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Impedance-Based Damage Diagnosis on Bolt-Jointed Structure Under Varying Temperature

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Abstract The electromechanical impedance(E/M)-based method detects local structural damages based on variations of electrical impedance signatures which are obtained from piezoelectric sensors bonded to the structure and excited in high frequency band. In this method, temperature changes may result in significant impedance variations and lead to erroneous diagnostic results of the structure. To tackle this problem, a new technique providing a 2-dimensional damage feature related to the temperature information is proposed to distinguish the structural damage from the undesirable temperature variation. For experimental tests to validate the proposed method, damages are introduced by bolt loosening to a bolt-jointed steel beam, and impedance signals are measured under varying temperature conditions through a piezoelectric sensor attached on the beam. A freely suspended piezoelectric sensor is additionally utilized to obtain temperature information indirectly from resistance signatures. From a relationship between the damage index (from a constrained sensor) and the temperature (from a freely suspended sensor or a temperature sensor), damages can be detected more clearly under varying temperature compared to other conventional approaches.

Keywords: Structural Health Monitoring, Electromechanical Impedance, Freely Suspended Sensor, Temperature Compensation

1. Introduction

In recent years along with the increasing requirements for structural safety and reliability of modern complex structural systems, the active sensing-based structural health monitoring (SHM) technique using piezoelectric sensors has been recognized as a promising tool to detect structural defects such as cracks, loosened bolts, and fatigue failures on structures due to its high sensitivity to damages [1]. In particular, the E/M impedance-based method has performed successful monitoring in detecting incipient damages on structures and many experimental implementations have been conducted in real structures [2-5].

The impedance-based SHM technique utilizes small piezoelectric sensors such as piezoceramic (lead(Pb)-zirconate-titanate; PZT) and macro-fiber composite (MFC) patches attached to a host structure, which function as self-sensing actuators. These sensors both excite the structure with high frequency sweeping and monitor any changes in structural mechanical impedance. The integrity assessment of the host structure can be made by monitoring the electrical impedance of the piezoelectric sensor. However, in this method, temperature variation due to surrounding changes shall be considered with careful attention, because it may result in significant

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impedance variations and lead to erroneous diagnostic results of the structure.

To date, several studies have been reported to reduce temperature variation effects on the measured impedance [1,6-9]. Sun et al. [7] used a cross-correlation damage metric between the baseline and the updated signature to compensate frequency shifts induced by temperature change. Park et al. [8] compensated both frequency and magnitude shifts using a modified root mean square deviation (RMSD) damage metric. Koo et al. [9] modified the method proposed by Park et al. [8] and developed an effective frequency shift method based on a maximum cross-correlation coefficient (CC) between the baseline and the concurrent impedance data. These methods for temperature compensation assumed that temperature changes cause considerable variations with both vertical and horizontal shifts on impedance measurements at the same damage condition. With this assumption, they focused on the modification of conventional damage metrics such as RMSD and CC metrics. However, since the change of impedance signature is complex under varying temperature and moreover the temperature effect varies depending on the selected frequency band, these frequency shifts-based approaches may not compensate temperature effects clearly and may have a potential to provide a false alarm for SHM.

In this study, a freely suspended piezoelectric sensor (FSPS) is additionally utilized to obtain temperature information indirectly from impedance signals under varying temperature. Temperature effects-free 2-dimensional damage features are introduced from the relationship between the conventional damage index of a piezoelectric sensor attached on a target structure and temperature information from a FSPS. The effectiveness of the proposed method is explicitly examined through experimental tests on a bolt-jointed beam under varying temperature conditions.

2. Theoretical Backgrounds

2.1 Genesis of the E/M Impedance-Based SHM

The E/M impedance-based SHM techniques have been developed as a promising tool for real-time structural damage assessment on critical members of large structural systems. They make use of a piezoelectric sensor, which forms a collocated sensor and actuator and is often referred to as a self-sensing actuator. The basis of this active sensing technology is the energy transfer between the actuator and the host mechanical system. The E/M impedance method utilizes high-frequency structural excitations of surface-bonded piezoelectric sensors by monitoring changes in structural mechanical impedances.

