Hybrid Health Monitoring for Damage Detection in Structural Joints

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ABSTRACT:

The purpose of this study is to develop a promising hybrid structural health monitoring system for structural joints. For this proposal, the combined use of vibration-based techniques and electro/mechanical impedance technique is employed. For the verification of the proposed health monitoring scheme, a series of damage scenarios are designed to simulate various situations at which the connection joints can experience during their service life. The obtained experimental results, modal parameters and electro-mechanical impedance signatures, are carefully analyzed to recognize the connecting states and the target damage locations. From the analysis, it is shown that the proposed hybrid health monitoring system is successful for acquiring global and local damage information on the structural joints.

INTRODUCTION

SHM (structural health monitoring) has distinct advantages over traditional infrastructure inspection methods such as visual and destructive inspections because SHM offer real-time, continuous analysis and detection of damage without intruding the structures. In addition, they can detect damage to internal members normally not available to inspectors. However, it seems that the promise of each developed SHM technique is still far away from complete although depending on selected technique, structures type, surrounding environment, and designed SHM system, some excellent successes have been reported. It should be noted here that whenever we say promise of the proposed system, the systems have to be able to detect damage (Level I method), accurately locate damage (Level II method), identify the magnitude of damage (Level III method), or/and produce a

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life-cycle assessment for the target structure (Level IV method). Accompanying those abilities is quite challenged, that is why a well-posed inspection plan should be coordinated for a specific target structure under a certain condition.

Depending on the acquired inspection data and the area inspected, we can categorize SHM into two possible ways, global and local. Global health monitoring is monitoring activity, which acquires the global health information of entire structure [1,2]. This activity includes detecting, locating, and identifying damage by comparing the dynamic response of the entire structure to a baseline model; hence, even the life-cycle assessment for the target structure can be made. Since the global health monitoring covers the entire structure, the sensors are generally distributed on overall structure with a large interval. Thus, the distributed density of the sensors is low, and the detailed local damage information in the obtained dynamic response would not be enough to judge the local damage state. Naturally, local health monitoring has grabbed the demand. The nondestructive testing and evaluation techniques used in manufacturing industries have spread into different industries such as civil engineering, aerospace engineering, etc [3-10]. In accord with the concept of health monitoring and nondestructive testing and evaluation, local health monitoring has been studied, developed. This monitoring activity does not cover the entire structure but the oriented local area. That is why the activity requires locally denser sensor arrays than the global health monitoring. Thus, it has the capability of more accurately locating damage such as cracks on small scale although local monitoring cannot characterize the entire structure, which means the life-cycle assessment of the target structure would not be easy with the local damage information only.

These two monitoring methods can complement. For a successful complement, a hybrid monitoring system should be developed. Probably, there are some trials for constructing a hybrid monitoring system. Here, we propose a hybrid global-local SHM. This SHM is designed to use vibration-based method as the global and electro/mechanical(E/M) impedance -based method as the local. The design is made because these two methods quite simple, straightforward, and promising in several demonstrations [1-11]. The proposition is supported by experiments. We select several damage scenarios on bolt joints connecting two aluminum beams. The damage scenarios compose the combinations of the numbers of loosened bolts. Conclusion is made by the observations from the experiments. This paper is organized as follows. First, the vibration-based damage detection technique is concisely explained. Second, the adopted E/M impedance-based method is briefly demonstrated. Third, the proposed hybrid SHM is introduced, and its effectiveness is verified through the designed experiments. Finally, the findings of this paper are summarized.

VIBRATION-BASED DAMAGE DETECTION

During the past two decades, a significant amount of research has been conducted in the area of nondestructive damage detection (NDD) via changes in the modal response of a structure. Those researches can be categorized into two types, frequency-based damage detection (FBDD) and mode-shape-based damage detection (MBDD) [1,2]. The frequency-based method has its own benefit since natural frequencies are relatively simple to measure. However, this method has some limitations – (1) significant damage may cause very small changes in natural frequencies, particularly for large structures, and these changes may become undetected due to measurement or processing errors, (2) variations in the mass of the structure or measurement temperatures may introduce uncertainties in the measured frequency changes. The mode-shaped-based method can overcome those difficulties because the changes in mode shapes are much more sensitive to local damage, compared to changes in natural frequencies. However, this method has also some limitations – (1) damage may not significantly influence mode shapes of the lower modes that are usually measured from vibration tests of large structures, (2) extracted mode shapes are affected by environmental noises from such sources as ambient loads or inconsistent sensor positions, and (3) the number of sensors and the choice of sensor coordinates may have a crucial effect on the accuracy of the damage detection procedure [1].

