Structural Tests using a MEMS Acoustic Emission Sensor

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ABSTRACT

In a collaborative project at Lehigh and Carnegie Mellon, a MEMS acoustic emission sensor was designed and fabricated as a suite of six resonant-type capacitive transducers in the frequency range between 100 and 500 kHz. Characterization studies showed good comparisons between predicted and experimental electro-mechanical behavior. Acoustic emission events, simulated experimentally in steel ball impact and in pencil lead break tests, were detected and source localization was demonstrated. In this paper we describe the application of the MEMS device in structural testing, both in laboratory and in field applications. We discuss our findings regarding housing and mounting (acoustic coupling) of the MEMS device with its supporting electronics, and we then report the results of structural testing.

In all tests, the MEMS transducers were used in parallel with commercial acoustic emission sensors, which thereby serve as a benchmark and permit a direct observation of MEMS device functionality. All tests involved steel structures, with particular interest in propagation of existing cracks or flaws. A series of four laboratory tests were performed on beam specimens fabricated from two segments (Grade 50 steel) with a full penetration weld (E70T-4 electrode material) at midspan. That weld region was notched, an initial fatigue crack was induced, and the specimens were then instrumented with one commercial transducer and with one MEMS device; data was recorded from five individual transducers on the MEMS device. Under a four-point bending test, the beam displayed both inelastic behavior and crack propagation, including load drops associated with crack instability. The MEMS transducers detected all instability events as well as many or most of the acoustic emissions occurring during plasticity and stable crack growth. The MEMS transducers were less sensitive than the commercial transducer, and did not detect as many events, but the normalized cumulative burst count obtained from the MEMS transducers paralleled the count obtained from the commercial transducer. Waveform analysis of signals from the MEMS transducers provided additional information concerning arrivals of P-waves and S-waves. Similarly, the analysis provided additional confirmation that the acoustic emissions emanated from the damage zone near the crack tip, and were not spurious signals or artifacts.

Subsequent tests were conducted in a field application where the MEMS transducers were redundant to a group of commercial transducers. The application example is a connection plate in truss bridge construction under passage of heavy traffic loads. The MEMS transducers were found to be functional, but were less sensitive in their present form than existing commercial transducers. We conclude that the transducers are usable in their current configuration and we outline applications for which they are presently suited, and then we discuss alternate MEMS structures that would provide greater sensitivity.

Keywords: Acoustic emission, MEMS, transducer sensitivity.

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1. INTRODUCTION

Acoustic emission (AE) testing is a useful technology for managing critical civil infrastructure components such as steel pressure vessels and bridges. These structures are considered to possess flaws that can approach fracture-critical size with time and use, such as fatigue cracks that can grow with repeated loading Therefore, they require periodic inspection to monitor such conditions. For example, some fatigue cracks may be stable, with only a subset experiencing continuing crack growth, and therefore AE sensing may be used to distinguish between inactive and active cracks. The term "acoustic emission" refers to transient ultrasonic waves that are released from microscopic zones, such as a crack tip, during irreversible damage, such as crack extension; therefore, acoustic emission constitutes evidence that a crack is active. However, impacts and friction effects also produce stress waves, and therefore it is necessary to discriminate true AE events from nonstructural events. Localization of the signal source at known (or suspected) fatigue crack locations is one key discriminant, and analysis of waveform characteristics is another.

By way of introduction, there is a well-established method for AE testing [1] to examine seamless, gas-filled pressure vessels (tubes). AE sensors are mounted at each end of the vessel, to permit an estimate of axial location from the relative arrival times. The vessel is pressurized to 110% of its normal fill pressure as data is acquired, and the raw AE data is filtered to eliminate nonstructural sources. The filtered data are then plotted against axial location. These locations of intense AE activity can then be characterized by detailed ultrasonic inspection to determine flaw size, shape, and orientation. The same method [1] prescribes instrumentation requirements including detector sensitivity, preamplifier characteristics, and parameters for signal processing. The method also prescribes the use of a pencil lead break as the preferred technique for conducting a system performance check, and therefore pencil lead breaks are regularly employed as a physical simulation of an AE event.

