

# A Study of Wireless MEMS Accelerometers for Civil Infrastructure Monitoring

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**Abstract** – In this paper, a proprietary wireless MEMS accelerometer system produced by Xbow Corporation is examined. The system has the potential for rapid low cost installation, which makes it an ideal tool for placement of large data arrays in earthquake engineering research projects. An overview of the device, a summary of the capabilities and limitations and the methodology for NEES integration is discussed in the paper.

**Keywords** – Wireless MEMS accelerometer, Infrastructure monitoring

## I. INTRODUCTION

Civil infrastructure systems represent critical components that are closely connected with the national economy and the public life [1]. As of Year 1998, 29 percent of the bridges in the United States were reported as being structural deficient or functionally obsolete by the Federal Highway Administration [2]. Using information collected from the sensors mounted on structures, timely and cost-effective maintenance can be performed and the life-cycle performance of civil structures is thus enhanced.

Laying out wires is a major issue in monitoring civil infrastructure. In order to better understand the distribution of stresses and strains within the structure, a program for comprehensive field instrumentation and monitoring was developed and implemented by researchers from Lehigh University's Center for Advanced Technology for Large Structural Systems (ATLSS). It has been observed that laying out the wires on the bridge is very labor intensive and consumes a significant portion of project time. Thus it is desirable to deploy wireless sensor networks in the civil infrastructure monitoring tasks.

As a part of the National Science Foundation George E. Brown Jr. NEES@Lehigh equipment grant, a series of advanced sensors were examined for application in earthquake simulation. This paper examines a proprietary wireless MEMS accelerometer system produced by Crossbow Technology, Inc. The system has the potential for rapid low cost installation making it an ideal tool for placement of large data arrays in earthquake engineering research projects. An overview of the device, a summary of the capabilities and

limitations and the methodology for NEES integration is discussed in this paper.

## II. EQUIPMENT OVERVIEW

The wireless sensor system consists of a four parts: 1) the mote - MICA2 processor/radio board, 2) the sensor board (MTS310CA), 3) the proto/data acquisition board (MDA500CA), 4) the serial PC interface board (MIB500CA). The wireless portion of system device consists of the MTS310CA sensor board mounted on the MICA2 processor/radio board with attached battery. This device transmits to the MDA500CA proto/data acquisition board mounted on the PC interface board (see Figure 1).

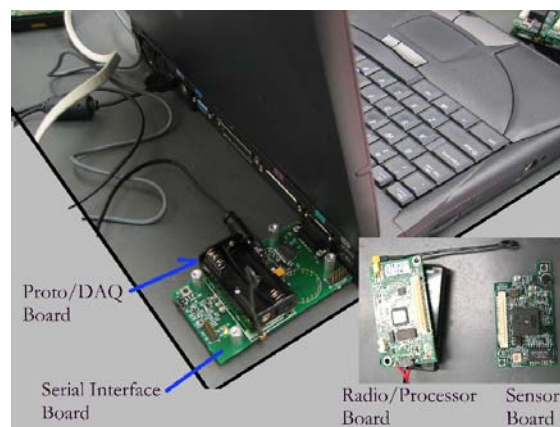


Figure 1: Device layout

### A. Motes

The Motes used in this research are the third generation of modules MICA2 and MICA2DOT which are shown in Figure 2(a) and (b) respectively. The design goal of these motes is to enable low-power wireless sensor networks. As shown in Figure 3, the major components of the motes include: (i) micro-processors modules with both digital IO and analog IO interfaces, (ii) a tunable frequency radio module for transmission and receipt of messages using the attached

antenna. (iii) a logger flash module for the non-loss program, and (iv) an IO expansion slot for sensor inputs.

The following features make the MICA2 and MICA2DOT suited to laboratory and field structure measurements:

- 868/916MHz, 433 or 315MHz multi-channel transceiver with extended range.
- TinyOS (TOS) Distributed Software Operating System v1.0 with improved networking stack and remote re-programming capabilities.
- Wide range of sensor boards and data acquisition add-on boards.
- MICA2DOT quarter-sized Mote is compatible with the much larger yet powerful MICA2 mote.



