Damage Detection and Correlation-based Localization Using Wireless Mote Sensors

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Abstract— **This study focuses on an experimental damage detection and correlation-based localization demonstration using wireless sensors. A simple cantilever beam has been constructed in the laboratory to serve as a test bed for measuring acceleration responses with these devices. The goal of this preliminary investigation is to test the feasibility and functionality of a Wireless Sensor Network (WSN) to detect and localize damage utilizing current wireless mote technology.**

I. Introduction

RECENT advances in micro-electro-mechanical systems (MEMS), namely wireless smart sensing technologies, have sparked the interests of many researchers in the field of vibration based structural health monitoring (SHM) [1]. In light of these developments current health monitoring system paradigms are shifting. With the potential of wireless MEMS technology it is reasonable to consider larger sensor arrays, i.e. more densely instrumented structures, as part of the formulation of a condition monitoring system. As such, new innovations encompassing the aspects of data and power management as well as adjudicatory algorithms must be developed to fully extort the capabilities of a comprehensive decentralized wireless sensor network.

Wireless sensor networks (WSN) integrate sensing, wireless communication, and computation into one platform [2]. The application of WSN for civil engineering applications of SHM has several key benefits compared to traditional wired sensor systems. WSN can reduce deployment expenses significantly because it avoids the prohibitive capital cost of wiring sensors and power sources over the entire structure. Now for the first time it is reasonable to consider networks of densely deployed sensors which create far superior sample point coverage over the structure. As such, this high-spatial-resolution data coupled with efficient adjudicatory algorithms could enhance the detection and location of damage with better accuracy and precision. On-board computational units allow wireless sensors to process the observational data locally before transmitting it back to a base station or end-user. If data is pre-processed and reduced at the acquisition site, this would help to mitigate power consumption and data loss issues inherent of wireless transmission. Moreover, wireless sensors can be structured in networks such that they can communicate and collaborate with each other, heightening the sensitivity of a SHM system.

Wireless sensing technology does have limitations which need to be addressed. Two well-known intrinsic restrictions of any wireless device are its power source lifetime and the range over which data can be reliably transmitted. While colleagues in other fields of applied physics and electrical and computer engineering make strides toward improving these characteristics, those of us interested in applications of this technology for SHM are focusing on system development, i.e. efficient monitoring techniques, which best extort the current state of WSN.

In 2004 Pakzad and Fenves presented test results considering noise characteristics for two accelerometers, ADXL202 and SiliconDesign1221, mounted on a wireless sensor board [3]. The study included dynamic range tests using a vertical shaking table, showing different noise sensitivities for each accelerometer. Lynch illustrated a brief trend of wireless technology for real-time structural monitoring along with several different analysis algorithms that have been embedded on wireless sensing units [4]. Caffrey *et al.* proposed a two-stage approach that used the selective sensitivity of modal parameters in terms of spatial distribution of wireless sensors and mobile actuator. First, a spectral analysis is performed at individual sensor nodes to compute a set of modal parameters. Then the data sets are

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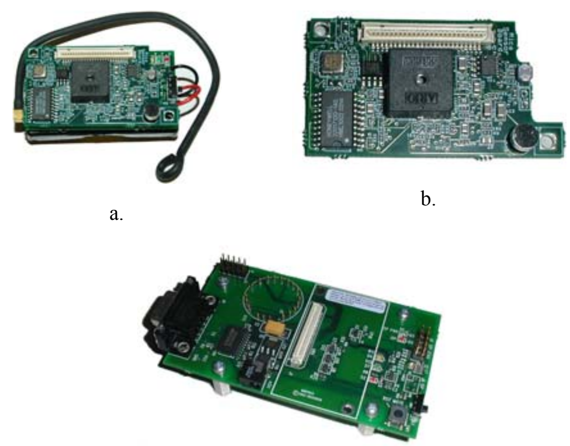
aggregated to create a global list of these parameters for damage detection. This approach was applied to the ASCE Task Group on Structural Health Monitoring's benchmark problem to detect structural damage. Glaser also presented two field applications of using wireless motes; one for measuring the acceleration of liquefied ground and the other one for wood-frame building on shake table [5]. The full-scale field test revealed practical difficulties of using wireless motes in terms of reliability and consistency. Currently Masuda *et al.* is developing wireless vibratory gyroscopes which will provide an alternative sensing parameter to rectilinear accelerations [1]. At this time the technology has not fully emerged and is lacking experimental validation. However, the use of this sensing technology for damage detection appears to be sound and promising.

