Wireless Structural Health Monitoring Using an Active Sensing Node

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Abstract

The development of an active sensing node has brought the traditional impedance-based structural health monitoring (SHM) technique to a new paradigm. The active sensing node consists of a miniaturized impedance measuring device (AD5933), a microcontroller (ATmega128L), and a radio frequency (RF) transmitter (XBee). A macro-fiber composite (MFC) patch interrogates a host structure by using a self-sensing technique of the miniaturized impedance measuring device. All the process including structural interrogation, data acquisition, signal processing, and damage diagnostic is being performed at the sensor location by the microcontroller. The RF transmitter is used to communicate the current status of the host structure. To validate the feasibility of the proposed active sensor node, two kinds of example studies are carried out: (a) corrosion detection on an aluminum beam and (b) loose bolt inspection on a bolt-jointed structure.

Keywords: wireless structural health monitoring, active sensing node, impedance, piezoelectric materials, radio frequency.

1. Introduction

Civil infrastructures such as buildings, bridges, dams, water supply lines, tunnels, and off-shore platforms are suffering the damage caused by fatigues, large earthquakes, strong winds, and environmental effects or traffic impact. Early detection of the structural damage or deterioration prior to local failure can prevent catastrophic failure of the structures. Sensors to monitor the structures have special requirements. They must be 1) inexpensive as many are required, 2) rugged as they are exposed to the strong elements of nature, 3) preferably wireless with some data processing capabilities, and 4) minimal power requirement or which can work with the harvested power. The large and complex civil infrastructures necessitate low cost but high effect smart sensors and appropriate technologies for data acquisition/reduction for rational health monitoring applications. The sensor systems should also be able to automatically detect, locate and assess damage anywhere within the structures, and to communicate the status to responsible authorities. In this context, this study proposes a self-contained active sensor system for impedance-based health monitoring of the civil infrastructures. The final goal of this research is to develop an intelligent multi-functional sensor which will utilize energy harvested from the ambient environment, analyze the sensing data on a single chip, and wirelessly provide the status of the structure to an end user.

The use of wireless sensors and sensor networks are becoming increasingly popular as a research topic for SHM system (Spencer \textit{et al.}, 2004). Many studies have simply described a means to acquire data on a structure and wirelessly transmit the data somewhere else for processing at host computer. Wirelessly transmitting all of the data is much more inefficient than local computing which simply transmitting the results and may be as simple as revealing that the structure is or is not damaged. The focus of this study is to deal with a wireless SHM scheme with local processing ability. A sensor network to detect strain in the structure was reported by Basheer \textit{et al.}, 2003. Each sensor has the ability to process the raw strain data using neighboring sensors and transmit the resulting information to an end user. Tanner \textit{et al.}, 2003 demonstrated local processing capabilities with off the shelf components in a wireless SHM system. A wireless active sensing unit to monitor civil structures has been designed by Lynch \textit{et al.}, 2004. Figure 1 illustrates several kinds of wireless sensor nodes the most widely used at the present. This paper presents a wireless active sensing node for a practical use of an impedance-based SHM technique.

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2. Impedance-based Structural Health Monitoring (SHM) Technique

Recent advances in the structural health monitoring (SHM) and nondestructive evaluation (NDE) field have led to the development of novel techniques such as smart sensors/sensor networks, on-line health monitoring and wireless telemetry. As one of the typical examples, an automated electro-mechanical impedance-based SHM technique using piezoelectric materials has been investigated with keen interest as a powerful and innovative NDE method for local damage detection of a variety of structures (Giurgiuțiu et al., 2000; Zagrai and Giurgiuțiu, 2001; Park et al., 2004; Park et al., 2006a). The electro-mechanical impedance-based SHM technique utilizes piezoelectric patch sensors such as PZT and MFC sensors as self-sensing actuators. The piezoelectric patches attached to a host structure excite the structure with high-frequency excitations, and simultaneously obtain the structural dynamic response as a shape of electrical impedance functions. By monitoring the changes of real parts of the electrical impedance functions of the piezoelectric patches, assessments can be made about the integrity of the host structure (Park et al., 2003). However, the electro-mechanical impedance-based SHM technique has some limitations because the measured impedance data may have considerable deviations caused by environmental or operational condition changes, particularly a temperature change (Park, G. et al., 1999). Thus, the technique sometimes gives false-positive indication even for healthy structures. In order to overcome this limitation, an outlier analysis based on Mahalanobis squared distance (MSD) measure taking root mean square deviation (RMSD) values of impedance signatures as a damage-sensitive feature vector was proposed by Park et al., 2006b. Through the proposed outlier analysis, an optimal threshold value that minimizes the false-positive indication rate could be determined.