(a) MICADOT mote (b) MICA2 mote without sensor board

Figure 2: Mote processor/transmission board

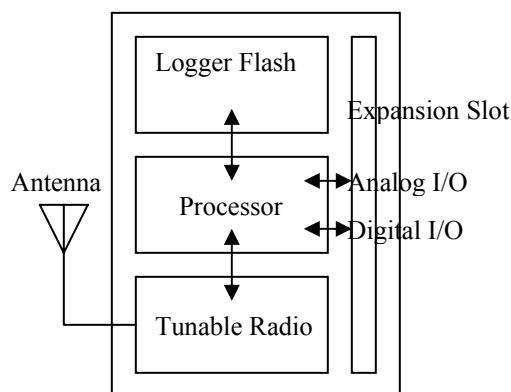


Figure 3: Mote components

The mote has a transmission capability of 38.4kbaud bandwidth. This allows for a maximum of 3840 10-bit samples to be transmitted in a single-hop network (i.e., one transmission leg from the sensor to the receiver). For larger networks with links that are more than one hop away from the sink node, the maximum value of data transmission rate will decrease. In our test system, every ten samples are packed as a 20-bit data packet with a 6-bit packet header. With this configuration, the maximum packet the network can allow is approximately 184 packets per second. If a rate of 100 samples per second is used, the maximum sensors the system can support are 18.

### B. Sensor Board

The MTS310CA sensor board obtains all measurements. The board is equipped with a Photo Diode, Thermistor, Microphone, Sounder, Magnetic Sensor, and a Micro Electrical Mechanical System (MEMS) based Accelerometer

sensor. The arrangement of sensors on the board is illustrated in Figure 4.

The sensing board includes multiple analog sensors that can be sampled by the ATML128's internal 10-bit AD converters. The sensors evaluated for this series of experiments are the bi-axial accelerometer ADXL202JE produced by Advanced Devices. Specification about that accelerometer indicate that the ADXL202JE is a low-cost, low-power, complete 2-axis accelerometer with a digital output, all on a single monolithic IC. It will measure accelerations with a full-scale range of -2g to +2g. The ADXL202JE can measure both dynamic acceleration such as vibrations and static acceleration like gravity. The accelerometer properties are summarized in Table 1.

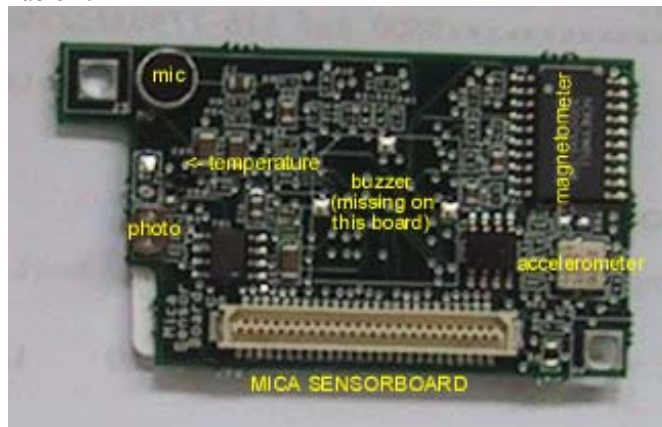


Figure 4: Sensor board for MICA2 motes

Table 1: ADXL202 accelerometer specifications

# Axis	2
Range	+/- 2.0g
Sensitivity	12.5% / g
Supply Current	0.6mA
Supply Voltage	2.7 to 5.0 V
Bandwidth	6 kHz
Resolution at 60Hz	2 mg
Shock Survival	1000 g
Temp Range	-40 to 85C