This study focuses on an experimental damage detection demonstration implementing a correlation-based methodology for damage localization using wireless sensors. Wireless motes are equipped with accelerometers and employed as the sensors in this study. A simple cantilever beam has been constructed in the laboratory to serve as a test bed for measuring acceleration responses with these devices. From the response time histories obtained appropriate signal processing techniques are employed to determine the frequency characteristics of the structure. By obtaining sets of healthy and damaged structure frequencies damage can be realized. A numerical model of the structure is then used in conjunction with the experimental sets of frequency characteristics to localize the damage.

The goal of this preliminary investigation was to test the feasibility and to better understand the functionality of a WSN to detect and localize damage utilizing the current wireless mote technology. At this time the wireless mote technology has not yet developed cost effective and energy efficient devices which offer processing units powerful enough for real-time on-board data reduction and feature extraction. As such, a decentralized WSN was not created in this experiment. Thus, here the streaming data capabilities of standard, off-the-shelf, low-bandwidth, wireless motes were evaluated. Data from the experiment was acquired at a central location, i.e. a laptop computer, and evaluated with common signal processing and correlation algorithms ex post facto, to detect and localize damage. An advantage of our approach lies in its capacity of detecting and localizing damages based on low bandwidth data collected by wireless sensors, which eliminates the need for expensive specialized sensor devices or complex data compression techniques [6].

II. Wireless Sensors

To demonstrate the use of wireless sensor networks for damage detection and localization, MPR410CB Mica2 motes are coupled with MTS310CA multi-sensor boards to acquire acceleration measurements [7] [8]. The Mica2 mote, shown in Fig. 1a, is a tiny embedded computing platform roughly the size of a matchbox and operates on two AA batteries. It consists of a 7.37MHz 8-bit Atmel Atmega 128L microprocessor, CC1000 radio, and 512KB of flash memory. The microprocessor contains 128KB of instruction memory and 4KB of data memory. The CC1000 radio communicates at 38Kbps over a maximum range of 100m, though the actual range and reliability varies substantially over time and space [9]. The Mica2 mote runs the TinyOS operating system [10], [2] and is programmable using the component-based NesC [11] programming language. Mica2 motes are representative of nodes used in a typical wireless sensor network.



a. b. c.

Fig. 1. Wireless Mote. a.) A MPR410CB Mica2 mote with a MTS310CA multi-sensor board. b.) The MTS310CA multi-sensor board. c.) The MIB510CA programming board/base station.

The MTS310CA multi-sensor board, shown in Fig. 1b, is used in conjunction with the Mica2 mote. The sensor board has an ADXL202JE two-axis accelerometer by Analog Devices [12]. Its specifications are shown in TABLE I. The motes have a programmable sampling frequency at which data can be acquired. The frequency at which the sensor is queried can be adjusted within the software. To reduce the number of messages transmitted, 10 measurements are cached and sent within a single message to the base station shown in Fig. 1c. The base station is connected to a laptop via a serial link, and it simply forwards all messages to the laptop. The laptop runs a Java application that logs the data for off-line analysis. Each group of 10 measurements within a message is tagged with a sequence number and source mote ID number, allowing the data logger to correctly arrange the resulting data. Since each message contains ten measurements, a single message loss will result in ten missing sensor readings. Complex acknowledgement and retransmit schemes are not implemented at this time to avoid problems due to additional overhead and worsened radio contention.

The motes use a simple carrier-sense-multiple-access (CSMA) protocol for taking ownership of the radio channel, resulting in decreased bandwidth due to contention and message loss due to wireless collisions. As more motes are added and the sampling frequency is increased, the chance for message loss increases. As such, a parameter study was performed to determine the optimal sampling frequency for a multi-mote sensing configuration at sampling frequencies of 25Hz, 100Hz, and 200Hz utilizing 2-4 motes simultaneously. Fig. 2 illustrates the direct relationship between data loss as both the number of motes and sampling frequency increase.