Since the development of the piezoceramic materials such as PZT, they have been used extensively in the fields of sensing and actuation including the electro-mechanical impedance-based SHM techniques. However, these materials have several properties that limit their use in field applications. Due to the ceramic nature of the monolithic piezoelectric material, they are very brittle, making them vulnerable to accidental breakage during handling and bonding procedures. In addition, they have very poor ability to conform to curved surfaces and are very dense and stiff causing mass loading and localized stiffness to be a factor when working with very flexible or lightweight structures. These limitations have motivated researchers to develop alternative methods of manufacturing the next generation of piezoelectric material. To resolve the inadequacy of monolithic piezoceramic material for real applications, utilizing a composite material consisting of an active piezoceramic fiber embedded in a polymeric matrix was investigated. Typically, when in fiber form crystalline materials lose much higher strengths, where the decrease in volume fraction of flaws leads to and increase in specific strength (Williams et al., 2002). In addition to this added strength of the base material, the flexibility of the polymer matrix allows the piezoceramic fibers to have greatly increased conformability to curved surfaces and provides a protective shell around the piezoelectric material. This polymer shell allows the piezofiber to withstand impacts and harsh environments far better than those monolithic piezoelectric materials. The result of configuring the piezofiber inside a polymer matrix is an actuator that can be incorporated into or bonded to a variety of structures. Based on above background, macro-fiber composite (MFC) actuators were constructed at NASA Langley Research Center (Wilkie et al., 2000). The MFC consists of three primary components; active piezoceramic fibers aligned in a unidirectional manner, inter-digitated electrodes (IDE), and an adhesive polymer matrix, as shown in Figure 2 (www.smart-material.com). The IDE is oriented orthogonal to the fiber direction allowing the larger d33 coefficient to couple the electric field to mechanical strain. This greatly improves the level of excitation applied to the structure. When embedded in a surface of the host structure, the MFC provides distributed solid-state deflection so as to efficiently excite the host structures. It is noted that the MFCs have directional sensing capability not seen in PZTs that could prove useful in damage location. In addition, the MFC electrodes are protected by Kapton, and would be robust sensors/actuators in corrosive environments. The MFC patches with above properties have been used as a self-sensing actuator for the electro-mechanical impedance method in some previous studies (Simmers et al., 2005; Park, S. et al., 2006b).

Conventionally, the impedance-based SHM method requires the use of impedance analyzers such as HP4194A.
or HP4294A. Such analyzers are bulky and expensive (around 41,000 USD) and are not attractive for online SHM system. With a current trend of SHM techniques heading toward unobtrusive self-contained sensors, development of a wireless active sensing node incorporating all the functions including on-board actuating/sensing, power generation, on-board data processing/damage diagnostic, and RF module is being strongly investigated. In particular, the approach integrating MEMS and wireless telemetry-based active sensing systems on the electro-mechanical impedance-based damage detection technique was started with Inman and Grisso, 2006.

3. A Proposed Active Sensing Node

One hardware component will need to measure the impedance of the structure of interest. Analog Devices has recently introduced single chip impedance measurement devices such as AD5933 and AD5934 (www.analog.com). The AD5933 and AD5934 impedance chips are nearly identical except for their sampling speeds. The AD5933 has a 1 MHz sampling rate, while the AD5934 uses a 250 kHz sampling speed. In order to demonstrate the functionality of the new chips, Analog Devices developed evaluation boards for both of the chips. The AD5933 evaluation board and its block diagram can be seen in Figure 3

![Figure 2. A Macro-fiber composite (MFC) patch (www.smart-material.com).](image2)

Using a USB connection and provided software, a user can make impedance measurements in the range of 10-100 kHz. The AD5933 primarily records the magnitude of the impedance. However, phase is also recorded, and the real and imaginary impedance components can be saved. In order to evaluate the possibility of incorporating the AD5933 chip, we compared the AD5933 impedance chip with the conventional impedance analyzer, HP4194A. The results of recording measurements in the 60-70 kHz frequency range are shown in Fig. 4. The same response is seen with both the HP 4194A impedance analyzer and the AD5933 impedance chip, and the same peaks are shown at the same frequencies. The conventional electro-mechanical impedance-based SHM technique which uses HP4194A has never been attractive for real-world applications because they are bulky and expensive (around $40,000). Therefore, this study employs the AD5933 which is low-cost ($150) and portable. Our final device incorporating this device would be an intelligent multi-functional sensor which utilizes energy harvested from the ambient environment of the host structure, analyzes the sensing data on a single chip, and wirelessly provides