### C. Receiver Board

Another MICA2 mote is used as the receiver board in our test system, the functionality of the receiver board includes: (i) to receive the data packet from the sensors, (ii) to relay the data into the COM port of a PC through the PC Interface Board, and (iii) to recalculate the timestamp such that the sensing data from the unsynchronized sensors can be displayed in the same screenshot. The receiver board will take the sensor node it discovered first as the reference sensor node. On receiving data packet from another sensor node, it changes the LastSampleCount variable in the packet according to the following formula:

$$LastSampleCount_{new} = LastSampleCount_{old} - (FirstSampleCount_{this} - FirstSampleCount_{ref})$$

#### D. PC Interface Board

The PC interface board enables the motes to talk with the computer. It enables (1) the computer to download compiled program to motes, and (2) the bi-direction communication between the mote and the computer in run-time through the UART port at speed 57600 bit/s for MICA2 (For MICA2DOT, the speed is 19200 bits/s). (3) An external power source is available such that the receiving mote will always have reliable power supply.

In our experiment, the COM port is configured as following:

- Speed: 115200 (any value larger than 57600 works fine)
- Data bits: 8
- Parity: Even
- Stop bits: 1
- Flow Control: None

#### E. Data Acquisition

Sensor nodes:

Ten sensing data are put together with necessary information in the format of :

```
typedef struct OscopMessage
{
    unsigned int_16    MOTE_ID;
    unsigned int_16    Channel_ID;
    unsigned int_16    LastSampleCount;
    int_16             DATA[10];
}
```

The packets are unicasted to the sink nodes by the sensor nodes once they are ready.

Sink nodes:

On receive these sensing packet, the sink node will adjust the LastSampleCount variable, such that the results from different sensors with different starting time can be shown in the same view-shot by the java program.

Java Program:

The goal of the java program running on the PC that is connected with the sink node through an interface board is to receive all UART inputs and display them on the screen. The program is available at NEES@Lehigh.

### III. NEES INTEGRATION

The wireless system transmits data to a host computer via a serial port connection. To integrate this data into the main NEES@Lehigh data stream a Data Turbine tool is used.

#### A. Data Turbine

Data Turbine is a dynamic data server and viewer based on ring buffer technology. It provides high performance data streaming reaching speeds over 10MB/sec and flexible data viewing. It is easily integrated with any Java-based application such as the application used for communicating with the MEMs wireless acceleration sensors using a simple API.

When the MEMs application is loaded, an exclusive Data Turbine connection is established for every wireless sensor on

the network. When a packet of data is received from any wireless sensor at the host PC, the packet is parsed into usable data such as ID, timestamp and raw acceleration data. The MEMs application sends the acceleration data to the Data Turbine protocol using a name ID for each sensor. The data is stored in the ring buffer and can be viewed by any user with an Internet browser.

Data Turbine is part of the NEES system and is formally accessed through the NEESpop website for authenticated NEES users only. The data is synchronized to a timestamp value and/or a count status. The data collected by Data Turbine is saved in the NEES repository and will have the capabilities of post-test viewing in the future. The viewer and the ring buffer are two different programs working together and the Data Viewer remains on NEESSteel at all times.

To display data on the Data Turbine data viewer the Data Turbine package must be run. This package is available at the Lehigh@NEES website.

### IV. LABORATORY FEASIBILITY STUDY

To assess their capability for laboratory measurement the MOTES were examined at the ATLSS Research Center NEES facility. The accuracy, the propensity for data loss, and the delay for the wireless testing system is examined. This evaluation is conducted through a side-by-side comparison of a hard wired accelerometer and two wireless MOTES. The wired accelerometer is connected directly to the NEES@Lehigh Pacific Instruments 6000 data acquisition system. To ensure accurate readings the wired accelerometer is sampled at 500 samples per second.

A simple test fixture is used to evaluate the accelerometers (Figure 5). A cantilevered steel bar with a lumped mass is used. The mass consists of the motes and the wired accelerometer. Three cantilever distances are used to evaluate different frequency ranges. One channel of data is sampled from each wireless accelerometer and compared to the wired value.