In AE events, most of the emitted energy is observed at frequencies between 100 kHz and 1 MHz. Commercial AE transducers may be either resonant or broadband, and generally employ a piezoceramic element to sense motion normal to the surface of the steel member. MEMS technology makes it possible to locate multiple transducer designs on a small area, which can provide additional information about the source, and that capability has been studied in our project. In principle, MEMS technology also invites the development of sensors integrated with signal processing, but that capability has not been addressed in our work. We developed two successive of MEMS devices, and in this paper we describe our observations of MEMS transducer performance in structural testing..

2. PREVIOUS WORK

The research team developed a MEMS device [2] for acoustic emission sensing, featuring a suite of 18 capacitive-type resonant sensors at ten different frequencies. Two different types of vibration mechanisms were employed: hexagonal plates in bending to create the resonant transducers at higher frequencies, and spring-mass systems termed "pistons" to create the resonant transducers at lower frequencies. The device, approximately 1 cm square, was fabricated in the MUMPS three-layer polysilicon surface micromachining process; stationary capacitor plates were fabricated in the lowest Poly0 layer, and the vibrating structures (the hexagonal bending plates, or the "piston" plates in the spring-mass systems) were fabricated in the next Poly1 layer. Characterization experiments showed one resonance within a reasonable range around the design frequency for a hexagonal transducer, and two resonances within a reasonable range around the design frequency for a piston transducer; squeeze-film damping was high, because of the small gap (1.25 μm) between the vibrating plate and the stationary plate forming the capacitor, and therefore the resonances were observable only under a vacuum environment. Laboratory studies [3, 4] showed that the MEMS transducers, under vacuum, could detect stress waves in steel specimens when acoustic emission was simulated physically by pencil lead breaks or ball impacts, and that the information extracted from the transducer signals could be used for source localization. For example, a representative experiment featured three MEMS devices mounted on a steel plate measuring 60x70x0.25 cm. A pencil lead break was applied at a particular location on the plate, signals were acquired at multiple transducers, and the source location was deduced from those signals. This experiment was repeated with four different locations for the pencil lead break, with good results. In those same laboratory studies, performed under vacuum, frequency domain analysis of the signals confirmed the expected resonant performance of the transducers.

3. DEVICE DESCRIPTION

It was recognized that operation under vacuum was undesirable for application to structural testing, and therefore an improved design was developed and tested [5]. The CAD layout of the MEMS device, which was used in all tests described in this paper, is shown in Figure 1. Based on our earlier studies, we determined that a smaller number of transducers would suffice, and that increased sensitivity was desirable. The device features six piston-type transducers, in rows C and D, with design resonant frequencies between 101 and 506 kHz, and a seventh transducer (B3) at 1 MHz. Again, for each piston-type transducer, two resonances were observed within a reasonable range around the design frequency. Compared to the earlier design, the area of each individual transducer was enlarged in order to increase the capacitance and thereby the transducer sensitivity. Referring to the six piston-type transducers in rows C and D, measured capacitances ranged between 34 and 40 pF; in the earlier device, which contained a greater number of transducers, measured capacitances for piston-type transducers ranged between 16 and 20 pF. In another comparison to the earlier design, the etch hole spacing was significantly shortened (from 30 μm to 13 μm) in order to reduce the squeeze-film damping and thereby achieve a moderately underdamped response. Resonances were observed and measured under atmospheric pressure, indicating that some degree of underdamped behavior had been achieved without requiring operation under vacuum.