Between those two possible approaches for global SHM, this study chooses frequency-based damage detection since (1) the purpose of our global SHM is not identifying the exact local damage information such as damage size but capturing the global information of the target structure such as damage detection and location, and (2) it is relatively simple to measure natural frequency. Thus, a damage location model is briefly described as follows.

Damage Localization Algorithm

For a multi degree of freedom structural system of *NE* elements and *N* nodes, the damage inflicted at predefined locations may be predicted using the following sensitivity equation:

$$\sum_{j=1}^{NE} F_{ij}\alpha_j = Z_i \tag{1}$$

in which $\alpha_j\left(-1 \le \alpha_j \le 0\right)$ is the damage inflicted at the *j*th location (i.e. the fractional reduction in *j*th stiffness parameter). The term Z_i is the fractional change in the *i*th eigenvalue and (by neglecting changes in mass due to damage) is given by

$$Z_i = \delta\omega_i^2 / \omega_i^2 \tag{2}$$

Here, $\delta\omega_i^2\left(= \omega_i^{*2} - \omega_i^2\right)$ is the change in the *i*th damped natural frequency before and after damage. The asterisk denotes the damaged structure. The term F_{ij} is the modal sensitivity of the *i*th modal stiffness with respect to the *j*th element.

$$F_{ij} = K_{ij} / K_i \tag{3}$$

where K_i is the *i*th modal stiffness $\left(K_i = \Phi_i^T \mathbf{C} \Phi_i\right)$ and K_{ij} is the contribution of the *j*th element to the *i*th modal stiffness $\left(K_{ij} = \Phi_i^T C_j \Phi_i\right)$. In addition, Φ_i is the ith modal vector, **C** is the system stiffness matrix, and C_j is the contribution of *j*th element to the system stiffness.

After some algebraic operations, to account for all available modes we form a single damage indicator (DI) for the *j*th member as

$$DI_j = \left[\sum_{i=1}^{NE} e_{ij}^2\right]^{-1/2} \tag{4}$$

where $0 \le DI_j < \infty$ and the damage is located at element j if DI_j approaches the local maximum point. In equation (4), the e_{ij} denotes localization error for the ith mode and the jth location, and e_{ij}=0 means that the damage is located at jth location using the ith modal information. The error index is written as follows:

$$e_{ij} = \frac{Z_m}{\sum_{k=1}^{NM} Z_k} - \frac{F_{mq}}{\sum_{k=1}^{NM} F_{kq}} \tag{5}$$

E/M IMPEDANE-BASED METHOD

Piezoelectric materials have useful mechanical and electrical properties. When piezoelectric materials are mechanically strained, an electrical field is produced, and vice versa. In addition, the materials have unique molecular structures, which allow bidirectional coupling between electric field and strain; hence, they are useful for self-sensing, power harvesting, and SHM applications [9,10]. Once piezoelectric materials are bonded to a structure, the electro/mechanical coupling allows the electrical impedance of the piezoelectric to be directly related to the mechanical impedance of the structure [9]. Therefore, by monitoring the electrical impedance of the piezoelectric, damage can be detected as the impedance signatures shifts from a healthy state to a damaged state, and the self-sensing properties of the piezoelectric allow one small piece of material to sense the input voltage and measure the output current. PZT (lead zirconate titanate) is typically used for the piezoelectric materials, so PZT is the key component in impedance-based SHM. Thus, the bonding condition between structure and PZT patch i.e. adhesive layer should be carefully treated for the consistent testing results [5]. To enhance sensitivity to incipient damage, the electrical impedance is usually measured at high frequencies, at which the wavelengths of the structural vibration are shorter than the damage to be detected. In general, high frequency (ranged 30 to 300 kHz) low voltage (less than 1V) structural excitations are used to monitor the electrical impedance of the PZT patch.