Liang et al. [10] first proposed a one-dimensional coupled E/M impedance analysis of adaptive system driven by a surface-attached PZT sensor (Fig. 1). Their research conceptualized that the E/M impedance at the terminal of a PZT sensor reflects the coupled-system dynamics, that is, the electrical impedance, $Z(\omega)$, as measured at the terminal of a PZT sensor, is directly correlated to the local mechanical impedance of the host structure, $Z_s(\omega)$, and that of the PZT sensor, $Z_a(\omega)$.

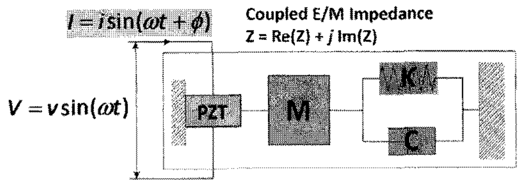


Fig. 1 1-D model to derive E/M impedance of a PZT bonded to a structure [10]

$$Z(\omega) = Re[Z(\omega)] + jIm[Z(\omega)] = \left[j\omega C\left(1 - \kappa_{31}^2 \frac{Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)}\right)\right]^{-1} \quad (1)$$

where C is the zero-load capacitance of a PZT and κ_{31} is the E/M coupling coefficient of a

PZT. Given that the mechanical impedance and the material properties of the PZT stay constant, the eqn. (1) shows that a change in the structure's mechanical impedance directly results in a change in the electrical impedance measured by the PZT. Since damages cause a change in the structure's local mass, stiffness, or damping properties and consequently its mechanical impedance, the structure's mechanical integrity can be assessed by monitoring the PZT's electrical impedance [2]. It should be noted that the impedance function, $Z(\omega)$, is a complex number. Bhalla et al. [6] and Park et al. [11] demonstrated that the real part (resistance) of the measured impedance is more sensitively changed due to the structural damage condition while the imaginary part (reactance) can be more effectively used for piezoelectric sensor self-diagnosis.

2.2 Statistical Damage Metric for Quantitative Damage Detection

By observing some changes of the E/M impedance acquired from a PZT attached on a host structure, assessments can be made about the integrity of the host structure. Since the impedance change provides only a qualitative assessment for damage detection, several scalar damage metrics have been proposed for quantitative measure of structural damages. Among them, the most commonly used indices are RMSD and CC metrics [12], which are described as

$$RMSD = \sqrt{\frac{\sum_{i=1}^{n}\{\mathrm{Re}(Z_0(\omega_i)-\overline{Z_0})-(\mathrm{Re}(Z_1(\omega_i))-\overline{Z_1})\}^2}{\sum_{i=1}^{n}\mathrm{Re}(Z_0(\omega_i)-\overline{Z_0})^2}} \quad (2)$$

$$CC = \frac{1}{N}\sum_{i=1}^{N}\frac{\{Re(Z_0(\omega_i))-\overline{Z_0}\}\{Re(Z_1(\omega_i))-\overline{Z_1}\}}{\sigma_{Z_0}\sigma_{Z_1}} \quad (3)$$

where $Z_0(\omega)$ is the impedance of the PZT measured in the healthy condition (baseline); $Z_1(\omega)$ is the impedance in the concurrent condition; n is the number of frequency points; $\overline{Z_0}$ and $\overline{Z_1}$ are the mean values of the resistances of $Z_0(\omega)$ and $Z_1(\omega)$; and σ_{Z_0} and σ_{Z_1} are the standard deviations of the resistances of $Z_0(\omega)$ and $Z_1(\omega)$. These metrics are scaled by the baseline measurement, $Z_0(\omega)$, and are corrected for the vertical shift between measurements by subtracting mean values. The vertical shift is mainly caused by changes in environmental conditions such as temperature and humidity [7]. With the RMSD metric, the greater numerical value of the metric means the larger difference between the baseline reading and the subsequent reading which indicates more obvious presence of damage in a structure. On the other hand, the smaller value of the CC metric means the larger difference between impedances and the clearer presence of damage.