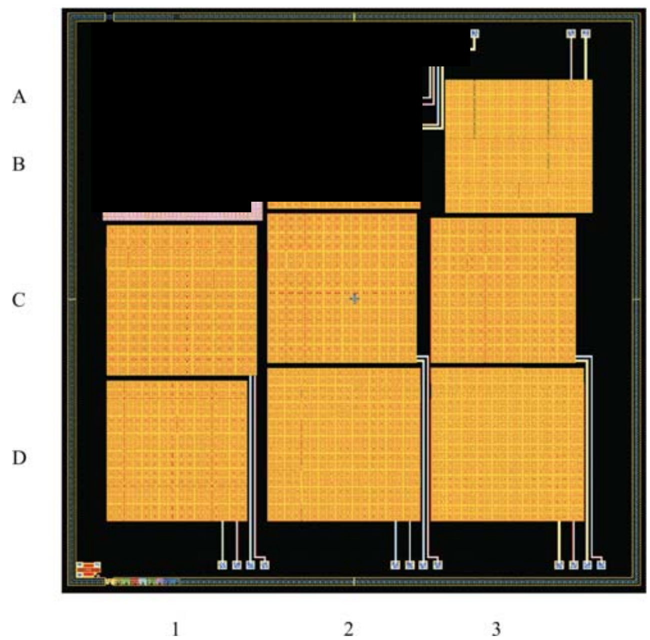


Figure 1. CAD layout of MEMS device

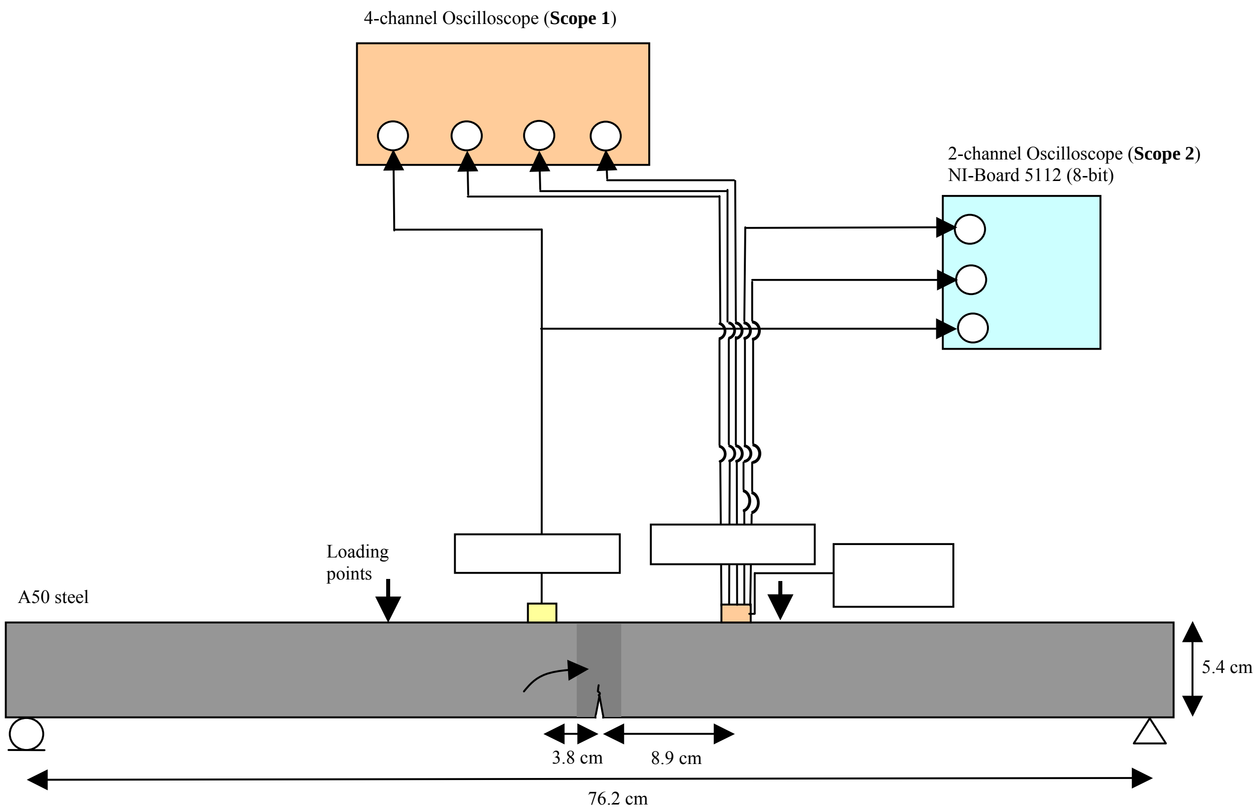
Finite element simulation studies suggest that the two resonances observed for each transducer, within a reasonable range around the design frequency, result from the combination of a spring-mass system translational mode with the lowest symmetrical mode in bending for the piston plate. We note that the devices also display many antisymmetrical modes, including rocking motion, which would not be expected to produce significant electrical response when excited mechanically.