Due to the benefits of the electro-mechanical impedance method, the researches on utilizing E/M impedance method to damage detection of several complex structures are found on several literatures [3-11]. Liang et al. [11] is probably the pioneer of the impedance method development. After them, various demonstrations have been followed such applications as scaled bridge section, cracked aircraft panels, concrete composites, pipeline networks, high temperature structures, bolted joints, and corrosion [6]. Currently, excellent reviews and applications on E/M impedance method are introduced by Bhalla and Soh [3], Giurgiutiu and Zagrai [8], and Park et al. [10]. This study is based on the impedance-based NDE technique proposed by Bhalla and Soh [3] for the local damage detection. Impedance and its inverse (admittance) are usually used for the signatures. In addition, Conductance and susceptance are also used for the signature distinguishes.

Based on Bhalla and Soh [3], the expression for the electro/mechanical admittance (the inverse of electro/mechanical impedance) is written as

$$\bar{Y} = 2\omega i \frac{w_a l_a}{h_a}\left[\left(\bar{\varepsilon}_{33}^T - d_{31}^2 \bar{Y}_{11}^E\right) + \left(\frac{Z_a}{Z + Z_a}\right) d_{31}^2 \bar{Y}_{11}^E \left(\frac{\tan \kappa l_a}{\kappa l_a}\right)\right] \tag{6}$$

$$\bar{Y}_E = \frac{1}{2}\bar{Y} = \omega i \frac{w_a l_a}{h_a}\left[\left(\bar{\varepsilon}_{33}^T - d_{31}^2 \bar{Y}_{11}^E\right) + \left(\frac{Z_a}{Z + Z_a}\right) d_{31}^2 \bar{Y}_{11}^E \left(\frac{\tan \kappa l_a}{\kappa l_a}\right)\right] \tag{7}$$

where $\bar{Y}_E$ can be termed as 'effective electro/mechanical admittance'. Damage to the structure will modify the drive point mechanical impedance Z, which will in turn affect $\bar{Y}$, therefore giving an indication of damage.

The complex admittance $\bar{Y}$ (units Siemens or ohm^{-1}) consists of real and imaginary parts, which are the conductance (G) and the susceptance (B), respectively. These can be measured by commercially available impedance analyzers [3].

As described before, via the changes of structural system due to damage, electro-mechanical impedance is changed; this change affects the magnitude of admittance and the resonant frequency of PZT patch mode in the thickness direction. From measuring the admittance and the resonant frequency, damage detection is possible.

HYBRID STRUTURAL HEALTH MONITORING

By combining the previously explained vibration-based and electro/mechanical impedance-based method, the hybrid structural health monitoring technique is proposed as designed in Figure 1. It is designed that the area of damage is predicted from the global monitoring, and the damage is located from the local monitoring. For the verification of the proposed hybrid monitoring method, bolt joints are inspected. The geometrical shape of the structural joint and the locations of accelerometers and PZT patches are shown in Figure 2. Four bolts are used to connect two aluminum beams. With the specimen, total three different damage scenarios are designed. Table 1 explains those scenarios. In the determinations, total six accelerometers (PCB 393B04) are used with constant intervals, and total four PZT patches are locally located on the bolt jointing area. Thus, the arrays are much denser than those of the accelerometers are.

For the vibration-based monitoring, acceleration data are obtained with the sampling frequency 1000Hz. Figure 3 shows the acquired acceleration signals and Figure 4 shows the frequency response function. From the frequency domain decomposition, natural frequencies are extracted, and they are shown in Table 2. For the E/M impedance-based monitoring, E/M impedance signatures are obtained using the impedance analyzer (HIOKI 3532) at 1 kHz sampling frequency and 1V voltage. In the experiment, the resonant frequency and admittances of PZT1 patch are obtained as shown in Figure 5.