2.3 Conventional Temperature Compensation Methods

Temperature variations due to surrounding changes should be considered with careful attention because piezoelectric sensor properties such as dielectric coefficient and piezoelectric constant are sensitive to the temperature variations, which may result in significant impedance variations and lead to erroneous diagnostic results of real structures [5]. To date, several studies have been reported to reduce temperature impacts on assessment with measured impedance signals. Park et al. [8] proposed a temperature-corrected scheme based on reconstruction of the conventional RMSD damage metric. The experimental results conducted on a bolted pipe joint showed that large fluctuations of impedance signals and horizontal shifts of resonant frequencies were minimized to indicate the presence of damage. Bhalla et al. [6] investigated the influence of structure-actuator interactions and temperature variations on impedance signatures. A concept of active component of admittance (inverse of impedance) signatures was introduced to utilize the direct interactive component after filtering the inert component. Koo et al. [9] proposed an effective frequency shift (EFS; $\tilde{\omega}$) method in order to compensate temperature effects on impedances, which is based on the frequency shift to obtain a maximum cross-correlation coefficient between the baseline impedance data, $Z_0(\omega)$, and the concurrent impedance data, $Z_1(\omega)$, as

$$CC_{EFS} = \max_{\tilde{\omega}} \left\{ \frac{1}{N} \sum_{i=1}^{N} \frac{\{Re(Z_0(\omega_i)) - \overline{Z_0}\}\{Re(Z_1(\omega_i - \tilde{\omega})) - \overline{Z_1}\}}{\sigma_{Z_0}\sigma_{Z_1}} \right\} \quad (4)$$

The experimental results on a steel truss member showed that the temperature change caused considerable variations with both vertical and horizontal shifts on impedance measurements at the same damage condition while excellent match could be obtained between these signatures after the EFS method was applied. However, since the change of impedance signal is changed with complex trend as well as frequency shifts varying with the selection of frequency band, the EFS method may not remove temperature effects clearly. Moreover, the selection of baseline signal for EFS method may largely affect on the diagnosis result.

3. Proposed Temperature Compensation Approach for E/M Impedance-Based SHM

This study proposed a new method to reduce temperature effects on impedance signals focusing on the supplementation of the EFS method. This method performs damage diagnosis based on the relationship between the conventional damage index and the temperature, and finally constructs 2-dimensional damage index. Although a conventional temperature sensor can be used to obtain temperature information, this study suggests a new scheme that a FSPS can be also utilized for temperature acquisition. When a piezoelectric sensor is freely suspended and no external loads are applied, it responds only to environmental changes, mainly temperature changes, and consequentially it brings significant changes in resistance of FSPS [5]. Therefore, a resistance change of FSPS can provide a temperature feature. It is noted that using a FSPS as a temperature sensor has a benefit not to require additional measuring equipments.

The overall procedure of the proposed damage diagnosis method under varying temperature is summarized in Fig. 2. First, impedance signals are obtained under varying temperature conditions from a piezoelectric sensor attached on the structure. Then, CC_{EFS} damage indices in eqn. (4) are calculated using

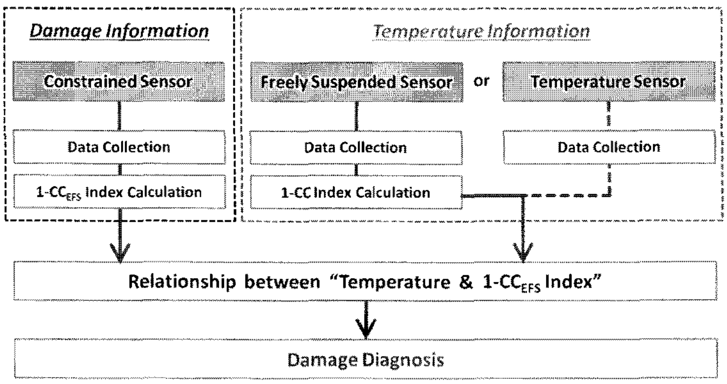


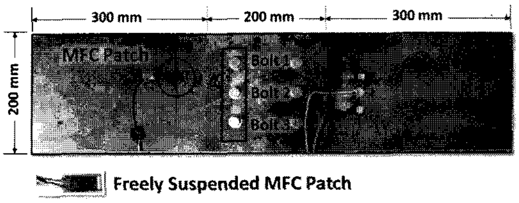
Fig. 2 Procedure of the temperature effects reduction method using temperature information

