온도변화에 자유로운 임피던스 기반 국부 손상검색

Temperature Effect-free Impedance-based Local Damage Detection

구 기 영* • 박 승 희* • 이 종 재** • 윤 정 방***

Koo, Ki-Young • Park, Seunghee • Lee, Jong-Jae • Yun, Chung-Bang

ABSTRACT

This paper presents an impedance-based structural health monitoring (SHM) technique considering temperature effects. The temperature variation results in a significant impedance variation, particularly both horizontal and vertical shifts in the frequency domain, which may lead to erroneous diagnostic results of real structures. A new damage detection strategy has been proposed based on the correlation coefficient (CC) between the reference impedance data and a concurrent impedance data with an effective frequency shift which is defined as the shift causing the maximum correlation. The proposed technique was applied to a lab-sized steel truss bridge member under the temperature varying environment. From an experimental study, it has been demonstrated that a narrow cut inflicted artificially to the steel structure was successfully detected using the proposed SHM strategy.

Keywords: *Impedance, structural health monitoring, temperature effects, effective frequency shift, correlation coefficients, outlier analysis*

1. Introdution

Structural health monitoring (SHM) has become an important issue in many fields such as civil, mechanical and aerospace engineering. In recent years, the electro-mechanical impedance method, which utilizes piezoelectric materials including piezoelectric ceramic (PZT) and macro fiber-composite (MFC) as collocated actuator-sensors, has emerged as a new nondestructive evaluation (NDE) technique. In this technique, a piezoelectric sensor is surface-mounted to the host structure by means of a high strength epoxy adhesive and its electrical impedance is extracted across a high frequency-band, typically of the order of kHz. The real part of this signature is used as a representation of the local dynamic parameters of the structure in the vicinity of the sensor. Damage to the structure in the vicinity of the sensor is expected to alter this signature thereby giving an indication of the imminent damage. However, there are

* KAIST 건설 및 환경 공학과 박사과정 Email: kykoo@kaist.ac.kr; shparkpc@kaist.ac.kr

*** KAIST 스마트 사회기반시설 연구센터 연구조교수 Email: jongjae@kaist.ac.kr

*** KAIST 건설 및 환경 공학과 교수 Email: ycb@kaist.ac.kr

many impediments to the practical application of the technique for NDE of real structures. The main challenge lies in achieving continuous monitoring of the impedance response of the piezoelectric sensor over sufficiently long periods under temperature varying environment. Several studies have been reported about the temperature variation effects on the impedance measurement. In particular, Park, G. *et al.* reported that temperature change results in a significant impedance variation (1999). Bhalla *et al.* also investigated the influence of the structure-actuator interactions and temperature on the impedance signatures (2003).

In this paper, a new impedance-based damage detection method under temperature variation environment is proposed based on the correlation coefficient (CC) between the reference impedance data and the concurrent impedance data with an effective frequency shift. An experimental study was carried out on a steel structural member with a macro-fiber composite (MFC) sensor. The feasibility of the proposed method introducing an artificial small cut on the structure was investigated under various temperatures.

2. Impedance-based Structural Health Monitoring Techniques

In general, the impedance-based SHM technique utilizes small piezoelectric sensors including piezoelectric ceramic (PZT) and macro fiber-composite (MFC) attached to a structure as self-sensing actuators to simultaneously excite the structure with high-frequency excitations and to monitor the changes in the measured impedance signature. The electro-mechanical impedance function of the coupled system can be represented as a function of frequency as (Giurgiutiu and Rogers, 1997)

$$Z_{total}(\omega) = [i\omega C(1-\kappa_{31}^2 \frac{Z_s(\omega)}{Z_A(\omega)+Z_s(\omega)})]^{-1} \tag{2.1}$$

where C is the zero-load capacitance of the piezoelectric sensor, κ_{31} is the electro-mechanical coupling coefficient of the piezoelectric sensor, Z_S is the impedance of the host structure, and Z_A is the impedance of the piezoelectric sensor. Thus, by observing changes in the electrical impedance measurement of the piezoelectric sensor, assessments can be made about the integrity of the host structure. (Soh *et al.*, 2000; Park, G. *et al.*, 2003; Park, S. *et al.*, 2006).

