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Low Cost Accelerometer Sensors - Applications and Challenges

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Abstract

Newly developed low cost MEMS based tri-axial accelerometers can be readily and economically installed on easily accessible structural forms, such as pedestrian bridges, and even urban trees, to perform field experiments for research and enhancing the learning experience of engineering student classes in dynamics and associated disciplines. In addition, nowadays such accelerometers normally form part of the protective system for the delicate moving parts of your laptop hard disk. This means that most modern laptop computers have the potential for doubling as vibration sensors and this inherent capability has been capitalised on by the Quake Catcher Network, which is hosted at Stanford (http://qcn.stanford.edu/), as a sort of early earthquake warning and monitoring system. This paper outlines some of the first hand experience gained by the author in the use of low-cost MEMS based accelerometers in dynamics applications and discusses some of the limitations of these sensors in these and other applications and the challenges being grappled with to overcome/alleviate them.

Keywords: accelerometers, vibration sensors, dynamics, modal analysis

1. INTRODUCTION

Micro-electro-mechanical systems (MEMS) based accelerometer sensors have been at the heart of many recent developments and applications that include the aerospace, automotive, computer manufacturing and home entertainment industries. For example, in the automotive industry they form an integral part of air-bag safety technology, and can be used to trigger deployment of a roll over bar or to instigate dynamic stability control, as needed. Their use in home entertainment, includes consumer electronics devices such as game controllers (Nintendo Wii), personal media players / cell phones (eg Apple iPhone), amongst others. In the notebook computer marketplace they are being used by many manufacturers to detect free-fall in order to shut down hard-disk operation thus preventing a potential “disk crash”.

This latter application area means that most modern notebook computers have the potential for doubling as vibration sensors. This potential capability has been capitalised on by a group led by Elizabeth Cochran, a seismologist at the University of California-Riverside, who came up with the idea of a project labelled QCN - the Quake Catcher Network, which is now hosted at Stanford (http://qcn.stanford.edu/).

1.1 The Quake Catcher Network Concept

The QCN project involves distributed computing - a method in which different parts of a computer program run simultaneously on two or more computers that are in communication with a central server over a network, effectively turning the laptops' accelerometers into earthquake monitors, (Cochran et al, 2009). With a dense grid of detectors in place, the potential is there for an early warning to be sent through the Internet to neighbouring cities should an earthquake strike, giving people precious time to prepare themselves before the seismic waves reach them. In addition, the distributed and relatively dense information/data set of a reasonably significant seismic event when captured from such a system would provide seismologists with an “information rich” enhancement to the relatively few sparse records from “traditional” seismographs leading to a better understanding of earthquakes and their properties. It should be noted that only seismic events greater than approximately Magnitude 3.5 would be detectable using the style of on-board MEMS accelerometers currently being used in notebooks so that less significant events would not “clutter” the system server and its communications with participant nodes of the QCN.

Should a potential participant of QCN not have a notebook with an on-board accelerometer, or be operating a desktop PC (these do not have on-board accelerometers as a matter of course), then a suitable low cost external MEMS-based accelerometer system that can be connected to the computer concerned via a USB port can be used instead and two such models are currently supported by QCN. Figure 1 depicts the JoyWarrior24F8 model sensor that can be purchased from the QCN network site ($US49.00 for private U.S. residents, a $US5.00 handling fee for U.S. schools).

Since going “live” in February 2008, and as of August 2009, the QCN has built up its membership to approximately 1500 measurement nodes with participants scattered throughout the world.