resistances in common with other conventional E/M methods. Simultaneously, temperature information is acquired from a FSPS based on CC indices calculated using resistances in eqn. (3) or from a temperature sensor. Finally, a curve between CC_{EFS} damage index and temperature is constructed which acts as a 2-dimensional damage index. When damages are occurred, this curve moves upward and a new curve is made with temperature variations. When temperature is varied, CC_{EFS} damage index moves along the curve without any shift of the curve. Therefore, hidden damage features can be effectively extracted under varying temperature conditions by monitoring the change of damage index versus temperature curve.

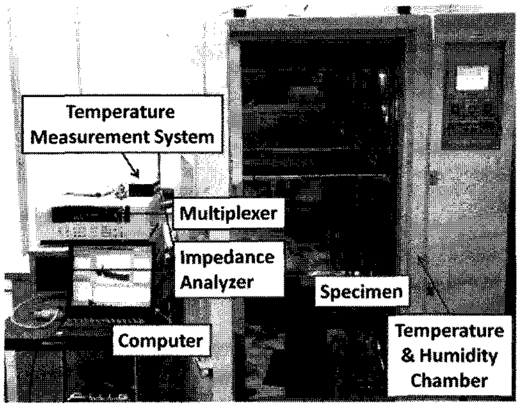
4. Experimental Investigation

4.1 Test Specimen and Test Setup

To examine the effectiveness of the proposed method, experimental tests under varying temperature conditions were conducted on a bolt-jointed steel beam (800×200×3 mm^3). This specimen consisted of three steel sections connected by six steel bolts as shown in Fig. 3(a). One MFC patch of 47×25×0.267 mm^3 (2814P1 Type; Smart Material©) was attached at a location of 50 mm apart from the bolt joint. This specimen was placed in a temperature and humidity chamber (EN-TH-1370; ENEX Co., Ltd.) to effectively control temperature under constant humidity. An additional MFC patch for a FSPS, which is the same as the patch attached on the specimen, was located near the specimen in this chamber to be exposed in the same environmental condition. Both surface-bonded MFC patches and FSPS were connected to a conventional impedance analyzer (Agilent 4294A) through a multiplexer (Agilent 34980A). A thermocouple was also placed near the FSPS for temperature measurement (A5113-13; Asahi Keiki



(a) Prepared bolt-jointed steel specimen



(b) Experimental setup

Fig. 3 Experimental setup for damage diagnosis on a bolt-jointed steel beam under varying temperature

Table 1 Damage scenarios

Case	Damage Description	Temperature Change
1	No damages	9 °C ~ 40 °C
2	Loosen Bolt #1 (70 N·m → 42 N·m)	9 °C ~ 40 °C
3	Additionally loosen Bolt #2 (72 N·m → 50 N·m)	9 °C ~ 40 °C
4	Additionally loosen Bolt #3 (70 N·m → 38 N·m)	9 °C ~ 40 °C

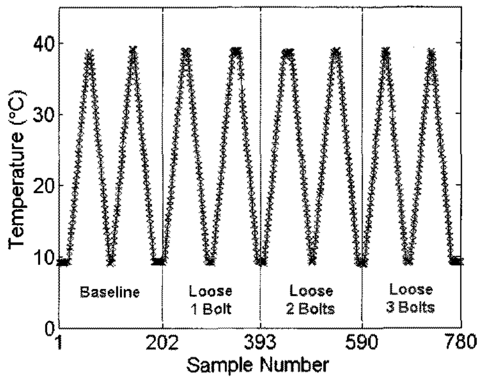


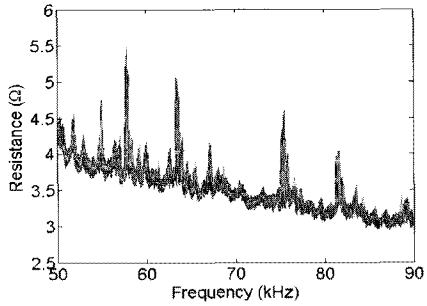
Fig. 4 Temperature profile

Co., Ltd.). The present experimental setup for the impedance-based SHM consists of a host structure, two MFC patches, an impedance analyzer, a multiplexer, a thermocouple, and a laptop computer equipped with the continuous impedance monitoring framework as in Fig. 3(b).