3. Experimental Iinvestigation

3.1 Test specimen and test setup

An experimental study was carried out to check the feasibility of continuous health monitoring technique using a MFC sensor on a steel truss member under the temperature varying environment. The MFC sensor was used to detect the presence of an artificial cut of 4 mm long and 0.5 mm wide inflicted on a welded zone of a 1/8 scale model (150 x 150 x 530 mm: Figure 1) for a vertical truss member of Seongsu Bridge, Seoul, Korea, which collapsed in 1994. A MFC sensor of 28 x 14 x 0.02 mm^3 was placed with a distance of 40mm away from the middle of the welded zone on the outside surface of a flange. A thermo-coupler was also placed near the MFC sensor for temperature measurement. The present experimental setup for the impedance-based SHM consists of a host structure, a MFC sensor, an impedance analyzer (HP4294A), a thermo-coupler, and a personal computer equipped with the continuous measurement program written in MATLAB.

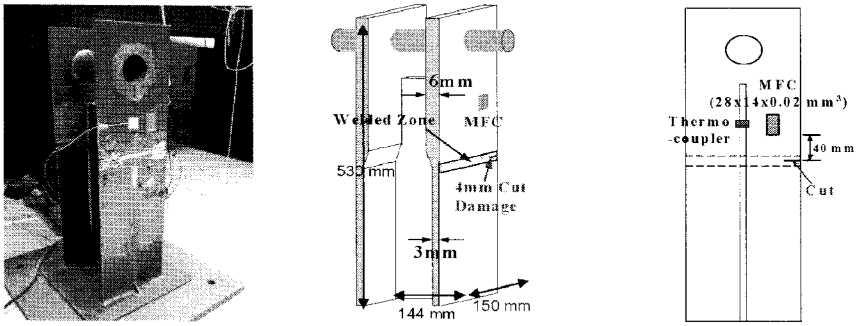
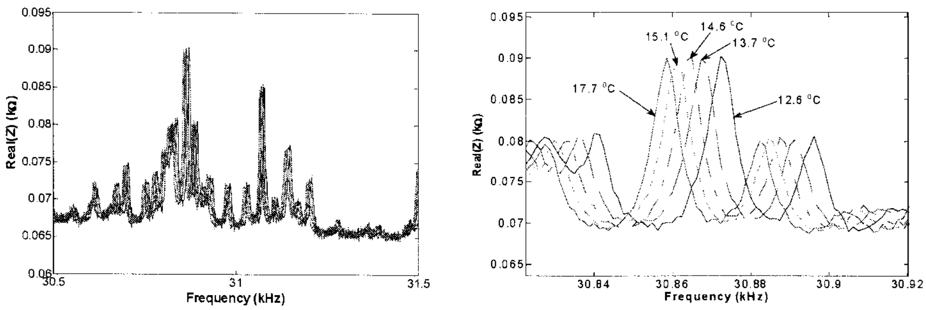


Figure 1.Test specimen, MFC sensor, and thermo-coupler

3.2 Variations in impedance data due to temperature effects

Temperature effects on the impedance signature of the MFC sensor attached to the specimen have been investigated. Firstly, the impedance and temperature measurements were carried out on the intact structure during the period over the three days. Typical impedance signatures for 198 baselines measured at several different temperatures are displayed in Figure 2, which shows that the temperature variations result in significant shifts with both vertical and horizontal directions of the impedance signatures.