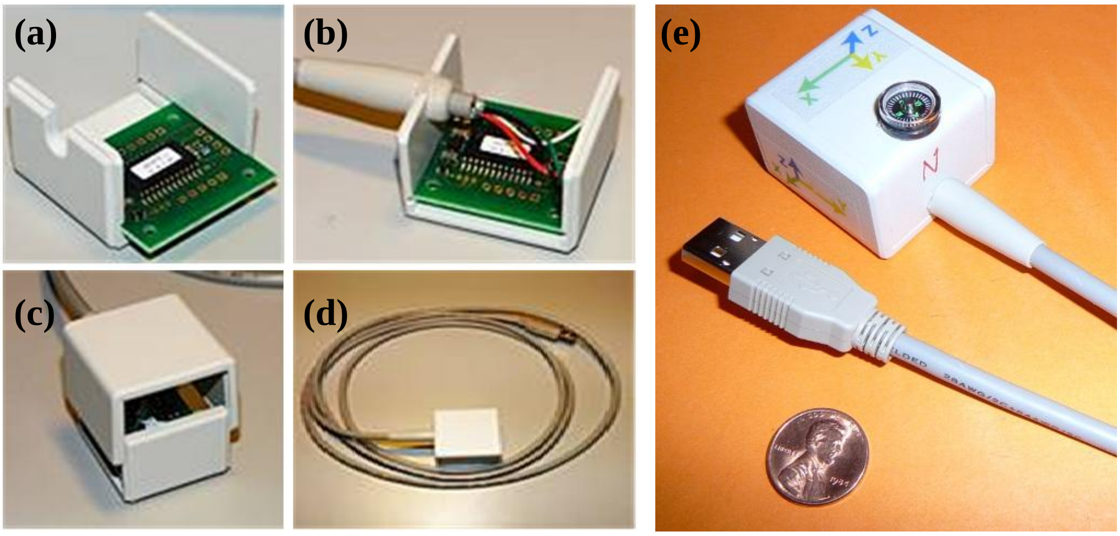

Fig. 1 (a) to (d) Assemblage of JoyWarrior24F8; (e) fully-assembled accelerometer

Although the majority of these sites are located in the U.S. and Europe (principally Italy and Germany) 48 of these are nodes are registered in Australia. In addition, QCN has been able to detect a Magnitude 5.1 earthquake in Reno, (May, 2008), a Magnitude 5.4 earthquake in Los Angeles, (July, 2008), a Magnitude 5.1 earthquake in Hawaii and a Magnitude 4.0 South-East of Los Angeles (April, 2009), and a Magnitude 4.5 earthquake in Germany, (May, 2009).

Figure 2 below provides recorded details of the Los Angeles, July, 2008 earthquake captured from one of the three QCN recording sites in the near vicinity (40 kms) of the epicentre, (further details: http://qcn.stanford.edu/earthquakes/2008/211/).