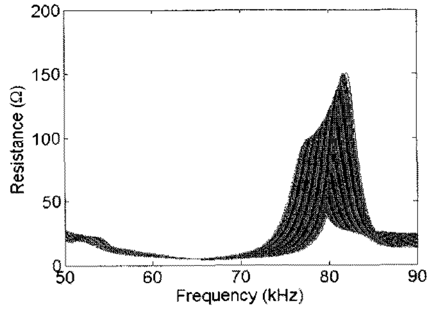
For temperature variations, the specimen was heated in a range of 9-40 °C periodically under constant humidity (30±1 %) condition. Simultaneously three damages were imposed by increasing the number of the loosened bolts in a sequence under varying temperature at the locations described in Fig. 3(a). Damage scenarios and temperature profile are summarized in Table 1 and Fig. 4.

4.2 Impedance Variations due to Temperature Effects

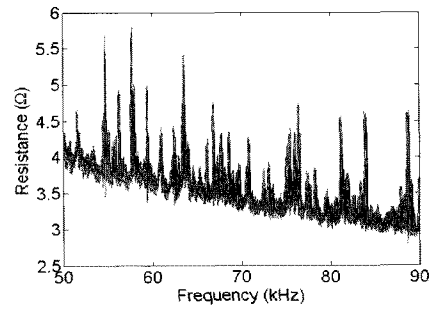
First, impedance measurements were made for each damage case under varying temperature in a frequency range of 50-90 kHz. This frequency range was chosen as it contains a good dynamic interaction between the PZT and the structure with multiple resonant peaks [2,5]. Figs. 5(a) and 5(b) shows measured resistance signatures from the FSPS and the MFC patch attached on the intact structure. Fig. 5(c) shows similar results of the attached MFC patch for a damage case with 4 loosened bolts. The temperature variations cause significant peak



(a) MFC patch attached on a structure (intact cases)

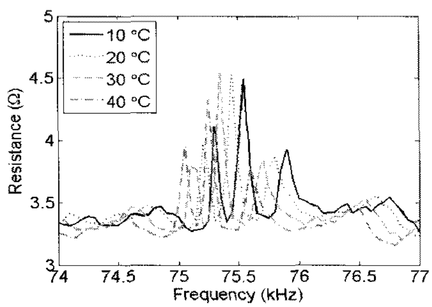


(b) Freely suspended MFC patch (intact cases)

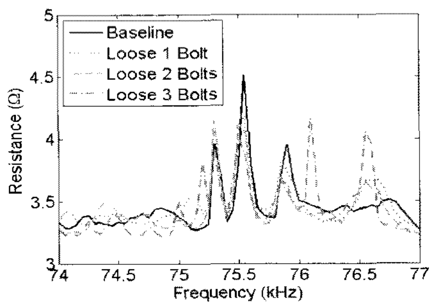


(c) MFC patch attached on a structure (damage cases with 4 loosened bolts)

Fig. 5 Resistance variations due to temperature variations in a range of 9-40 °C

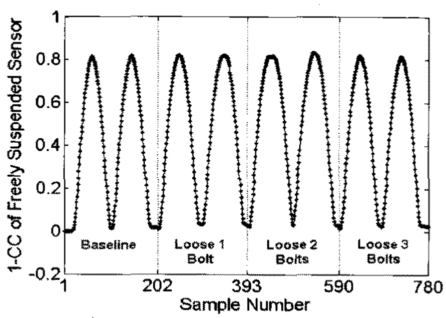


(a) Resistance variations caused by varying temperature

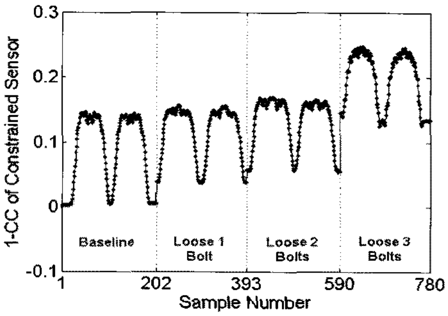


(b) Resistance variations caused by damages at the same temperature (10 °C)