Frequency-Based Damage Detection

Figure 6 shows the damage localization from the previously explained frequency-based damage detection method. The areas over the damage index 1.5 compose elements 93-108 for damage 1, 89-113 for damage 2, and 90-113 for damage 3. The location of damage of damage cases 1 and 2 is near element 95, and the locations of damages of damage case 3 are near elements 95 and 98. This facts show that it is difficult to locate the exact damage locations from the global method but that it secures at least the approximate damage locations.

Table 1: Damage scenarios.

Damage case	Scenario
1	Bolt 1 loosed
2	Bolt 1 and 2 loosed
3	Bolt 1, 2, and 3 loosed

Table 2: Natural frequency of test structure (Hz).

Damage case	Mode 1	Mode 2	Mode 3	Mode 4
Undamage	12.61	36.91	70.07	118.35
Damage 1	12.58	36.94	69.95	118.70
Damage 2	12.55	36.89	69.82	118.08
Damage 3	12.51	36.93	69.25	117.71

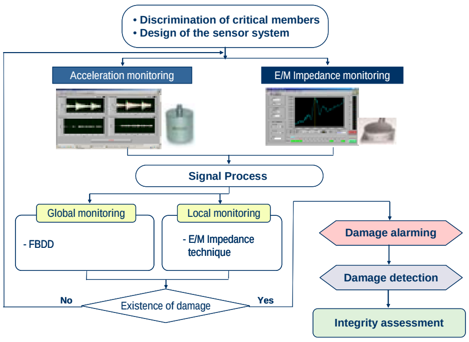


Figure 1: Hybrid health monitoring system.

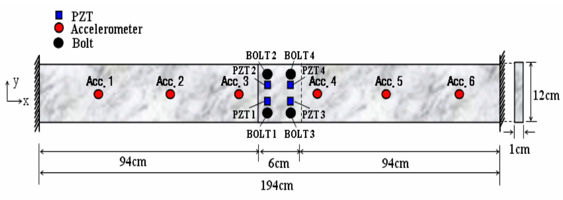
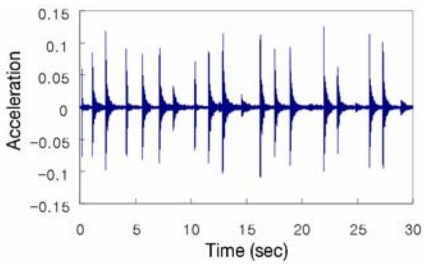


Figure 2: Experimental Setup.



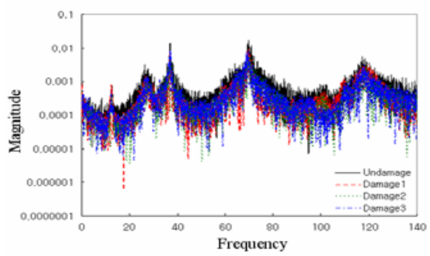


Figure 3: Time response of acceleration signal. Figure 4: Frequency response function.

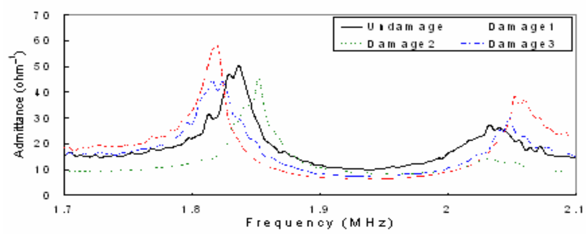
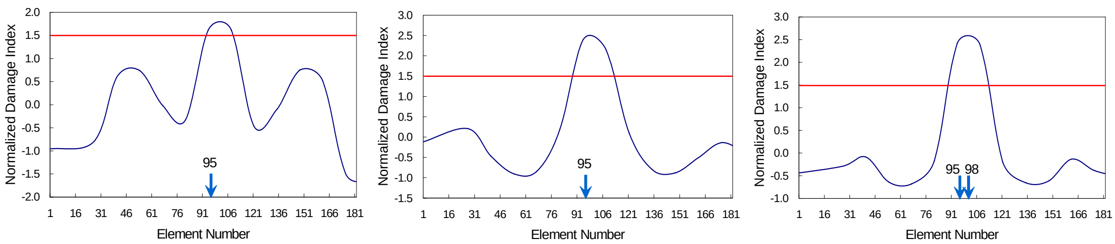


Figure 5: Admittance of PZT1 patches.



