoceramic sensor was twice the SNR measured for the MEMS sensors. Bridge testing was undertaken with the sealed MEMS sensor but meaningful acoustic emission signals were not detected by the MEMS sensors. The piezo sensors, however, did detect acoustic emission from the instrumented connection angle. At this point in the product development, WinS will adopt the wireless platform with the piezoelectric sensors, until such time that the MEMS capacitive sensors demonstrate at least comparable sensitivity.

TABLE 3 Comparison of piezoceramic and MEMS sensor maximum signal amplitude, noise level, and SNR.

	Max Amplitude (Volts)	Noise Average (Volts)	SNR (dB)
PAC R15	0.500	0.031	24
MEMS 126 kHz	0.563	0.125	13
MEMS 500 kHz	0.250	0.063	12
MEMS 351 kHz	0.500	0.125	12

PLANS FOR IMPLEMENTATION

Clients are ready to adopt the wireless technology once it has been subjected to more long-term testing. The technology will have be to installed along side the wired technology for an entire bridge testing season before it can be used independently. Our engineers must document the performance of the new technology to show that it provides comparable results on a consistent basis under a wide range of field test conditions. In is anticipated that this process will take 6 to 12 months. At the end of this period, the wired system will be phased out and replaced by wireless technology.

Moving forward, the current platform will also be considered for use with sensors that may have applications beyond fatigue monitoring. These could include sensors capable of detecting local seismic activity and low frequency bridge vibration. Applications for these sensors could include earthquake detection, flood detection, and bridge damage due to impact. Sensors for these applications may include geophones accelerometers, and a variety of fiber optic sensors.

GLOSSARY

Acoustic emission (AE): Transient stress waves generated by active fatigue cracks in steel bridge fracture critical members.

Acoustic emission activity: The number of acoustic emissions detected inside the sensor array by at least 3 of the sensors.

Acoustic emission intensity: Intensity is defined as the average signal strength of the acoustic emission in decibels (dB).

Acoustic emission index (AE Index): This is a composite value that based upon the observed acoustic emission activity and intensity. The AE Index ranged from 1 to 4 and contributes to the calculation of the Fatigue Crack Index.

Fatigue crack index (FCI): The output from WinS' proprietary acoustic emission bridge inspection procedure that provides recommended maintenance action and re-inspection interval.

Fatigue critical member: A fracture-critical member is a tension member whose failure would result in collapse and catastrophic failure of the bridge.

Legacy hardware: Acoustic emission hardware that has been used by the majority of the inspection service providers for the last two decades. The hardware is hardwired to sensors and requires a personal computer for operation.

MEMS: MicroElectric Mechanical System

MOTE: Short for remote. A wireless MOTE system contains sensors, its own CPU, memory, power source, and RF transmitter.

Noise: Unwanted acoustic phenomena that may originate from mechanical and/or electrical sources. Sources include crack face rubbing, mechanical friction, and electromagnetic sources.

PolyMUMPs: A commercial MEMS fabrication process.

SABRE^{TM}: An acronym for **S**tructural **A**coustics for **B**ridge **R**eliability **E**ngineering, the trademark name under which WinS markets and sells steel bridge acoustic emission inspection services.

Source location: The procedure by which acoustic emission sources are located in fracture critical components through analysis of emission arrival times at the individual sensors.

μSABRE^{TM}: The wireless version of SABRE^{TM} an acronym for **S**tructural **A**coustics for **B**ridge **R**eliability **E**ngineering