Fig. 6 Resistance variations due to temperature variations and damages

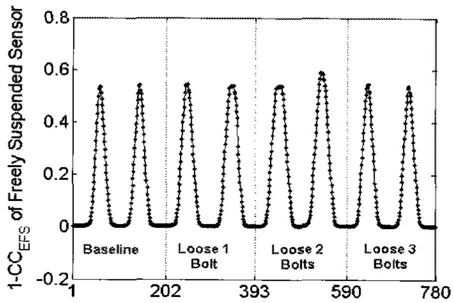


(a) 1-CC index of freely suspended sensor

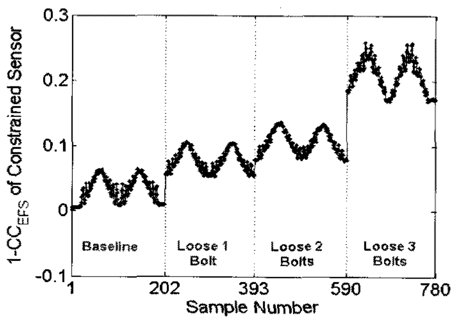


(b) 1-CC index of constrained sensor

Fig. 7 Conventional 1-CC metric calculated by using resistance signals



(a) 1-CC_{EFS} index of freely suspended sensor



(b) 1-CC_{EFS} index of constrained sensor

Fig. 8 Temperature compensated 1-CC_{EFS} metric calculated by using resistance signals

frequency shifts in the resistance signatures in both horizontal and vertical axes as well as fluctuations in peak resonance magnitudes[8,9]. From this phenomenon, the temperature compensation strategy robust to the ambient temperature variation shall be required for the impedance-based SHM for real applications.

To more precisely observe the effects of the temperature variation and induced damages, example resistance records are presented in Fig. 6. Fig. 6(a) shows the temperature effects on the resistance signatures. From this figure, it is found that an increase in temperature mainly leads the shifts of peak frequencies and the fluctuations of peak magnitudes. Fig. 6(b) shows the damage effects at the same temperature condition (10 ˚C). Compared to the temperature effects, various unexpected peaks are observed due to damages as well as peak fluctuations. This kind of change is the basis of E/M impedance-based monitoring of structure [5].

Conventional CC metric defined in eqn. (3) is calculated to quantify the effects of both temperature and damage on resistances. Here, CC metric is subtracted from 1 for convenience. Fig. 7 shows the results of 1-CC values obtained from the FSPS and the constrained MFC patch on the beam. In case of the FSPS, 1-CC values largely fluctuate between 0 and more than 0.8 due to the temperature variation and no other significant changes are observed by induced damages as in Fig. 7(a). In case of the constrained sensor, 1-CC values is changed more than 0.1 due to surrounding temperature change while less than 0.05 is changed by damage occurrence. It indicates that the temperature variation may hide the damage feature in resistance signature so that it may be hard to identify structural damages by using conventional damage metric.

Then, the EFS method proposed by Koo et al. [9] as in eqn. (4) was applied for temperature compensation. Fig. 8 presents the