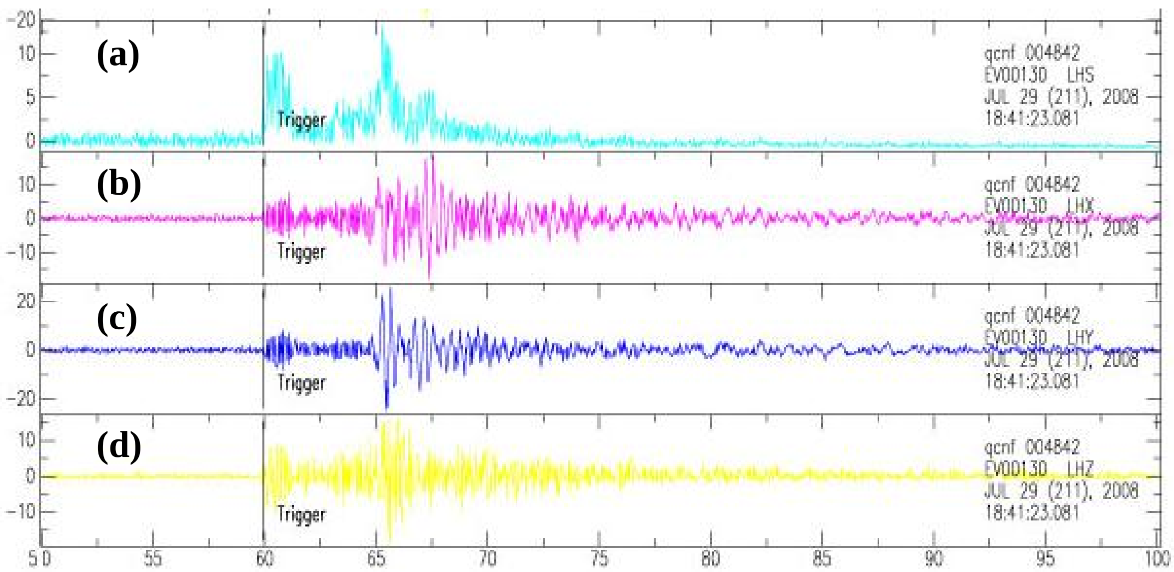

Fig. 2: QCN site vibration records: (a) significance filter (current shaking compared to shaking in the past minute); (b) left to right (not oriented geographically); (c) front to back; (d) vertical motion (Source: http://qcn.stanford.edu/earthquakes/2008/211/)

1.2 Using MEMS Accelerometers in other Structural Engineering Applications

Naturally MEMS based accelerometer sensors can be used in other structural vibration measurement and monitoring applications – not just for seismic (ground vibration) measurements. A number of different sensor schemes have been developed for this purpose possessing a wide range of attributes and performance characteristics. These would include:

- Wireless sensors
- USB/Serial port accessed accelerometers
- Self-contained battery powered accelerometer logging systems

A few trial experiments using Wireless Sensor Networks (WSNs) that incorporate MEMS based accelerometer and other sensors have been performed to assess their suitability for conducting periodic (or even continuous) Experimental Modal Analysis (EMA) and/or Structural Health Monitoring (SHM) applications, (Xu et al, 2004; Chung et al, 2004; Kim at al, 2006; Mechitov et al, 2006; Wu et al, 2007; Mascarenas et al, 2008). Whilst these trials have been considered to be reasonably successful, the experience of implementation has highlighted some technical issues surrounding power availability/management, jitter and time synchronization in data sampling of multiple time series of measurement, resolution in vibration measurement of sensor nodes, etc. Methods of addressing these issues in the use of WSNs in vibration measurement applications currently still reside in the research and development arena (Guneriwal et al, 2003; Wesson, 2005; Sazonov et al 2005).

In the case of limitations in WSN performance associated with power consumption, the more immediate solutions of using a larger battery (space/size not an issue) or incorporating solar charging of a rechargeable battery source (solar panelling can be installed nearby) have also been trialled with some success. Research into more novel "power harvesting" techniques that attempt to solve power issues in WSNs is still ongoing (Seah et al, 2009). It is obvious that provision of continuously available power from traditional sources (eg the power-grid) using wiring would negate the benefits of wireless technology in a WSN application unless of course the distances/logistics of accessing the output from the sensors concerned using wiring would be unattractive.

Where access to location(s) of measurement using MEMS based accelerometer sensors is not an issue, then USB/Serial port accessed versions of such sensors can prove to be attractive in such circumstances, eg Phidgets ±3g Triple Axis USB Accelerometer (Phidgets, 2009) and Sparkfun Tri-Axis v5 serial accelerometer, (Sparkfun, 2009a).

Where access is more problematic and wired power availability is an issue in "continuous" monitoring applications, then self-contained battery powered accelerometer logging systems may be more attractive. These systems would require periodic battery replacement and/or data recording medium (often an SD card) recovery/replacement, as needed, the frequency of which would depend upon power management and data recording strategies in these devices.

2. MEMS BASED ACCELEROMETERS CONNECTED TO COMPUTERS

USB MEMS based accelerometers, such as the Phidgets ±3g Triple Axis with 64 Hz maximum sampling rate (Phidgets, 2009) and serial port accelerometers, such as the Sparkfun Tri-Axis v5, (Sparkfun, 2009) are very attractive low-cost solutions for when short term monitoring of vibration at a single or limited number of multiple measurement points on a structure proves adequate. Most laptop/notebook computer manufacturers no longer provide serial ports on their more recent models, having opted to instead support multiple USB ports. Whilst this would certainly make it immediately attractive to develop a vibration monitoring station using a notebook computer connected to a USB MEMS based accelerometer with suitable interface software for logging data it does not preclude serial port versions of such accelerometers from being used as there are now a number of low cost plug-and-play USB-Serial interfaces commercially available for this purpose, (Haritos, 2008b).