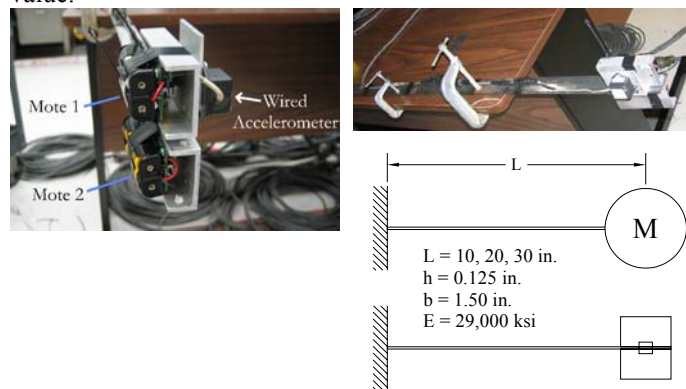


Figure 5: Cantilever test setup

#### A. Transmission Distance

To examine transmission issues, the wireless system is examined within the ATLSS test facility. The receiver computer is located within the NEES control room adjacent to the test floor. Four transmission locations are chosen to

represent the different interference that may occur within the lab environment. The first location is within the control room. This setup minimizes any physical or electronic interference that could occur. The second location is directly outside of the control room on the lab floor. In this location the device is subjected to electronic as well as moderate physical interference. The third location is along the walkway. This location represents the most severe conditions. Significant physical interference (note all ATLSS walls are steel) and electronic interference exist. The final location is across the lab floor in the main region where NEES studies will be conducted.

### B. Results

The relationship between packet lost rate and the transmission distances and the relative vibration frequency are shown in Table 2 and Table 3. From the table, we conclude that (i) the distance in which the wireless node can effectively communicate without losing significant amount of sample data is limited. (ii) The sample data loss rate of the out-of-shelf system will be affected by the frequency and strength of the system vibration dramatically. (iii) For different sensor nodes, the pattern of the affection can be completely different. Since the pattern is not completely understood yet, we suggest that in order to establish a reliable test system, research on the affection patterns should be conducted such that the consistency of the system can be improved. To minimize data loss a multi-hop transmission and multiple sink configurations should be considered. To decrease data error at high frequencies the device characteristics need to be improved.

### C. Accuracy

To examine the accuracy of the system the measured frequencies are compared. The results obtained through wireless sensor #1 and wireless sensor #2 are compared with the reference result measured from the wired sensor output. The resulting values correlate well.

The vibration frequencies are calculated as following: (i) According to each set of samples, a vibration curve is generated Figure 6. (ii) The time value of the first peak point is recorded as  $T_1$ . (iii) The time value of another peak point that belongs to the same vibration sequence as  $T_1$  is recorded as  $T_2$ . (iv) The number of peaks between  $T_1$  and  $T_2$  are counted as  $n$ . (v) The frequency value under this condition can be calculated as  $f = \frac{n+1}{T_2 - T_1}$ . In most cases 34 consecutive peaks are measured. In cases where data loss occurs a smaller number of cycles are used to compute the measured frequency.