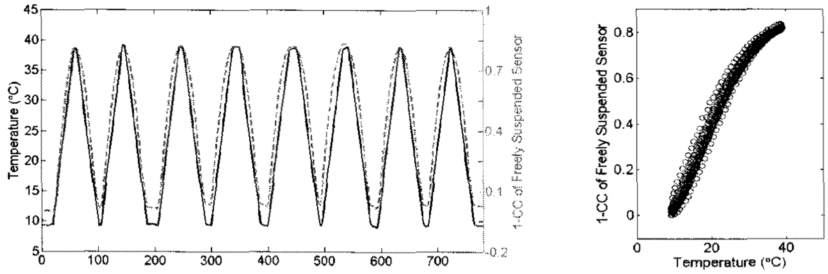
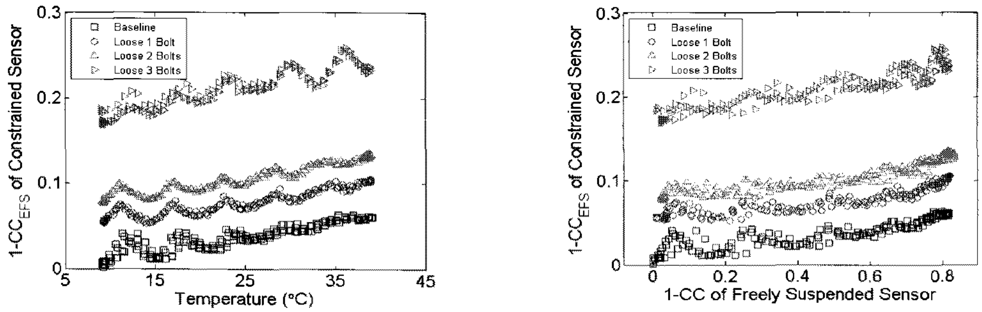


Fig. 9 Relationship between temperature and 1-CC metric obtained from a FSPS



(a) 1-CC_{EFS} index depending on temperature

(b) 1-CC_{EFS} index depending on 1-CC index of freely suspended sensor

Fig. 10 Relationship between 1-CC_{EFS} index and direct/indirect temperature

results of the temperature-compensated damage metric. It is noticed that the CC_{EFS} damage metric is subtracted from 1 for convenience. While the conventional 1-CC metric could not distinguish damages at all due to the temperature variations, the 1-CC_{EFS} damage metric shows much better performance by reducing the temperature-induced fluctuations. However, significant fluctuations remain more than 0.56 change for the FSPS case and 0.06 for the constrained sensor case, while damages induce only 0.02-0.1 change of index value. From these results, it is found that CC_{EFS} also has a possibility to lead a false alarm. Therefore, supplementation of this method is required to improve the accuracy of the E/M impedance-based damage diagnosis under varying temperature conditions.

Here, one important observation is found that the resistance of the FSPS is purely affected by the temperature and follows the temperature trend [5]. Especially, the conventional 1-CC metric of the FSPS in Fig. 7(a) shows the well-fitted relationship with the temperature scenario. Fig. 9 presents the result of comparison between 1-CC values of FSPS against the measured temperature using a thermocouple. The temperature is correlated with 1-CC values of FSPS showing around 0.98 correlation coefficient, which is enough to make a positive link between these data. Therefore, it indicates that the 1-CC metric of the FSPS can be utilized to obtain temperature data indirectly without other temperature measuring systems.

4.3 Relationship between Damage Index and Temperature

Using the indirectly obtained temperature information and the conventional CC_{EFS} damage metric, a new relationship was constructed. Fig. 10(a) shows the trend of conventional 1-CC_{EFS}

damage metric against the 'direct' temperature information obtained from a thermocouple. Almost linear relationship was established with a slope of approximately 0.07. As damages became more critical, this curve shifted upward and was separated from the baseline curve at intact case. When the 'indirect' temperature information obtained from a FSPS was used, a similar trend with the use of a thermocouple was observed as in Fig. 10(b). It means that the FSPS can be used as a temperature sensor indirectly and the proposed approach has a potential to improve the reliability of the E/M impedance-based damage diagnosis under varying temperature conditions.