TABLE I

SPECIFICATIONS OF THE ADXL202JE TWO-AXIS ACCELEROMETER

Channels	2
G-range	±2 g, 1g = 9.81m/s^2
Bandwidth	50Hz
Resolution	2mG RMS
Sensitivity	167mV/G ±17%
Offset	2.5 V ± 0.4V

In more extreme cases with three motes sampling at 200Hz each, the motes are collectively attempting to transmit 15.84Kbps and the effects of network saturation are readily observed as more than half of the packets are lost, c.f. Fig. 2. All data acquired and presented in this paper was obtained using three motes simultaneously, each sampling at a 100Hz. The response time history shown in Fig. 3 illustrates the nominal amount of data loss observed during experiments utilizing three motes at 100Hz.

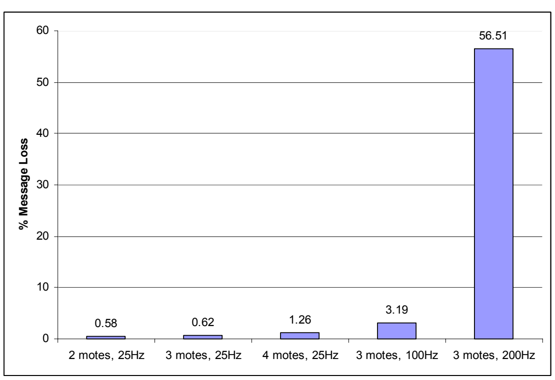


Fig. 2. Percent message loss over varying number of motes and sampling frequencies.

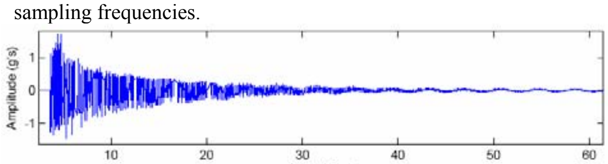


Fig. 3. Typical response time history.

III. CORRELATION-BASED DAMAGE LOCALIZATION

The concept of linear correlation has been widely accepted as a reliable means to resolve the location of damage in simple structural systems. Crawley and Adams presented one of the earliest studies which used a vector dot product correlation of natural frequency changes as a metric for damage localization [13]. Later, Lew introduced a similar correlation-based method that identified the type and location of damage by monitoring the changes in transfer function coefficients [14]. In Lew's study, the coefficient of correlation simply represented the cosine of the angle between two parameter vectors. In both studies the analysis was performed as such, one vector was populated with the measured parameter of choice, i.e. frequency changes or transfer function coefficients, which were obtained from the damaged structure. Then a suite of hypothesis vectors were generated from numerical model of the structure such that each vector within the suite synthesized a unique damage location. As such, when the hypothesized vector accurately represented the true damage state of the structure the vectors would be collinear and the cosine of the angle between them would tend to unity.

Messina *et al.* proposed a similar correlation concept based on the Modal Assurance Criterion (MAC) to develop the Damage Location Assurance Criterion (DLAC) [15][16][17]. A MAC value measures the extent of linear correlation between an experimental and analytical mode shape and is typically used for validating the fidelity of an analytical model. In their work Messina and company argue that the MAC concept can be extended to the frequency characteristics of a structure and present convincing results supporting the concept. As such, the DLAC method measures the correlation of a vector of experimental natural frequency change ratios with a vector of analytical natural frequency change ratios instead of mode shapes. In subsequent work the DLAC method further evolved to the Multiple Damage Location Assurance Criterion (MDLAC) which, as the name implies, can accommodate the existence of multiple damage location scenarios [17]. However we leave the discussion here as the scope of our study is limited only to single damage location scenarios.