2.1 Application to Teaching of Structural Dynamics

The illustration of basic concepts in the description of structural vibration in a teaching environment can be greatly facilitated using a vibration monitoring station consisting of a notebook driven MEMS based accelerometer and suitable interface data-logging software. Figure 3 illustrates the use of such a system on a simple Single Degree Of Freedom (SDOF) oscillator consisting of a slender vertical cantilever with a concentrated end mass. Portions of the data capture from a simple "pluck test" are depicted in Fig 3(b) and (c) for the vertically up and down orientation condition of the cantilever, respectively. This data capture enables students to readily investigate differences in natural frequency and damping (and its amplitude dependence) for these two configurations and to relate results to theoretical models, (Haritos, 2008b).

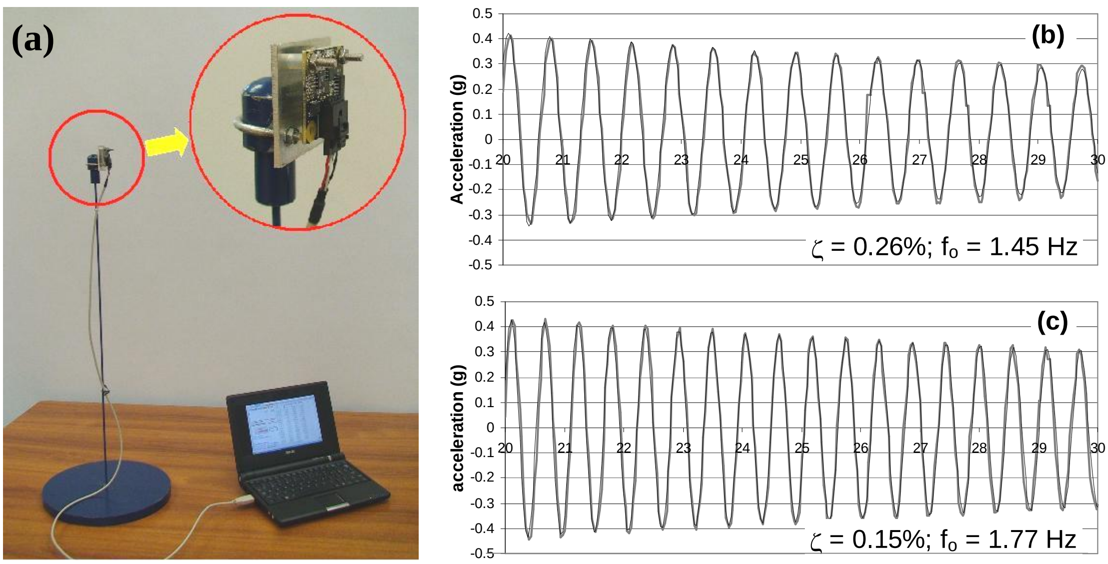

Fig. 3: Experimental investigation of a vertical cantilever using a Phidget accelerometer
(a) photograph of attachment
(b) in-line acceleration for cantilever oriented vertically upwards
(c) in-line acceleration for cantilever oriented vertically downwards

2.2 Application to Pedestrian Bridge Vibration Monitoring

The vibration monitoring station depicted in §2.1 and illustrated in Fig. 3 can be further enhanced by introducing multiple MEMS based accelerometers suitably housed in weatherproof enclosures for outdoor use on targeted structures. Data-logging software needs be modified to suit the number of accelerometers in the data capture but this proves not to be too difficult a task using a Visual Basic program called up from within the familiar MS-Excel platform. This operating environment not only produces a user-friendly outcome for the data-logging but also facilitates the subsequent analysis and treatment of the data capture from within MS-Excel.

A notebook driven vibration monitoring station with MS-Excel data-logging software for logging a single or a pair of Phidgets ±3g Triple Axis accelerometers has been used on a number of occasions by the author in support of research student projects relating to human-induced vibration of pedestrian bridges, (Haritos, 2008a; Mohammed & Haritos, 2008; Haritos, 2008c).