4.4 Damage Diagnosis Using Outlier Analysis

The outlier analysis was applied for more systematic damage diagnosis. It is a kind of robust unsupervised learning pattern recognition tools, which simply determines whether a new pattern is significantly different from the previous patterns or not ignoring any negligible differences automatically [9]. Assuming a multivariate normal distribution (MVN) of sample patterns, the deviation of the candidate outlier (x_ζ) from the rest of the population can be measured by Mahalanobis square distance (MSD) measure given by

$$D_\zeta = (x_\zeta - \mu)^T \textstyle\sum^{-1} (x_\zeta - \mu) \tag{5}$$

where μ is the mean of samples; $\sum$ is the covariance matrix of samples; and D_ζ is a deviation measure. For the proposed case, μ and $\sum$ were exclusively computed from the baseline system without including potential outliers. The deviation measure, D_ζ, was then compared with the threshold value D_{th}. Herein, when $D_\zeta > D_{th}$, x_ζ is classified as an outlier, which means that x_ζ is in a damaged state. The basic concept of this outlier analysis is illustrated in Fig. 11.

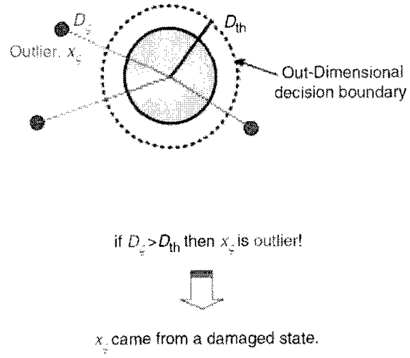
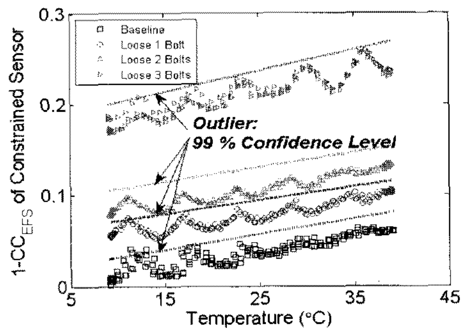
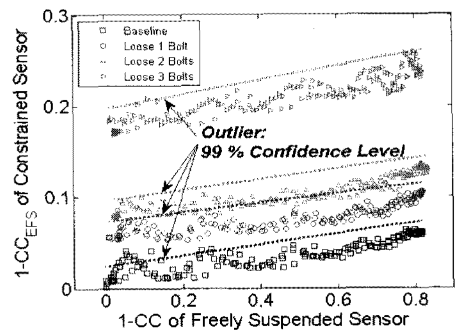


Fig. 11 Multivariate outlier analysis for novelty detection [9]



(a) Damage diagnosis using temperature



(b) Damage diagnosis using 1-CC index of freely suspended sensor

Fig. 12 Damage alarm utilizing 99 % confidence level constructed with 1-CC$_{EFS}$ index and temperature

For damage detection considering the fluctuations in the relationship between 1-CC$_{EFS}$ metric and temperature, the optimal threshold values were investigated with a statistical confidence level of 99 % through an outlier analysis as in Fig. 12. In this analysis, all CC$_{EFS}$

values and temperature information before each damage step were utilized as the basis data to update the threshold level of the outlier analysis. It was found that, after each damage is inflicted, $1\text{-}CC_{EFS}$ values increase abruptly above the corresponding threshold curve and forms a new curve updating the relationship between two variables. Here, the rate of false positive alarms was smaller than 4.9 % in the intact case. From these results, it was validated that the proposed method is a reliable approach for E/M impedance-based damage diagnosis under varying temperature. However, it is noted that the threshold levels should be properly selected considering both the daily temperature range and the minimum target damage level [9].

5. Conclusion

In the E/M impedance-based SHM techniques, temperature variations result in significant impact on impedance measurements. Especially, resonant frequency shifts and magnitude changes are observed in impedance signatures, which may lead to erroneous diagnostic results. Therefore, this paper proposed a new approach to reduce the temperature effects and complement the conventional EFS method. Through experimental tests on the bolt-jointed steel beam, temperature effects were explicitly examined and then a 2-dimensional damage index was constructed utilizing the relationship between the temperature information and the conventional damage index with an outlier analysis. Here, the temperature information was obtained directly from a conventional thermocouple and indirectly from a FSPS based on the concept that the resistance change of a FSPS is related to the temperature. Experimental results indicated that the proposed method is more reliable for damage diagnosis under varying temperature than other conventional methods. Now additional researches are underway to extract both temperature information and damage features through only one piezoelectric sensor for more practical damage detection in real field.

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