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# Intelligent bolt-jointed system integrating piezoelectric sensors with shape memory alloys

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**Abstract.** This paper describes a smart structural system, which uses smart materials for real-time monitoring and active control of bolted-joints in steel structures. The goal of this research is to reduce the possibility of failure and the cost of maintenance of steel structures such as bridges, electricity pylons, steel lattice towers and so on. The concept of the smart structural system combines impedance based health monitoring techniques with a shape memory alloy (SMA) washer to restore the tension of the loosened bolt. The impedance-based structural health monitoring (SHM) techniques were used to detect loosened bolts in bolted-joints. By comparing electrical impedance signatures measured from a potentially damage structure with baseline data obtained from the pristine structure, the bolt loosening damage could be detected. An outlier analysis, using generalized extreme value (GEV) distribution, providing optimal decision boundaries, has been carried out for more systematic damage detection. Once the loosening damage was detected in the bolted joint, the external heater, which was bonded to the SMA washer, actuated the washer. Then, the heated SMA washer expanded axially and adjusted the bolt tension to restore the lost torque. Additionally, temperature variation due to the heater was compensated by applying the effective frequency shift (EFS) algorithm to improve the performance of the diagnostic results. An experimental study was conducted by integrating the piezoelectric material based structural health monitoring and the SMA-based active control function on a bolted joint, after which the performance of the smart 'self-monitoring and self-healing bolted joint system' was demonstrated.

**Keywords:** structural health monitoring; GEV distribution; SMA washer; self-monitoring; self-healing

## 1. Introduction

Bolted joints are commonly used for the connections between structural members because the quality control of the connection is much easier than other types of joints such as welded joints and riveted joints. Therefore, it is important that the structural integrity of the bolted joints is monitored continuously. These connections invariably promote damage growth and are often difficult to inspect due to the nature of the geometry and the loading in structures (Park *et al*. 2003). Especially, steel structures such as bridges, electricity pylons and steel lattice towers have large

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numbers of bolted joints which need to be inspected periodically. The most frequent failure for bolted joints is self-loosening (Simmons 1986). To prevent this mode of failure, the concept of the self-monitoring and self-healing bolted joint is proposed in this study. This concept combines a PZT(one of piezoelectric materials, Lead Ziconate Titanate)-based health-monitoring technique with SMA (Shape Memory Alloy)-based actuators to restore tension in a loosened bolt. In the previous researches, the SMA was investigated to repair structures by themselves. Rogers *et al.* used SMA recovery force to reduce the damage in graphite/epoxy host materials (Rogers *et al*. 1991). To achieve that goal, SMA wires were embedded in the host materials and activated to close the crack propagation. Haimi et al. used SMA actuators for pre-tensioning threaded joints (Haimi *et al*. 1997). The SMA actuator was used for structural control during and after seismic events by timed release of chemicals such as concrete or polymer by Dry (Dry 1994). Gaul proposed a semi-active joint which could control the normal force in the friction interface of the joints (Gaul 1997).

In this study, a bolted-joint, which includes the PZT sensor and the SMA washer as an actuator is investigated. To detect the self-loosening damage, electromagnetic impedance signatures are measured from the PZT which is attached to a bolted-joint structure using a self-sensing circuit based on a voltage divider. The self-sensing circuit is cost-effective hardware to measure impedance signals, as compared to the conventional measuring systems. If the bolt lost the torque by the self-loosening, impedance signals would be changed by the dynamic characteristics of the host structure. Once this fluctuation is detected, the SMA washer installed between bolt and nut combination is heated. Then, the SMA washer is axially extended by the ability to convert heat into mechanical energy through a phase transition and the lost torque is recovered. Additionally, the recovering effects are validated from damage metrics which are compensated on temperature variation due to the heated SMA washer. The theory behind these techniques and the overview of the proposed 'Self-monitoring and Self-healing Bolted joint System' are presented in the following sections.