As an example of how effective and expedient the first time use of the single Phidgets ±3g Triple Axis accelerometer version of this vibration monitoring station turned out to be, it was possible to visit and determine the pedestrian induced vibration characteristics of all six pedestrian bridges along Melbourne's Eastern freeway spending close to an hour of data capture on each bridge all on the one day, (Haritos, 2008a). Table I identifies and describes the six bridges all of which were of different structural design.

Figure 4(a) depicts data capture at a 64Hz sampling rate for 15 contiguous records in progress on Bridge#1 with a typical 64 second portion of the vertical accelerometer trace depicted alongside, (Fig. 4(b)). Two or three such data sets were captured on each bridge to allow ensemble averaging of response spectra from several 64 second portions of record within each data set in the subsequent analysis and processing of the data.

Table I: Description of the six pedestrian bridges over Melbourne's Eastern freeway

Bridge #	Location	Description
1	Trenerry Cres., Abottsford	Four span (slight) curved beam on pier
2	Estelle Street, Bulleen	Three span curved beam on pier
3	Heyington Ave., Doncaster	Steel frame, timber deck, suspension
4	Eram Rd., Doncaster	Single span tapered frame
5	Joseph St., Blackburn Nth	Arch over, inclined stringers
6	Cabena St., Donvale	Arch under, braced vertical deck support

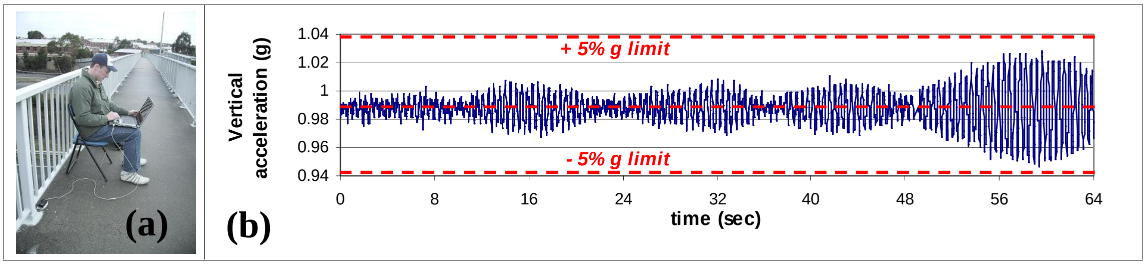

Fig. 4: Single pedestrian excursion of Bridge#1 (a) Sampling (b) Example trace

A spectral analysis fitting procedure as well as a "Randec" analysis was adopted to estimate the first mode natural frequency and damping ratio of each bridge. Visual inspection of the time domain data established maximum acceleration response levels to single pedestrian excitation over an approximate 50 minute total duration of record sampling (most bridges).

Table II provides a summary of the results from the analysis of the data capture. It is clear from this table that all bridges satisfy the ± 5% g acceptance criterion for peak level of single pedestrian excitation despite the fact that they all possess relatively low damping and lie in the so-called "troublesome" range of first mode natural frequency (1.5 Hz to 3.5 Hz) as identified in AS5100.2.

Table II: Results of dynamic response characteristics of the six pedestrian bridges

Bridge (#)	1	2	3	4	5	6
f_o (Hz)	2.19	1.95	2.84	3.05	2.73	2.75
ζ *(% crit)*	0.8	1.4	0.6	1	1.5	0.6
Acc. Limits *(% g)*	4	2	5	2.5	3	3

3. MEMS BASED ACCELEROMETERS PACKAGED AS STAND-ALONE DATALOGGER UNITS

Most MEMS based accelerometer designs provide a continuous output for the acceleration of the sensitive axis of concern (whether single, dual or tri axis models) in the form of a ratio-metric voltage to the input voltage over the "g" range of their operation. As a result, the simple procedure of aligning the sensitive axis of the accelerometer in the "+ve" vertical direction with gravity to take an initial voltage reading, V1, then reversing the orientation by 180 degrees to orient in the "-ve" vertical direction for a second reading, V2, allows user calibration of individual accelerometer axes to take place. For example the "offset voltage" (corresponding to 0 g) is simply (V1+V2)/2 and the "sensitivity" in Volts/g is given by (V1-V2)/2 for that axis.