The effectiveness of a correlation-based technique to locate damage hinges on ones ability to capture both a sufficient and accurate set of the system's modal parameters. It is important to note that this is a twofold requirement in the realm of accuracy. Obtaining an accurate set of experimental modal parameters is almost always an issue, but obtaining an accurate set of analytical parameters which correspond well to the real structure as-built can also prove to be a challenge since an updated, i.e. a dynamically tuned, analytical model is not always available in practice. Sufficiency, that is obtaining large enough set of parameters, is not typically a problem with a numerical model; however, it is common that only a limited number of natural frequencies can be realized experimentally. Both accuracy and sufficiency introduce errors into the correlation-based technique and can hinder its ability identify and uniquely localize damage.

A notable benefit of the linear correlation-based technique is that the selected magnitude of damage simulated in the suite of hypotheses vectors does not significantly affect the results of damage localization. Considering only the single damage scenario, this implies that the technique is not computationally intensive as only a single suite of damage hypothesis vectors need to be generated. While a multi-damage scenario is more likely in practice and would clearly increase the computational requirements, it is believed that the insensitivity of this technique to the hypothesized damage magnitude would prove to be beneficial.

In this study the DLAC correlation method is utilized, refer to Eq. (1) [17][16]. Here the first *n* modal frequency changes due to damage, $\Delta\omega = \left(\omega_h - \omega_d\right) / \omega_h$, are observed. Where, ω_h and ω_d denote the vectors of experimentally determined natural frequency of the healthy and damaged structure, respectively. Note that $\Delta\omega$, the frequency change, is normalized with respect to the structure's healthy frequencies. Normalizing in this fashion equally weights all modes of the frequency change vector and reduces bias introduced from higher modes. Likewise, a suite of hypothesis damage vectors, also consisting of the ratios of natural frequency changes, $\delta\omega_j$, is synthesized from the analytical model of the structure.

$$\mathrm{DLAC}_j = \frac{\left|\{\Delta\omega\}^{\mathrm{T}}\{\delta\omega_j\}\right|^2}{\left(\{\Delta\omega\}^{\mathrm{T}}\{\Delta\omega\}\right)\left(\{\delta\omega_j\}^{\mathrm{T}}\{\delta\omega_j\}\right)} \tag{1}$$

It is important to note that Eq. (1) can only be used to detect single damage occurrences, more complex methodologies, such as the MDLAC technique, must be employed to locate multiple damage locations.

IV. Experimental Damage Detection and Localization

To validate the performance of off-the-shelf wireless motes with accelerometers for damage detection and localization using streaming data, a laboratory experiment is conducted. The test structure employed is a 2.74m by .76m by .065m steel beam, fixed rigidly at the base so as to simulate a vertical cantilever beam. The beam is instrumented with five wired AC accelerometers located at equally spaced intervals, c.f. Fig. 4. Mote accelerometers are located on the beam adjacent to their wired counterparts for response comparison. The results presented in this study correspond to experiments using three motes located at S2, S3, and S4 on the beam.

Damage is effectively simulated by clamping a bar mass equivalent to 10 percent of the total beam mass at three different locations along the beam. The damage locations are denoted in Fig. 4 as D1, D2, and D3, and are at distances from the base of 1.33m., 1.89m, and .65m, respectively. Localizing damage at the three different damage sites is considered to be of varying levels of difficulty, as the effect of the additional mass on the system parameters lessens as it tends toward the fixed end of the beam. Conversely, the effect of mass change on the modal parameters becomes more pronounced as the mass moves further from the fixed boundary condition.

The beam was struck such that the primary modes of vibration excited would be those about the weaker axis of bending. The input excitation was assumed to be similar to a pure impulse. The strike location was consistent throughout all tests and its relative location on the beam is denoted by the Dirac delta in Fig. 4.

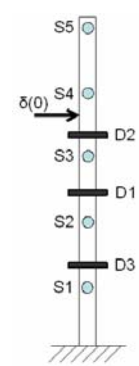


Fig. 4. Schematic of the cantilever beam test structure; the impact point is denoted by the Dirac delta function, instrumentation locations and damage locations are annotated as S1-S5 and D1-D3, respectively.