![Figure 3. A Miniaturized impedance measuring chip (AD5933) and block diagram (www.analog.com).](image3)

![Figure 4. Comparison of impedance measurement from AD5933 and HP4194A.](image4)
the status of the structure to an end user. The big picture of the intelligent multi-functional sensor was conceptually designed by Inman and Grisso (2006), as illustrated in Fig. 5.

Mascarenas et al., 2006 designed a wireless active sensing node which consists of a miniaturized impedance measuring device (AD5933), a microcontroller (ATmega128L), and a radio frequency (RF) transmitter (XBee), as illustrated in Fig. 6 (around $300). ATmega128L is an 8-bit microcontroller (Atmel AVR) and costs $5.00. It operates at low power levels, and has different peripheral features and memory capabilities. In addition, open-source C compilers are available. The RF transmitter utilized in this study is a 2.4GHz XBee radio (Maxstream). It costs only $19.00 and operates from 3.3 V power supply. In addition, a variety of antenna configurations are available. Current RF module covers a range corresponding to distances of 30 m (indoor) and 100 m (outdoor).

In the on-board sensor system, all the process including structural interrogation, data acquisition, signal processing, soft computing and damage diagnosis is being carried out in near real-time at the sensor location. And only damage diagnostic result implying ‘damage’ or ‘no damage’ will be transmitted to the end-user through the RF telemetry. Finally, the LED light shows ‘green’ or ‘red’ color according to ‘intact’ or ‘damage’ state, respectively. The overall concept for online wireless SHM system using the active sensing node is displayed in Fig. 7. In reality, the individual components used to actually make up the sensor node should be able to fit on a single printed circuit board (PCB) roughly the size of a credit card. To validate the feasibility of the proposed active sensing node, two kinds of example studies have been carried out in this study: (a) corrosion detection on an aluminum beam and (b) loose bolt inspection on a bolt-jointed structure.

4. Example Studies

![Online wireless SHM system using an active sensing node.](image-url)
4.1. Example study I: Corrosion detection on an aluminum beam

An example study for corrosion detection testing was carried out on a simple beam made from a 6063 T5 aluminum alloy. As shown in Figure 8, two MFC patches of $4 \times 2.54 \times 0.0267$ cm$^3$ associated with the AD5933 was surface mounted to the specimen of $83 \times 2.54 \times 0.2$ cm$^3$. One baseline case, four different intact cases with different boundary conditions, and four different corrosion cases (at two different locations and with two different corrosion depths at each location) were artificially inflicted in sequence, as described in Table 1. Each corrosion case has a coverage area of $2.54 \times 2.54$ cm$^2$. According to the damage scenario, the electro-mechanical impedances were measured with a frequency range of 65-66 kHz from MFC #1 as in Fig. 9, and the RMSD metrics were calculated, as displayed in Fig. 10(a). Note that same procedure was repeated at MFC #2 for all the damage case. The RMSD metrics calculated from MFC#2 are shown in Fig. 10(b). Then, an optimal threshold value to enhance the damage detectible capability of the current system so that minimize a false-positive damage indication rate was obtained as 7.59 from an outlier analysis (Park et al., 2006b). As a result, it is observed that the RMSD changes of the impedance signatures due to 'boundary condition change' are not significant as compared with the changes due to real corrosion damage. Also, it is concluded that the RMSD metric easily identified the damaged cases from the intact cases, and also distinguished fairly well between four different degrees of the corrosion. At this point, it is noted that the damage diagnostic result implying 'damage' or 'no damage' was transmitted to the base station through the RF telemetry, and the LED light of the base station showed "green color" on intact states and "red color" on damage states. In other words, it can be concluded that the proposed active sensing node can be an effective tool for detecting corrosion damage in aluminum structures.