Some MEMS based accelerometer can also (or as an alternative) provide a digitised output (usually 10- or 12-bit) for the acceleration of the sensitive axis of concern as they include an ADC (Analogue to Digital Conversion) step in their design.

MEMS accelerometer designs with analogue or digital outputs can be incorporated as sensor inputs to relatively inexpensive data-logging systems that can be either user-built eg using the Sparkfun Logomatic data-logger, (Sparkfun, 2009b) or have more recently been commercially produced eg the Gulf Coast Design Concepts (GCDC) models X6-1A and X6-2 (see: http://www.gcdataconcepts.com/products.html).

The author has trialed his own user-built Sparkfun Logomatic datalogging system pack using an analogue tri-axial MEMS accelerometer to occupy 3 of the 8 available input logger channels in both pedestrian bridge and tree dynamic response measurement applications with some success, (Haritos & James, 2008). Figure 5 (a) depicts the data-logger pack components and the die-cast housing complete with battery power supply and Fig 5(b) depicts the logger in operation, strapped to a tree trunk undergoing excitation under the effects of strong wind.

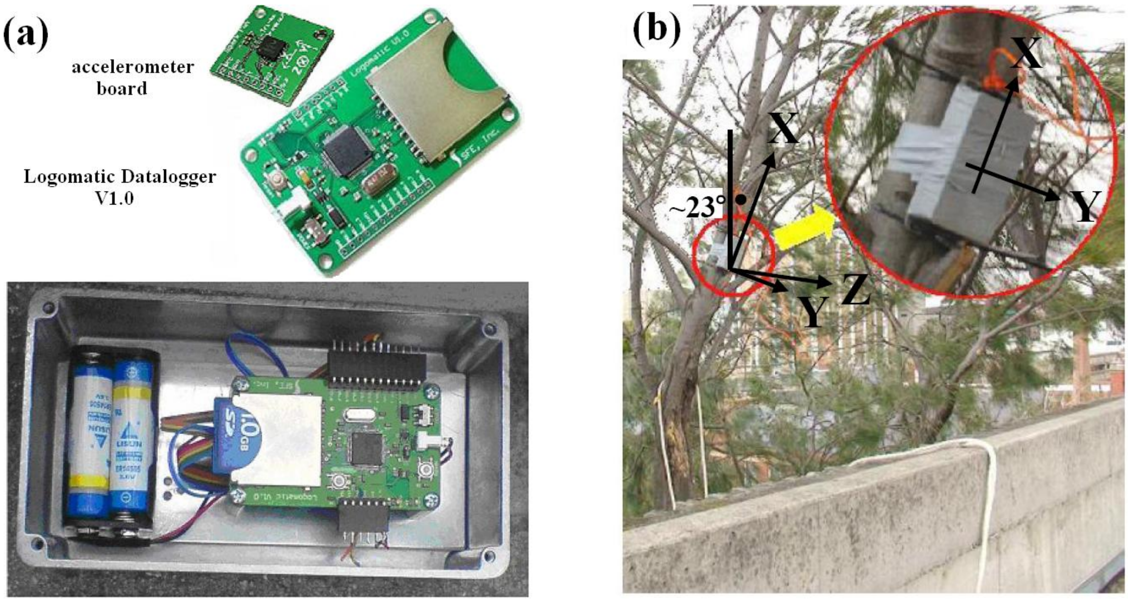

Fig. 5: (a) Logomatic data-logger accelerometer system pack   (b) Pack mounted on tree

Results obtained from the tree trunk acceleration response data recorded using the Logomatic data-logger pack included basic dynamic characteristics such as natural frequency and wind-speed dependent (aerodynamic) damping, (Haritos & James, 2008).