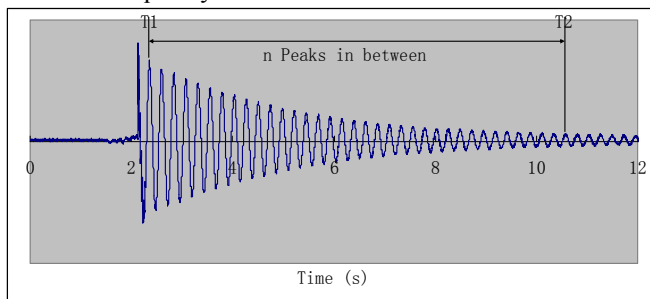


Figure 6: Vibration frequency calculation method

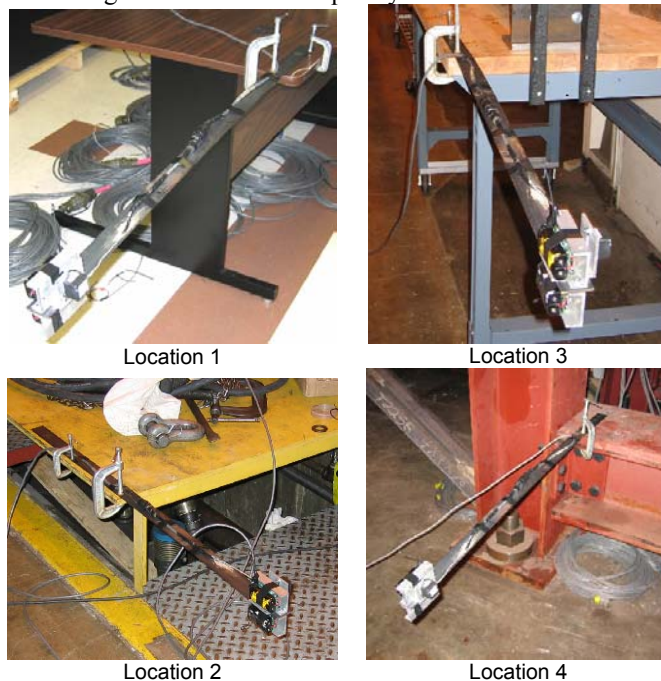
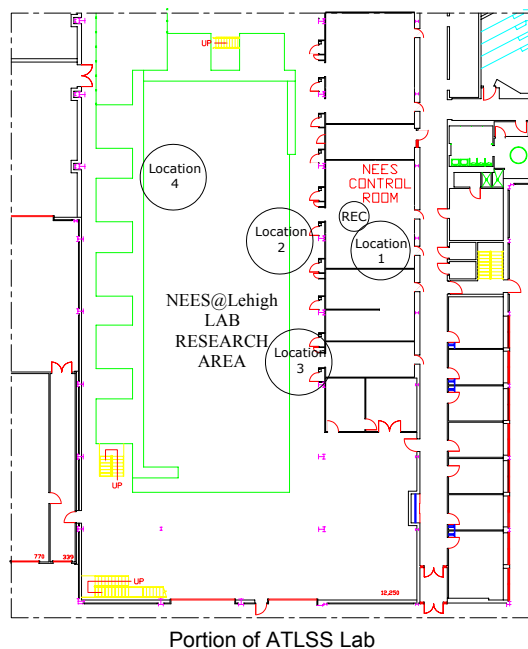


Figure 7: Sample locations

Table 2: Sample loss

Test	Cantilever Length [in.]	Distance from Mote to Receiver / Location	Mote 1 Packet Loss [%]	Mote 2 Packet Loss [%]
1	30	8.5ft (Location 1)	3.7	4.55
2	20	8.5ft (Location 1)	0	2.63
3	10	8.5ft (Location 1)	3	1.21
4	30	25ft (Location 2)	1.4	0
5	20	25ft (Location 2)	0.95	0.95
6	10	25ft (Location 2)	44.4	1.48
7	10	45ft (Location 3)	34.3	98.1
8	10	45ft (Location 3)	29.8	-
9	20	50ft (Location 4)	2.1	52.17
10	30	50ft (Location 4)	7.8	3.64
11	10	50ft (Location 4)	33.7	87.36
12	10	50ft (Location 4)	35.8	-

Table 3: Measured frequency response

Test	Wired Device Frequency (reference)	Mote 1		Mote 2	
		Frequency	Error	Frequency	Error
1	N/A	9.406	N/A	9.390	N/A
2	4.11	4.252	-3.29%	4.252	-3.3%
3	N/A	2.271	N/A	2.267	N/A
4	12.38	12.063	2.60%	11.913	3.9%
5	4.31	4.344	-0.78%	4.344	-0.8%
6	2.33	2.312	0.60%	2.302	1.0%
7	2.31	2.344	-1.27%	N/A	100%
8	2.32	2.327	-0.26%	2.327	-0.3%
9	4.39	4.394	-0.13%	4.425	-0.8%
10	11.64	11.711	-0.57%	11.377	2.4%
11	2.32	2.275	1.90%	N/A	100%
12	2.29	2.275	0.73%	2.275	0.7%

The results indicate that if the wireless transmission is not affected the error will be less than 4%.