The experiments conducted utilized unsynchronized acceleration response time histories obtained simultaneously from three wireless motes at a sampling rate of 100 Hz. Attempts were made to sample at rates exceeding 100 Hz; however, as discussed previously, severe data loss hindered the spectral analysis. The motes used in this experiment were not equipped with the required on-board computational power to perform in-situ feature extraction or data reduction. Thus, raw time history data is received at the base station, stored on a portable computer, and later post-processed.

Spectral analysis of the response time histories was completed using MATLAB® via the periodogram method. One frame of data was used from each sensor. As such no averaging in the time domain occurred. The natural frequencies of the cantilever beam were identified by manually selecting the peaks in the power spectrum of the response time history. Refer to Fig. 5 for a typical power spectrum of the healthy structure.

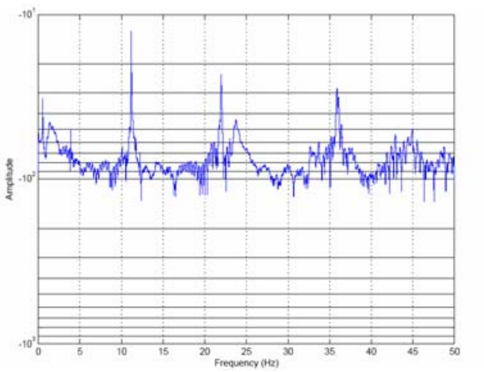


Fig. 5. Typical power spectrum of the healthy structure.

Eight tests were conducted on the healthy beam. Each test produced a set of four natural frequencies. The identified natural frequencies from each test were averaged together and deemed the healthy beam frequencies, i.e. $\omega_{Healthy}$. Likewise, four tests were conducted for each particular damage scenario to obtain three sets of averaged damaged beam frequencies, i.e. $\omega_{D\,1}$, $\omega_{D\,2}$, and $\omega_{D\,3}$.

A. Damage Detection Results

To identify changes in the structure, damage hypotheses frequencies are generated from a finite element (FE) model of the cantilevered beam. The model consists of nineteen Euler-Bernoulli beam elements having transverse and rotational DOF at each node. The analytical damage frequencies presented in TABLE IV were created by lumping mass at nodes corresponding to the actual location of the experimental damage cases. TABLE II and TABLE IV present the experimentally identified and numerically simulated natural frequencies of the test structure, respectively. To better understand the difference between the frequencies obtained experimentally with wireless sensors and the analytical frequencies, a traditional modal parameter test was conducted using wired sensors, c.f. TABLE III. The modal analysis using wired sensors presents frequencies which are in fair agreement with those obtained with the wireless motes. Unfortunately, the results presented in Tables II and III were not obtained simultaneously due to computer software problems. As such, the slightly higher frequencies observed in modes 2-4 of Table III are most likely due to the slight reduction in the beam's mass as the battery powered motes were not attached to the structure while data was acquired for these test. Despite the discrepancies noted between the wired and wireless frequencies a distinct shift between healthy and damaged frequencies is still apparent, thus we say damage can be detected.

Significant deviations in natural frequencies exist between those obtained experimentally and byway of the FE model. These differences are most likely attributed to an imperfect clamped boundary condition at the base of the beam and additional mass of the battery powered motes which was neglected in the FE model. In practice, a high-fidelity, tuned FE model of an as-built civil engineering structure is often unavailable. Thus, damage detection methodologies should be robust to modeling errors of the type observed here. Therefore to offer a valid real-world analysis, the FE model was not updated in this study.

TABLE II

EXPERIMENTALLY IDENTIFIED NATURAL FREQUENCIES USING WIRELESS MOTES (HZ)

Mode	$\omega_{Healthy}$	$\omega_{D\,1}$	$\omega_{D\,2}$	$\omega_{D\,3}$
1st	.54	.51	.48	.53
2nd	3.91	3.61	3.83	3.82
3rd	11.16	11.16	10.46	10.25
4th	21.95	20.49	21.46	20.54

TABLE III

EXPERIMENTALLY IDENTIFIED NATURAL FREQUENCIES USING WIRED SENSORS (HZ)

Mode	$\omega_{Healthy}$	$\omega_{D\,1}$	$\omega_{D\,2}$	$\omega_{D\,3}$
1st	.50	.50	.50	.50
2nd	4.00	3.75	4.00	3.88
3rd	11.50	11.50	10.75	10.50
4th	22.63	21.00	22.13	21.25