3.1 Commercially Packaged MEMS based accelerometer data-loggers

GCDC produce MEMS based accelerometer data-loggers X6-1A (requires a single AA battery) and X6-2 (contains an internal hardwired rechargeable Lithium-Polymer battery, charged via USB), (refer to Fig. 6) that offer a number of attractive features, (see: http://www.gcdataconcepts.com/products.html), that include:

- Low cost, compact size (approx. 105mm long and 25mm square)
- 3-axis low noise MEMS accelerometer
- User selectable ±2g and ±6g ranges
- User selectable sample rates of 20, 40, 80, and 160 Hz *(and 320 Hz for X6-2)*
- 12-bit resolution (leads to 1milli-g resolution in ± 2g range)
- Compact, rugged, and ready to use packaging
- Easily readable comma separated text data files
- User selected dead band setting (sample only when nominated threshold exceeded)
- Accurate (2 PPM) time stamped data using Real Time Clock (RTC)
- Data recorded to a field removable 1Gb micro-SD card (included)
- Data transfer compatible with Windows/Linux/Mac via Universal Serial Bus (USB) interface (no special software required)

A side-by-side comparison of the performance of the two model GCDC accelerometers with each other and the Phidgets USB accelerometer was attempted using single pedestrian excitation response measurements on Bridge#1 (described in §2.2) at approximately the 5/12 span position on the West edge of the deck.

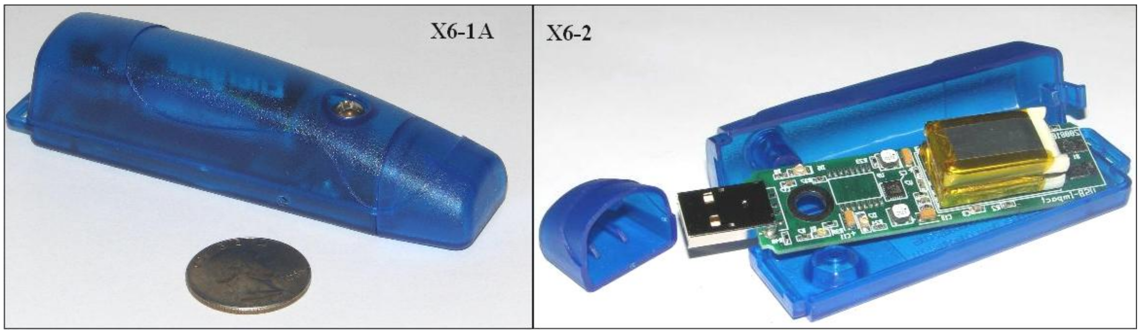

Fig 6: View of GCDC MEMS based accelerometer data-loggers X6-1A and X6-2

The GCDC accelerometers were set to sample at 160 Hz whilst the Phidgets sampled at its maximum rate of 64 Hz. It was not possible to obtain temporal synchronization of all three measurements at the time data capture took place, not only because simultaneous triggering/commencement of data capture was not possible on these separate hardware units but also because the rate of data capture differed between the units. The nominal 160 Hz sampling rate was observed to be actually 160.8Hz on the X6-1A and 159.1Hz on the X6-2 model. Data from the GCDC accelerometers was "block-averaged" down to a 40Hz sampling rate from the raw data values so as to be closer to the 64 Hz sampling rate of the Phidgets accelerometer for comparison purposes.

Contiguous data series of 4096 data points from the Phidgets (10 off of 64 second duration) and from both GCDC accelerometers (6 off of ~102.4 second duration) were analysed to produce ensemble averaged normalized acceleration response spectra for comparison purposes. Figure 7 depicts these spectra plotted to 20Hz (the Nyquist frequency for the GCDC accelerometers). It is observed in this figure that although the performance of the X6-1A accelerometer is similar to that of the Phidgets, it is able to capture the second mode bridge activity around 8-9 Hz more clearly. As far as the X6-2 is concerned, it would appear that this accelerometer is much less noisy and is able to depict the second mode peak around 8-9 Hz quite distinctly compared to the other two. All three accelerometers picked up the details of the first mode at 2.20 Hz quite well.