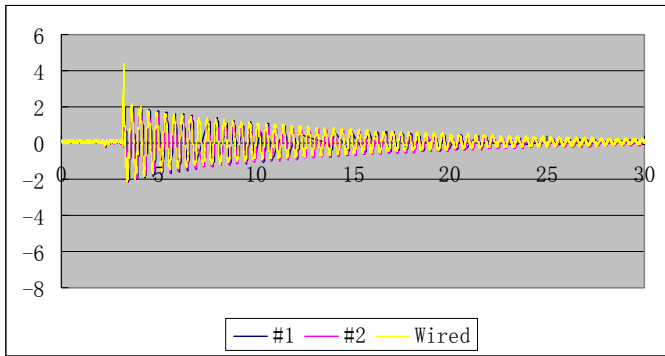
#### D. Data flow

Several data records are shown in the following figures to depict the process of the experiments. Since the MEMS measurement system and the wired sensing system do not share the same timing reference, there is a constant time lag need to be removed from the two systems.

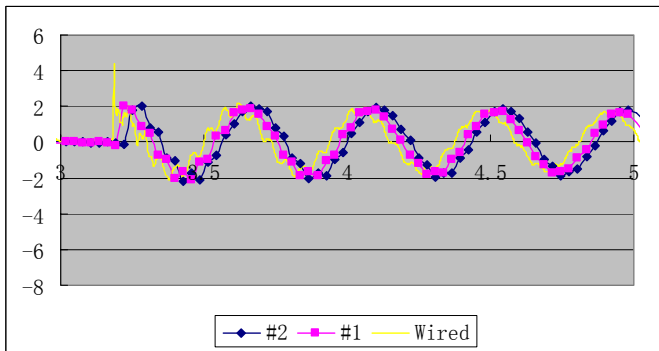
Moreover, during the experiments, we start the two systems by clicking the buttons at roughly the same time, which provides another random time delay difference between the two systems. Figure 8 to Figure 11 presents the measured

wired and wireless data. The data is shifted to in time to align the data. The wireless data lags the wired data by 0.1 to 30 seconds.

Figure 11 illustrates the condition in which significant packet losses occur. In (a), the curve reconstructed from #1 sensor's data is a 30% packet loss occurs while sensor #2 has a loss greater than 90%. Notice that in the zoomed-in view, the packet losses happens without any peak points lost.

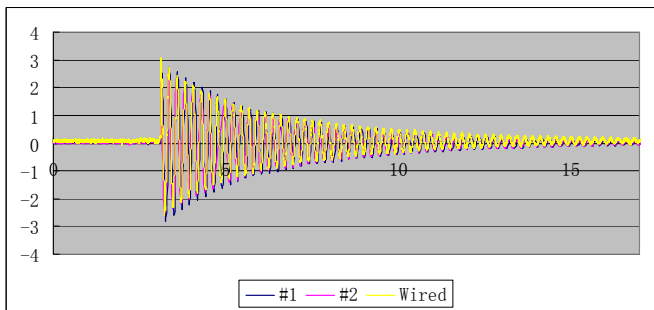


(a)

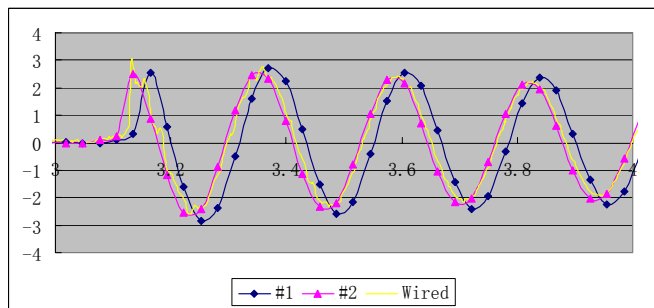


(b)