(a) damage 1 (b) damage 2 (c) damage 3

Figure 6: Damage localization results of frequency-based damage detection.

E/M Impedance-Based Damage Location

From the previously explained E/M impedance method, the resonant frequency shifts for each damage case are obtained, and shown in Figure 7. For more analysis, RMSD (root mean square deviation) of admittance are calculated, evaluated, and shown in Figures 8. From the figure, it is concluded that a sensor close to a bolt loosened is much sensitive to the damage. For example, PZT 1 is sensitive to the damage of bolt 1 (damage case 1) and PZT 2 is sensitive to the damage of bolts 1 and 2 (damage case 1 or 2). In cases of PZT 3 and PZT 4, it seems that the sensors are more sensitive to the damage cases 1 and 3 than to the damage case 2.

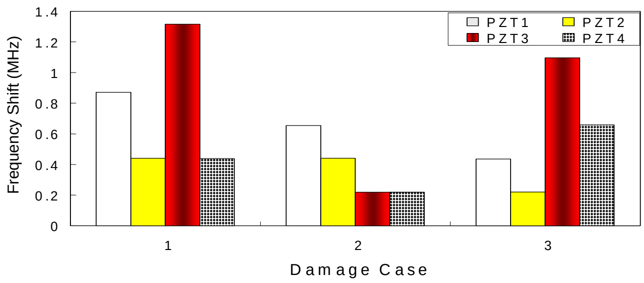
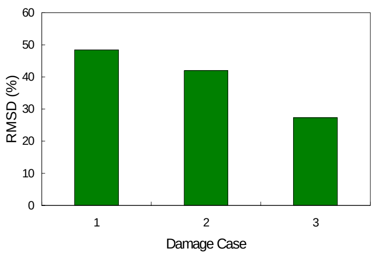
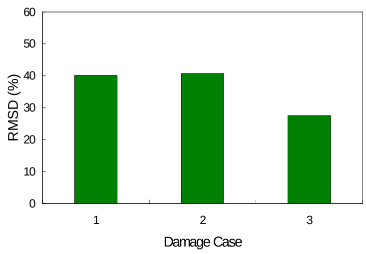
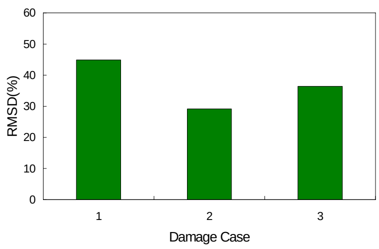


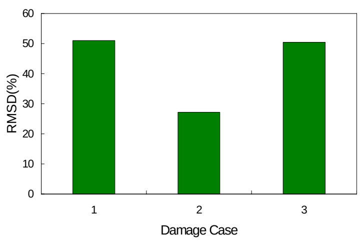
Figure 7: Frequency shift on damage scenarios.





(a) PZT1 (b) PZT2





(c) PZT3 (d) PZT4

Figure 8: RMSD (%) of admittance.

CONCLUSIONS

To develop a promising hybrid structural health monitoring system, which enables to detect damage by the dynamic response of the entire structure and more accurately locate damage with denser sensor array, the hybrid use of mechanical vibration and electro-mechanical impedance is proposed. For the verification of the proposed health-monitoring scheme, a series of damage scenarios are designed to simulate bolts loosening at which the connection joints can experience during their service life. The obtained experimental results, modal parameters (natural frequency) and electro-magnetic impedance signatures (admittance and resonant frequencies), are carefully analyzed to recognize the damaged area and the target damage locations. From the analysis, it is shown that the proposed hybrid health monitoring system is successful for acquiring global and local damage information on the structural joints; hence, its effectiveness is verified. This technique would be efficient for structural health monitoring, which is required to capture both global structural response and exact damage location of locally damaged structures.

ACKNOWLEDGEMENTS

This study was supported by Korean Science and Engineering Foundation (KOSEF) through Smart Infra-Structure Technology Center (SISTeC) in the program year of 2006.

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