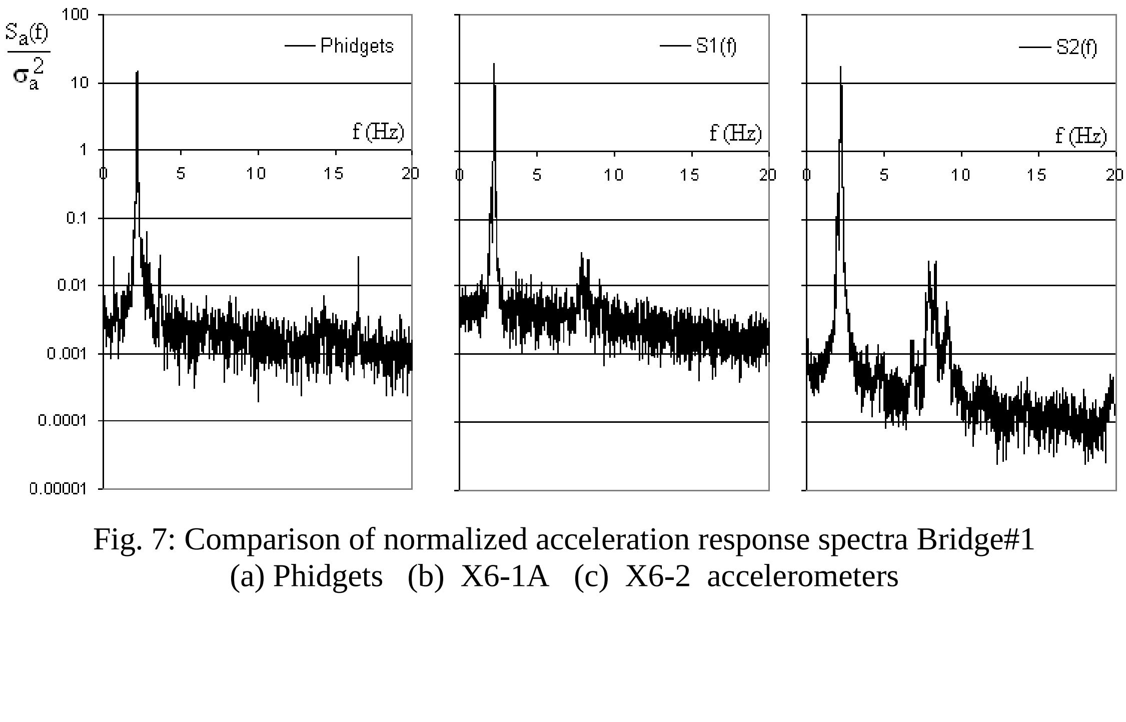

Fig. 7: Comparison of normalized acceleration response spectra Bridge#1
(a) Phidgets (b) X6-1A (c) X6-2 accelerometers

4.0 CONCLUDING REMARKS AND FUTURE DEVELOPMENTS

Low cost MEMS based accelerometers can be used in a number of application areas including early warning earthquake systems, eg QCN, and in teaching and research in structural dynamics, as detailed in this paper. Accelerometers themselves can be uni-axial, bi-axial or tri-axial in design with analogue or digitized (or both) output options. USB or serial connected (wired) forms of these accelerometer systems can be used in single point or limited multi-point vibration measurement applications. In the latter situation, EMA can be performed on the resultant measurements because data synchronization is controlled by sweeping through each accelerometer measurement channel at the desired sampling rate at the clock speed of the computer being used for the measurement station.

MEMS based accelerometers in WSNs where EMA is being attempted are still cost effective (when compared to their traditional wired counterparts) but power limitations with wireless transmission and synchronization issues with multiple data nodes normally preclude anything other than short term monitoring situations.

Compact self-powered accelerometer data-logging systems, whether purpose-built, or of the commercial variety are ideally suited to short (several hours) to medium term (several days) vibration monitoring applications, especially for measurements at a single point. Because some models offer time-stamping via a RTC to 2PPM accuracy, it may be possible to use these data-logging systems for performing EMA on the measurements after exercising software re-sampling of the data to achieve the necessary data synchronization. The author is currently exploring a cubic spline interpolation algorithm in conjunction with purpose-produced event marking before and after data capture for performing synchronized re-sampling in a controlled fashion on multi-point measurements using the GCDC accelerometer data-logging systems in pedestrian bridge EMA applications.

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