(a) Impedances at several difference temperatures (b) Frequency shift due to temperature variation

Figure 2 Impedance variations due to temperature variations

3.3 Effective frequency shift by correlation analysis

As mentioned earlier, the impedance and temperature measurements were carried out continuously during a long period for the healthy (intact) state. The total number of the measurements is 198. The first and 58th impedance signatures (both for the intact cases) on the MFC sensor are shown in Figure 3. The solid line presents the first impedance measurement at 15.3°C which was selected as the reference data. The dotted line presents the 58th impedance measurement at 25.3°C. To compensate the frequency shift due to the temperature variation described previously, an effective frequency shift method by the correlation analysis is introduced in this study. The correlation coefficient (CC) between the reference impedance data $x(\omega_i)$ and the concurrent impedance data with a frequency shift $y(\omega_i - \tilde{\omega})$ is calculated. The effective frequency shift ($\tilde{\omega}$) is defined as the shift corresponding to the maximum correlation between the reference impedance data and the concurrent impedance data as

$$\max_{\tilde{\omega}} CC = \max_{\tilde{\omega}} \{ \frac{1}{N} \sum_{i=1}^{N} (x(\omega_i) - \overline{x}(\omega_i))(y_i(\omega_i - \tilde{\omega}) - \overline{y}(\omega_i - \tilde{\omega})) \} / \sigma_X \sigma_Y \quad (3.1)$$

where $\overline{x}(\omega_i)$ and $\overline{y}(\omega_i)$ are the mean values of the impedance signatures of the intact cases at ω_i and σ_X and σ_Y are the standard deviations. From Figure 4, it is observed that the maximum correlation with a correlation coefficient of 0.9808 occurred at the frequency shift of 43.75 Hz. In this case, therefore, a shift of 43.75 Hz effectively compensates the temperature variation of 10°C. Figure 5 shows the impedance signature of Test #58 after the effective frequency shift along with the reference signature (Test #1). Excellent match between two signatures can be observed. The correlation analyses incorporating the effective frequency shift were also carried out on the other measurements of the intact case. Figure 6 shows that the maximum correlation coefficients for the same intact cases are very high as 0.85-1.0 for the maximum temperature variation of 19°C. The results indicate that the temperature effects may be reasonably removed using the effective frequency shift.

3.4 Correlation coefficient-based damage detection using the effective frequency shift

The feasibility of the impedance-based damage detection technique using the proposed effective frequency shift was investigated for a damage case with an artificial cut of 4 mm long and 0.5 mm wide inflicted in the welded zone of a flange, as shown in Figure 1. The distance between the MFC sensor and the cut damage was 40 mm. After the damage infliction, series of impedance measurements were carried out under the maximum temperature variation of 17.3°C. The maximum correlation coefficient (CC) was evaluated between the reference (intact) impedance data and each of the concurrent impedance data with a proper effective frequency shift, and the results are shown at the later part of Figure 7. The results indicate that after the 4mm cut damage is inflicted, the CC values dropped abruptly.

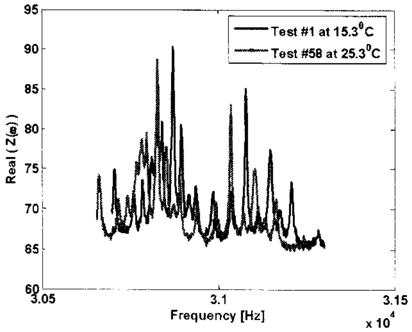


Figure 3.Impedance data before the effective frequency shift (Tests #1 and #58)

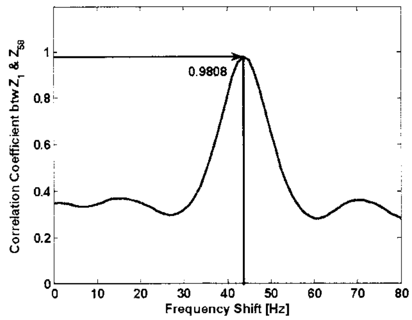


Figure 4.Correlation function between Tests #1 and #58 with a frequency shift

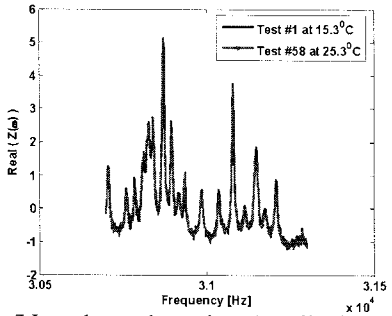


Figure 5.Impedance data after the effective frequency shift (Tests #1 and #58)