### Table 1. Damage description for example study I

<table>
<thead>
<tr>
<th>Cases</th>
<th>Scenario</th>
<th>Corrosion degree (Thickness reduction)</th>
<th>Corrosion location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Baseline</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 2</td>
<td>Intact 1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 3</td>
<td>Intact 2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 4</td>
<td>Intact 3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 5</td>
<td>Intact 4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Case 6</td>
<td>Corrosion 1</td>
<td>2.5%</td>
<td>18 cm away from MFC #1</td>
</tr>
<tr>
<td>Case 7</td>
<td>Corrosion 2</td>
<td>5.0%</td>
<td>18 cm away from MFC#1</td>
</tr>
<tr>
<td>Case 8</td>
<td>Corrosion 3</td>
<td>2.5%</td>
<td>55 cm away from MFC#1</td>
</tr>
<tr>
<td>Case 9</td>
<td>Corrosion 4</td>
<td>5.0%</td>
<td>55 cm away from MFC#1</td>
</tr>
</tbody>
</table>

4.2. Example study II: Loose bolt Inspection on a bolt-
jointed aluminum beam

Another example study inspecting loose bolts in a bolt-jointed aluminum structure was performed. As shown in Fig. 11, the MFC patch of $4 \times 2.54 \times 0.0267$ cm$^3$ associated with the AD5933 was surface mounted to the specimen that consists of two aluminum beams of dimension $61.5 \times 5 \times 0.4$ cm$^3$ jointed together with four pairs of bolts and nuts of diameter 8mm. The MFC patch was placed at 16 cm apart from the middle of the joint section of the specimen. During the experiment, the boundary condition for the specimen was held as ‘free-free’ condition. Damage scenario for healthy and damage states repeated by several times was artificially inflicted in sequence, as described in Table 2. Electro-mechanical impedances according to the damage scenario were measured at a frequency range of 60-70 kHz from the AD5933, as shown in Fig. 12(a). Then, the RMSD metrics were calculated according to each damage case, as displayed in Fig. 12(b). An optimal threshold value for damage detection to enhance the damage detectible capability of the current system so that minimize a false-positive damage indication rate was obtained as 0.32 from an outlier analysis (Park et al., 2006b). It is also noted that the damage diagnostic result implying ‘damage’ or ‘no damage’ was transmitted to the base station through the RF telemetry, and the LED light of the base station showed ‘green color’ on intact states and ‘red color’ on damage states. Conclusively, it can be said that the proposed active sensing node possesses a very good damage detectible capability by providing consistent results according to bolt-loosening (damaged) and retightening (healthy) states in the bolt-jointed structure. However, the above results show that the current method is difficult to detect the location of the damage, so it may be necessary to combine the method with other NDE techniques like Lamb waves or acoustic emission methods to locate the damage more exactly.

5. Conclusions

This study presents experimental results using an active sensing node incorporating a miniaturized impedance measuring device (AD5933), an on-board microcontroller (ATmega128L) and a RF/wireless telemetry (XBee) devised for online wireless SHM system to detect damage in civil infrastructures. The scope of this study is to experimentally verify how well the electro-mechanical impedance method using the proposed active sensing device can detect and quantify damage which may occur in structural members. Two kinds of feasibility tests applying the current system to a laboratory sized aluminum beam have been performed: (a) corrosion detection test and (b) loosening bolt inspection test. Electro-mechanical impedance was measured according to the damage scenario designated

<table>
<thead>
<tr>
<th>Cases</th>
<th>Scenario</th>
<th>Damage Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Baseline</td>
<td>-</td>
</tr>
<tr>
<td>Case 2</td>
<td>Intact Case</td>
<td>Tighten</td>
</tr>
<tr>
<td>Case 3</td>
<td>Damage Case</td>
<td>Bolt #3: loose</td>
</tr>
<tr>
<td>Case 4</td>
<td>Healthy Case</td>
<td>Retighten</td>
</tr>
<tr>
<td>Case 5</td>
<td>Damage Case</td>
<td>Bolt s #2 and #4: loose</td>
</tr>
<tr>
<td>Case 6</td>
<td>Healthy Case</td>
<td>Retighten</td>
</tr>
</tbody>
</table>
for each test, and the changes of the impedance signature before and after damage were observed. As a result, it was confirmed that the current system can detect the damage such as corrosion and loosening bolts by showing the change of the impedance signature due to the damage consistently. The results reported here provide motivation to apply the current active sensing system to in-service structures by implying the automated on-line health monitoring technique. One can envision significant safety enhancement and cost savings through the wide implementation of the novel sensor system for health monitoring of real-world civil infrastructures. To construct online wireless SHM system with ubiquitous computing environment, multi-nodes and sensor networks will be implemented to realistic civil structures in the near future.

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