Measured Q factors for the six transducers ranged from 1.8 to 4.6. Analysis shows that the Q factor is significantly influenced both by squeeze-film effects and by radiation into air, and the relatively low Q factors are understandable as a consequence of those two dissipative mechanisms. In retrospect, somewhat higher Q factors would have been desirable. In the remainder of this paper we describe the performance of the MEMS transducers, subject to structural excitation and operating in an atmospheric environment, and compare their performance to that of conventional piezoceramic resonant AE transducers.

4. APPLICATION IN LABORATORY STRUCTURAL TESTING

4.1 Experimental block diagram

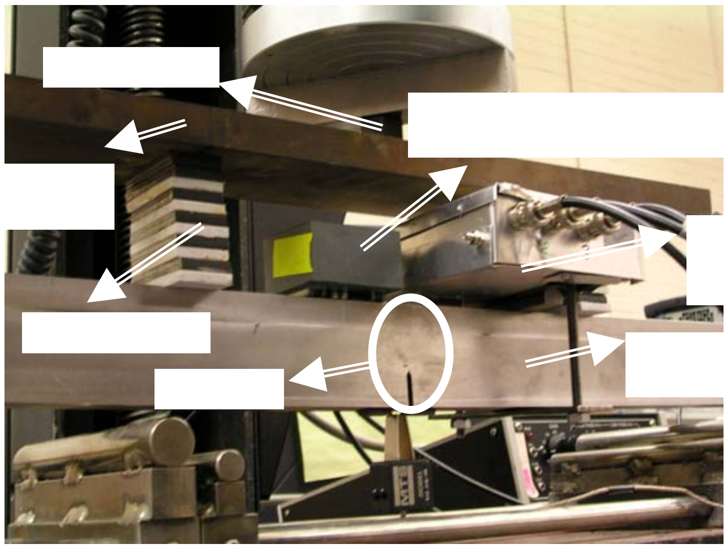
We tested the performance of the MEMS device by measuring acoustic emissions generated within a welded steel beam specimen under a four-point bending test. Two segments of A50 steel were welded at midspan with E70-T4 electrode material to create a specimen with dimensions of 76.2 cm length, 5.4 cm height and 2.5 cm width. The specimen was fatigue pre-cracked in the weld material at 10 Hz for about 15000 cycles, to create a notch at midspan with a depth of 0.6 cm. Acoustic emissions were detected using five transducers on the MEMS device and one commercial acoustic emission transducer from Physical Acoustics Corporation (PAC). The MEMS transducers and PAC transducer were connected to 20X preamplifiers, and acoustic emission events were recorded with two instruments. Scope 1 was a Tektronix TDS2014 four-channel, 100 MHz oscilloscope with 8-bit resolution, and scope 2 was a fast 8-bit National Instruments (NI) board that can record longer duration signals than Scope 1. Each scope was controlled and synchronized by a Labview program. In addition to the acoustic emission transducers, there were transducers to measure displacement and load at the loading point of the steel beam. Displacement and load at the middle were recorded at every 0.5 sec. Data were collected and stored from all instruments after each acoustic emission trigger event. Since this data storage takes a few seconds to complete, a very slow loading rate (0.0025 mm/min) was chosen to minimize the loss of acoustic emission events. Figure 2 shows the experiment setup drawing and channel configurations. The trigger sources for Scope 1 and Scope 2 were the PAC transducer.



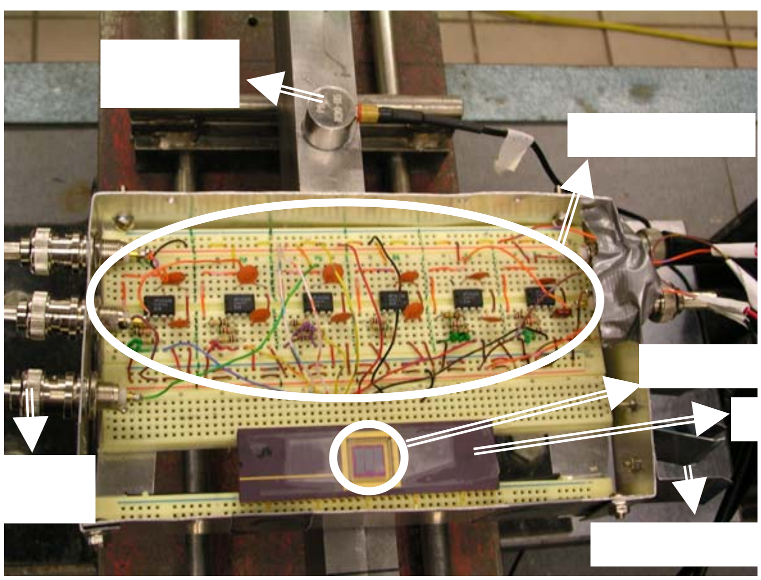
Channels	1	2	3	4	5	6
Transducers	PAC	Piston-C3	Piston-C2	Piston-C1	Piston-D3	Piston-D2
Resonant frequency(kHz)	300	252	207	150	570	317