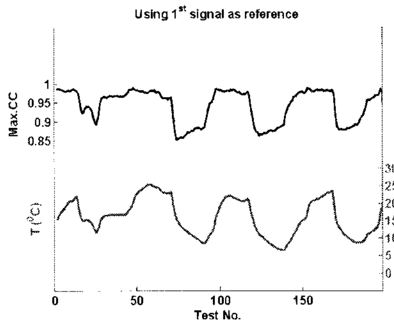


Figure 6.Maximum correlation coefficients with the reference case incorporating effective frequency shifts

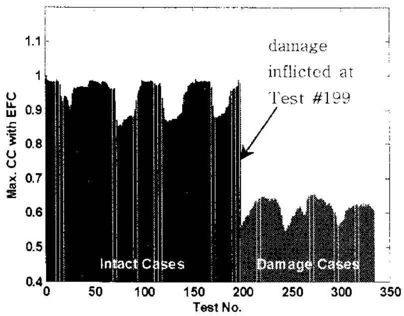


Figure 7. Maximum correlation coefficients-based Damage Detection

4. Concluding Remarks

The feasibility of the impedance-based structural health monitoring (SHM) technique to diagnose the integrity of the structures has been investigated under the temperature varying environment. The temperature variation resulted in a significant impedance variation, particularly a frequency shift in the impedance, which may lead to erroneous diagnostic results regarding the integrity of real structures. In order to minimize the effects of the temperature variations, a new damage detection strategy based on the correlation coefficient (CC) between the reference impedance data and a concurrent impedance data with an effective frequency shift has been proposed. The proposed technique was applied to a lab-sized steel truss bridge member with the temperature variations. The results demonstrated that the proposed impedance-based SHM technique can be effectively used for diagnosing the structural integrity, even with the presence of the temperature variations.

Acknowledgements

This work was jointly supported by the Smart Infra-Structure Technology Center (SISTeC) at KAIST sponsored bythe Korea Science and Engineering Foundation, and the Infra-Structure Assessment Research Center (ISARC) sponsored by Ministry of Construction and Transportation, Korea. This financial support is greatly appreciated.

References

Bhalla, S., Naidu, A. S. K., Soh, C. K. (2003) Influence of structure-actuator interactions and temperature on piezoelectric mechatronic signatures for NDE, *Proceedings of SPIE on Smart Materials, Structures, and Systems*, 5062, pp.263-269.

Giurgiutiu, V., Rogers, C. A. (1997) Electro-mechanical(E/M) impedance method for structural health monitoring and nondestructive evaluation, *International Workshop on Structural Health Monitoring*, September 18-20, Stanford, CA, pp.433-444.

Park, G., Kabeya, K., Cudney, H., Inman, D. J. (1999) Impedance-based Structural Health Monitoring for Temperature Varying Applications, *JSME International Journal*, 42(2), pp.249-258.

Park, G., Sohn, H., Farrar, C. R., Inman, D. J. (2003) Overview of Piezoelectric Impedance-Based Health Monitoring and Path Forward, *The Shock and Vibration Digest*, 35(6), pp.451-463.

Park, S., Yun, C. B., Roh, Y., Lee, J. J. (2006) PZT-based active damage detection techniques for steel bridge components, *Smart Materials and Structures*, 15, pp.957-966.

Soh, C. K., Tseng, K., Bhalla, S., Gupta, A. (2000) Performance of smart piezoceramic patches in health monitoring of a RC bridge, *Smart Materials and Structures*, 9, pp.533-542.