Figure 8: Acceleration (g's) vs. time for cantilever length of 10 in. at location 2 (a) Entire vibration curve wired result shift left for 0.77s (b) magnified view

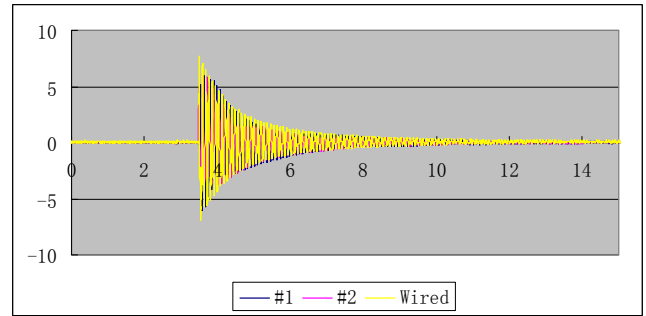


(a)

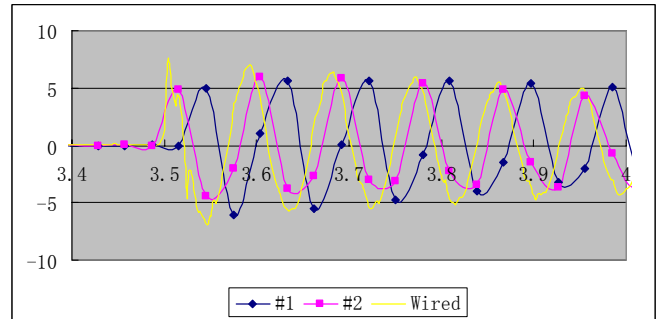


(b)

Figure 9: Acceleration (g's) vs. time for cantilever length of 20 in. at location 2 (a) Entire vibration curve wired result shift left for 0.59s (b) magnified view

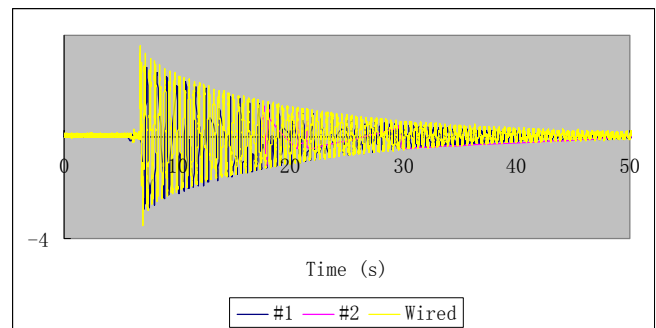


(a)

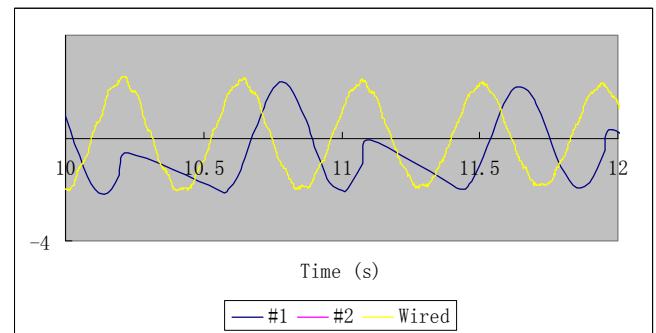


(b)

Figure 10: Acceleration (g's) vs. time for cantilever length of 30 in. at location 2 (a) Entire vibration curve wired result shift left for 1.1s (b) magnified view



(a)



(b)

Figure 11: Acceleration (g's) vs. time for cantilever length of 30 in. at location 3 (a) An entire vibration with wired result shift left for 11s (b) A zoomed-in view

## V. CONCLUSION

. This paper examines a proprietary wireless MEMS accelerometer system produced by Xbow Corporation. The system has the potential for rapid low cost installation making it an ideal tool for placement of large data arrays in earthquake engineering research projects. An overview of the device, a summary of the capabilities and limitations and the methodology for NEES integration is discussed.

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