Figure 2. Laboratory test configuration

Figure 3 shows the test setup with the MEMS device and the PAC transducer. Steel-teflon layers were sandwiched at the loading points to eliminate noise. The MEMS device, mounted in a ceramic package, was shielded against environmental noise by an aluminum housing which includes 20X amplifiers, BNC jacks, power lines for the MEMS device, and ground. The MEMS device was coupled to the specimen by a steel block which was glued by superglue to both the specimen surface and the ceramic package surface, and the PAC transducer was coupled to the specimen using vacuum grease and mounted with a magnet. As shown in Figure 3b, although the areas of the MEMS device and the PAC transducer are similar, the MEMS device contains seven transducers at that same location. Improved packaging, circuit layout, and housing would permit the MEMS device to be placed with a smaller footprint than used in this experiment.



(a)

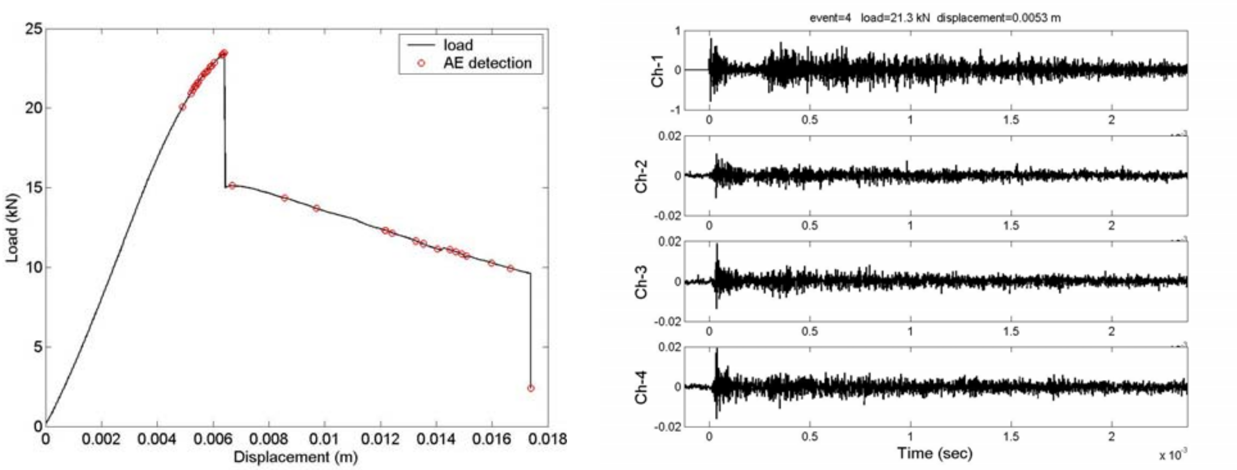


(b)

Figure 3. (a) Test configuration, (b) MEMS device and housing with 6-channel amplification

4.2 Experimental results

Figure 4a shows the load-displacement history with the AE events detected from Channel 1. Damage appears to accrue at a load level of roughly 20 kN, followed by a first, large load drop at 21.3 kN. Damage continues along a decreasing segment of the load-displacement curve, before a second load drop near 10 kN. The MEMS transducers detected 60% of the acoustic emission events detected by the commercial transducer before the first load drop. Along the decreasing segment of the load-displacement curve, there were 16 small amplitude AE events recorded by the PAC transducer, three of which were recorded by the MEMS transducers. The experiment ended with the second large load drop. Figure 4b shows the four signals at Scope 1, at the time of the large load drop from 21.3 kN.