## 2. Theoretical background

### *2.1 Impedance based structural health monitoring*

In developing a self-sensing and self-healing bolted joint, piezoelectric impedance-based health-monitoring method has been employed for the effective evaluation of structural bolted joints (Antonios *et al*. 2006, Faria *et al*. 2011, Giurgiutiu *et al*. 2002, Giurgiutiu *et al*. 2004, Lee and Park 2011, Muntges *et al.* 2001, Park *et al*. 2006, Park *et al*. 2000, Lovell and Pines 1998). The basic concept of the impedance-based structural health monitoring method is the use of high frequency vibrations to monitor the local area of a structure for changes in structural impedance that would indicate damage (Liang *et al*. 1994, Park *et al*. 2011). The impedance measurements can readily give information on changing parameters, such as resonant frequencies, that will allow the detection of damage. Since the piezoelectric (PZT) patch is bonded to the structure, the structure is deformed with the PZT and produces a local dynamic response to the vibration. The response of the system is transferred back from the piezoelectric patch as an electrical response. The electrical response is then analyzed, and since the presence of damage causes the response of the system to change, damage is shown as a phase shift or magnitude change in the impedance. Bhalla *et al*. have demonstrated that the real part of the measured admittance is more sensitively changed due to the structural damage condition compared with the imaginary part (Bhalla *et al*. 2002).

In this study, a self-sensing based SHM system has been used (Lee and Sohn 2006). A simple voltage divider with a reference capacitor was used to construct a self-sensing circuit, as shown in Fig. 1.

In this system, the impedance of the structure, $Z(\omega)$ is calculated as Eq. (1).

$$Z(\omega)=\frac{V_p(\omega)}{I(\omega)}=\left[i\omega C_p\right]^{-1}\cong\left[i\omega C_r\left(\frac{V_o(\omega)}{V_i(\omega)-V_o(\omega)}\right)\right]^{-1} \tag{1}$$

where $V_i(\omega)$ and $V_o(\omega)$ are the input voltage and the output voltage from the self-sensing circuit, and $C_r$ and $C_p$ are the reference capacitance and the zero-load capacitance of PZT, respectively. After acquiring the signals at the piezoelectric sensors, sinusoidal response signals are transformed from time-domain to frequency-domain using FFT (Fast Fourier Transform) for analyzing the signals in the frequency domain.

### *2.2 Statistical damage indices for damage detection: RMSD and cross-correlation coefficient*

By observing a number of changes of the impedance acquired from a PZT attached to a host structure, assessments can be made about the integrity of the host structure. Since the impedance changes provide only a qualitative assessment for damage detection, several scalar damage metrics have been used for the quantitative measure of structural damages. Peairs *et al*. compare several damage metrics, while the most commonly used indices for the impedance method are the root mean square deviation (RMSD) and the cross-correlation coefficient (CC) as (Peairs *et al*. 2002)

$$RMSD=\sqrt{\frac{\sum_{i=1}^{n}\left[\mathrm{Re}\left(Z_0(\omega_i)\right)-\mathrm{Re}\left(Z_1(\omega_i)\right)\right]^2}{\sum_{i=1}^{n}\mathrm{Re}\left(Z_0(\omega_i)\right)^2}} \tag{2}$$

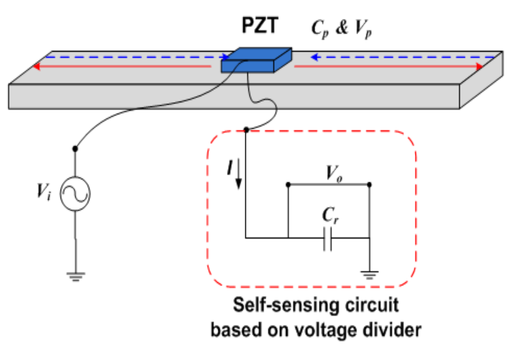



Fig. 1 Self-sensing circuit for impedance measurement (adapted from [16])

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; $\bar{Z}_0$ and $\bar{Z}_1$ are the mean values of the impedance signals of $Z_0(\omega)$ and $Z_1(\omega)$, respectively; $\sigma_{Z_0}$ and $\sigma_{Z_1}$ are the standard deviations of the real parts of $Z_0(\omega)$ and $Z_1(\omega)$. These metrics are scaled by the baseline measurement, 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. The greater numerical value of the RMSD metric indicates a larger difference between the baseline reading and the subsequent reading, and this fact indicates clearer presence of structural damages. On the other hand, a smaller value of the CC metric indicates a larger difference between the baseline reading and the subsequent reading. When we use 1-CC for the damage indices, the larger difference between the baseline and the subsequent reading will indicate the damage clearly.