TABLE IV

NUMERICALLY SIMULATED NATURAL FREQUENCIES (HZ)

Mode	$\omega_{Healthy}$	$\omega_{D\,1}$	$\omega_{D\,2}$	$\omega_{D\,3}$
1st	.70	.69	.66	.70
2nd	4.39	4.02	4.28	4.26
3rd	12.28	12.24	11.49	11.27
4th	24.06	22.43	23.77	22.38

B. Localization Results

To localize structural damage the FE model was used to generate a suite of nineteen analytical damage hypotheses frequency change vectors. Each set of hypothesis frequencies were created by increasing the mass by one percent at a single node. Using the DLAC method previously described the damage was localized.

Localization results for three different damage cases are depicted in Fig. 6. Here the calculated DLAC coefficients are plotted along the length of the beam. Recall that a correlation factor equal to unity represents perfect co-linearity of the hypothesis and experimental frequency change vectors. Since experimental error exists damage is said to be localized to areas where the DLAC value is near unity.

Experimental results are represented with a solid line, while the accompanying dashed line shows the results of a simulated FE analysis of the damage condition. The vertical dashed line indicates the true location of mass change in the beam. It is obvious that the peak of coefficient value successfully indicates the correct location of damage in all three cases. Again, since we are only dealing with a single damage case, the location of damage can be uniquely identified; however, from Fig. 6b, it is clear that damage case D2 (1.89m from the floor) exhibits a slightly inaccurate localization result. This result is primarily due to the fact that mass change in this particular location produces similar frequency change vector which can also be caused by other damage locations. The numerically simulated values of correlation factor (dashed line) between D2 and the free end of the beam are relatively high (above 0.5) compared to other potential damage locations, indicating that it is difficult to distinguish the true damage location in that span using only the first four natural frequencies. Although there exist some multiple peaks in the correlation factors (Fig. 6b), no false negatives occurred in the experiment therefore the results of damage localization are satisfactory. Also, the modeling errors that caused an offset of natural frequencies between the experiment and FE model were not a significant concern for damage localization using correlation-based method.

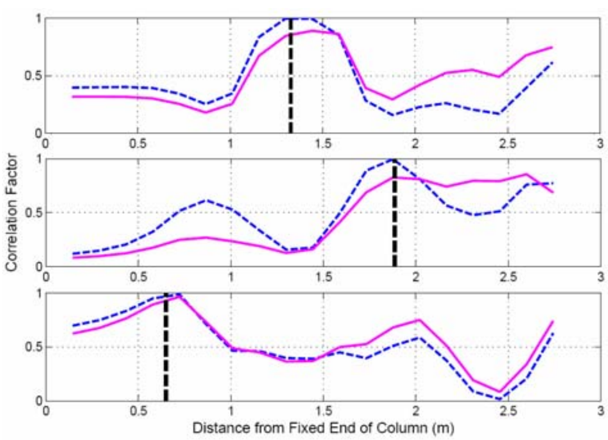


Fig. 6. DLAC correlation factors vs. length of beam; solid lines are experimental results, dashed lines are simulated results, vertical dashed line indicates true damage location. Damage locations: a.) D1, b.) D2, and c.) D3

V. Conclusion and Future Strides

In this paper a demonstration of wireless sensor data for damage identification and localization has been successfully performed. The results indicate that an accurate set of modal parameters can be obtained using streamed time history data from accelerometers paired with off-the-shelf wireless motes. The experimentally obtained healthy and damaged natural frequencies correspond well with those obtained with traditional wired sensors. Using the DLAC correlation technique, damage identification and localization was successfully achieved using features extracted from wireless acceleration time histories.

In continuation of this study future research efforts will be focused on the following issues: sensor power management techniques such as a periodic sentinel-sleep scheduling, data synchronization for mode shape determination, investigation of piecewise-continuous mode shape algorithms to facilitate damage localization in decentralized data collection/processing environments, and instrumentation of a more complex civil structure outside of the laboratory.

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