(a) (b)

Figure 4. (a) Load-displacement curve with detected AE events, (b) transient signals detected at P = 21.3 kN

There is a considerable signal amplitude difference between yielding and crack opening. The vertical dynamic range of 8-bit oscilloscopes was insufficient to capture both events without saturation. We attempted to capture more completely the small amplitude events, because there were only few large crack opening events and because the small amplitude events were a stricter test of the MEMS transducer performance. While the MEMS transducers could not detect all events recorded by the PAC transducer, Figure 4 indicates that they captured all fundamental events including the initiation of yielding and crack opening.

The detection of multiple transducer outputs from the same location provided some additional information about the AE source location and its identification. Some events were detected by only two MEMS transducers, while the others missed the event. Covering a wide frequency spectrum reduces the probability of error that might occur because of an out-of-range frequency condition. In addition, based upon the arrival times, we can distinguish between signals emitted from the damage zone as compared to signals emitted at the load points or the reaction points. Finally, having multiple data provides to identify the correlation between transient signals and acoustic emission event more accurately.

5. DEVICE MOUNTING

The MEMS device must be supplied with preamplification and electronic shielding, and must be mounted to the steel substrate with effective acoustic coupling. The closest reasonable placement of the preamplifiers is desirable, because stray capacitance reduces the signal strength. Similarly, electronic noise directly degrades the detection capability, and therefore full shielding is mandatory. Figure 3 shows the configuration employed in the laboratory experiments, with six channels of preamplification implemented on a breadboard and contained in a housing measuring 100x170x40 mm, exclusive of the projecting batteries. The configuration was suitable for transverse mounting on the upper surface of the beam in the first application tests, shown in Figure 3, but not for general field use. Figure 5 shows a compact housing with four channels of hand-wired preamplification developed in August 2005 for application on a steel bridge truss, and Figure 6 shows the circuit implemented in October 2005 on a custom PC board, further reducing package dimensions.

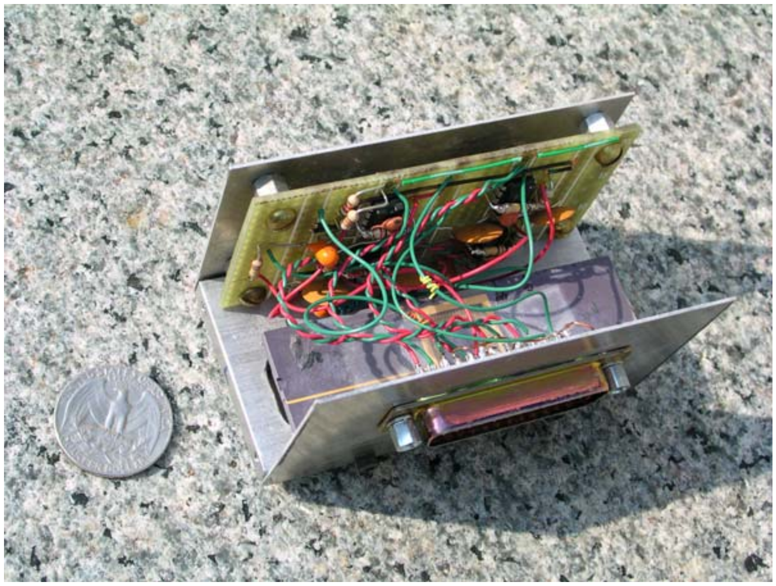


Figure 5. MEMS device and housing with 4-channel amplification, 45x75x115 mm, August 2005

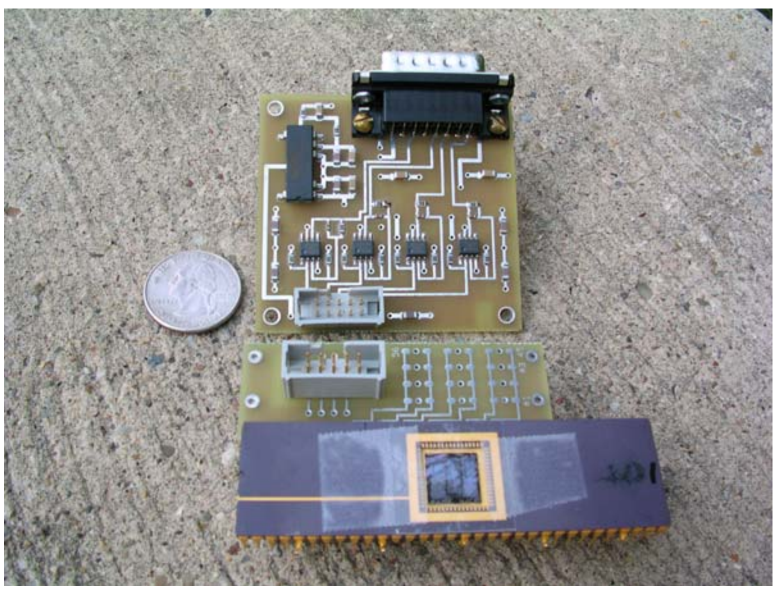


Figure 6. MEMS device and custom PC board with 4-channel amplification, October 2005; housing (not shown) 45x50x90 mm

The MEMS device was mounted and wirebonded to the ceramic DIP package as shown. A steel bar, 15-mm square, was affixed with epoxy to the underside of the ceramic package to serve as a coupling block, for subsequent similar epoxy attachment to the steel substrate. Pencil lead break tests confirmed that coupling was achieved, and the laboratory tests confirmed the transmission of true AE events to the MEMS device. During development of the field housing, we performed laboratory tests (not shown) on alternate geometries for the coupling block, including cylinders and cones of different heights. In those tests we detected relatively little difference in coupling, and therefore we undertook our first field tests with the steel bar as the coupling block.

6. RESULTS OF 2005 FIELD TESTING

The intent of field testing in 2005 was to provide side-by-side observations of the performance of MEMS sensors as compared to conventional piezoceramic AE transducers. In August 2005, an AE monitoring installation was installed for testing purposes on the Victoria Bridge in Montreal, which was constructed at the end of the 19th century as a series of steel truss spans. Figure 7 shows one of the bridge spans instrumented in the study, with an oncoming freight train serving as a representative intended test loading [6, 7].

Figure 7. Steel truss bridge instrumented for monitoring study

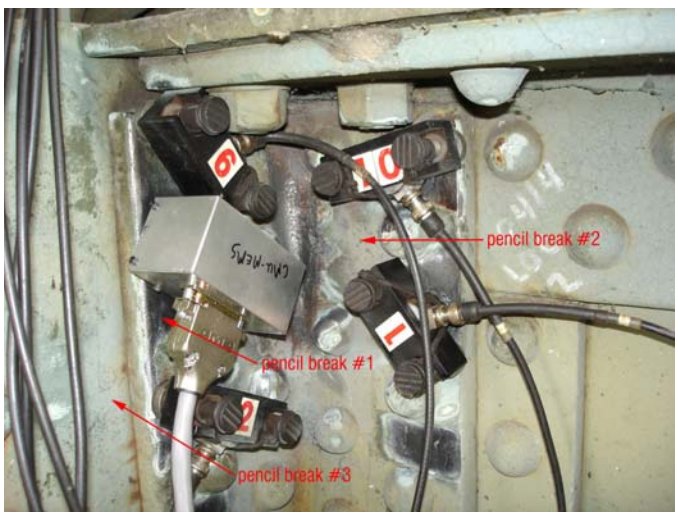


Figure 8. MEMS device and four commercial transducers mounted on riveted connection angle

Figure 8 shows a riveted connection, part of the floor framing system, within which the connection angle was selected for monitoring. Four commercial piezoceramic sensors were installed, two on each leg, and the CMU-MEMS device, in the housing shown in Figure 5, was mounted within the sensor array as shown. In the same manner used in laboratory experiments, one of the commercial transducers was used as the trigger for data collection. Figure 9 shows typical results from a pencil lead break test, plotting raw data from the commercial transducer (top trace) along with the data (after preamplification) from three of the sensors on the MEMS device. The MEMS sensors clearly detected the event, with waveforms comparable to the data obtained from the commercial transducer. However, the amplitude scales are not equal, but are 10X higher in the traces of the MEMS data. Therefore, Figure 9 shows that the commercial piezoelectric transducer, prior to any preamplication of its signal, is an order of magnitude more sensitive than the MEMS sensor. Figure 9 also shows the noise level in the MEMS sensor, and it is evident that the signal to noise ratio is modest.

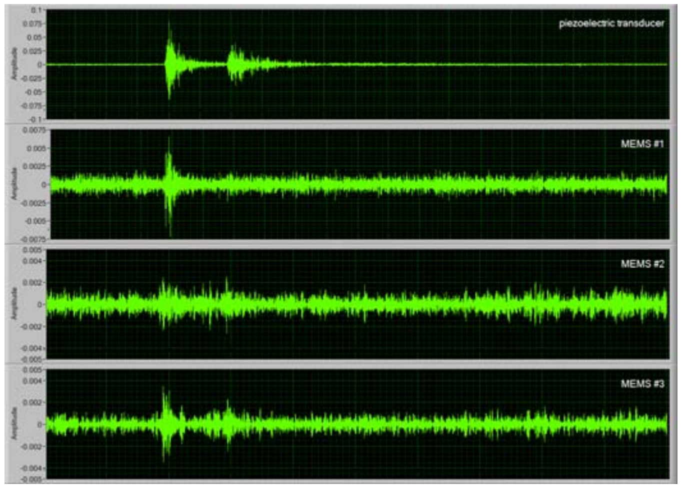


Figure 9. Response of commercial transducer (top trace) and three MEMS channels to pencil lead break

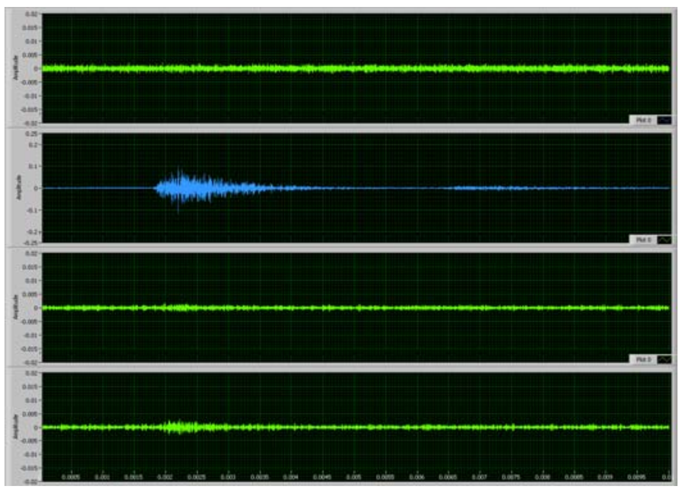


Figure 10. Response of commercial transducer (second trace) and three MEMS channels under freight loading

Whereas the commercial transducers were installed for a test of long term monitoring, the MEMS transducer was deployed only temporarily, with data being collected during the passage of several freight trains. Figure 10 shows a representative record triggered during a freight passage, in which the raw data from the commercial transducer is the second trace from the top. It is not assumed that structural AE events occurred under that loading; the records shown are indicative of the signals induced by friction at an existing interface, but they serve to provide the comparison sought between the MEMS and the commercial transducer. Only one of the three MEMS sensors has detected the event, with a signal barely above the noise level. Also, the amplitude scale on the MEMS channel is again 10X higher than that on the raw data from the commercial transducer.

7. DISCUSSION AND CONCLUSIONS

The MEMS device in its present configuration is capable of detecting AE events, but a comparison to commercial transducers leads us to conclude that its sensitivity (or its signal to noise ratio) should be increased by at least one order magnitude before further implementation efforts are undertaken. Two approaches are under study for that purpose. Based upon our earlier experimental studies with pencil lead breaks, and upon our analysis of the squeeze-film damping, we determine that the sensitivity should reach or exceed the desired level if the device can be housed in a coarse vacuum; we note that commercial MEMS products such as accelerometers regularly receive permanent evacuated packaging, and therefore this would not involve a new precedent. Another approach, which will reduce transducer size and make it less sensitive to the effects of stray capacitance, is to develop transducers that use piezoresistive sensing. In earlier experimental studies [8] we showed a comparative advantage of piezoresistive sensing over capacitive sensing, but those devices were fabricated in a CMOS process that was subsequently discontinued. However, Bahreyni [9] has recently demonstrated the fabrication of piezoresistive cantilever structures in the MUMPS process, which can be adapted for AE sensing; it is unclear at this time whether those devices can be operated under atmospheric pressure, or whether they too would require an evacuated housing.

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