Effective frequency shift (EFS) by means of the cross-correlation analysis was used in this experiment to compensate the impedance variation due to the temperature change, which was proposed by the previous research (Koo *et al*. 2009). Herein, the effective frequency shift $\tilde{\omega}$ for an impedance data $y(\omega)$ is defined as the shift corresponding to the maximum cross-correlation with the reference impedance data $x(\omega)$ as

$$\max_{\tilde{\omega}} CC = \max_{\tilde{\omega}} \left\{ \frac{1}{N} \sum_{i=1}^{N} \frac{\left(x(\omega_i) - \bar{x}\right)\left(y(\omega_i - \tilde{\omega}) - \bar{y}\right)}{\sigma_X \sigma_Y} \right\} \tag{3}$$

where $\bar{x}$ and $\bar{y}$ are the mean values of the two impedance signatures of $x(\omega)$ and $y(\omega)$, respectively; and $\sigma_X$ and $\sigma_Y$ are the standard deviations. Note that the effective frequency shift method may compensate the vertical shifts as well by subtracting the mean values from the original signatures.

Temperature variations due to surrounding changes should be considered with careful attention because piezoelectric sensor properties such as the 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. To date, several studies have been presented to reduce temperature impacts on assessment with measured impedance signals. Park et al. proposed a temperature-corrected scheme based on the reconstruction of the conventional RMSD damage metric (Park *et al*. 1999). The experimental results conducted on a bolted joint showed that large fluctuations of impedance signals and horizontal shifts of resonant frequencies were minimized to indicate the presence of damage.

The experimental results on a bolted joint showed that the temperature change caused considerable variations with both vertical and horizontal shifts on impedance measurements at the same damage condition, while an excellent match could be obtained between these signatures after the EFS method was applied.

### *2.3 Damage detection using outlier analysis - establishment of threshold level using Generalized Extreme Value (GEV) distribution*

Damage diagnosis is performed by applying outlier analysis to the damage index values obtained in the previous section. In this section, the basic concept of outlier analysis is briefly reviewed and extended to the consecutive outlier analysis for detecting outliers.

The outlier analysis aims to establish simply whether or not a new pattern is significantly different from the previous patterns, while at the same time automatically ignoring any negligible differences such as random fluctuations due to noise. That is, an outlier is an observation that significantly differs from the remainder of the population and therefore the outlier is believed to be generated by an alternate mechanism (Barnett and Lewis 1994). After calculating the damage metrics, it is necessary to determine the appropriate threshold for the damage metric that distinguishes between the intact and damage condition. In this study, the 95% confidence level threshold of the intact condition was adopted using the generalized extreme value (GEV) distribution which is one of the outlier analyses. In probability theory and statistics, the GEV distribution is a family of continuous probability distributions developed within extreme value theory to combine the Gumbel, Fréchet and Weibull families, also known as types I, II and III extreme value distributions, respectively (Coles 2001).

In the extreme value theorem, the GEV distribution is the limit distribution of the properly normalized maxima of a sequence of independent and identically distributed random variables. Because of this, the GEV distribution is used as an approximation to model the maxima of long (finite) sequences of random variables. After the bolt is loosened, the damage indices would dramatically increase (or decrease). This statistical pattern is similar to the characteristics of the GEV distribution and hence damage can be effectively detected using the GEV distribution. The generalized extreme value distribution has a cumulative distribution function, as shown in Eq. (4)

$$GEV : \bar{\phi}\left(x;\mu,\sigma,\xi\right) = \exp\left\{-\left[1+\xi\left(\frac{x-\mu}{\sigma}\right)\right]^{-1/\xi}\right\} \tag{4}$$

For $1+\xi\left(x-\mu\right)/\sigma > 0$ , where $\mu \in R$ is the location parameter, $\sigma > 0$ is the scale parameter and $\xi \in R$ is the shape parameter.

### *2.4 Self-healing bolted joints using shape memory alloy*

As mentioned previously, the damage control portion of the self-healing bolted joint utilizes SMA technology. The shape memory effect occurs as a result of a phase transformation when cooled from austenite (its high temperature cubic structure), to martensite, with a monoclinic lattice structure, which resembles a parallelogram in two dimensions. One accepted explanation of atomic movement allowing the shape memory effect is that instead of the parallelograms aligning in the same direction, alternating rows of atoms tilting either right or left are formed. This is referred to as a twinning because the atoms form mirror images of each other. When the material is deformed, it detwins and the parallelograms all lie in the same direction. Upon heating, the SMA returns to its austenitic crystal structure and pre-deformed shape. If the SMA is restrained during this process, stress will be generated in the material (Waram 1993). Using these characteristics, the SMA is used as a washer of the bolted joint to recover the loosened torque.

## 3. Experimental study

### 3.1 Experimental setup

Fig. 2 shows the equipment setup used in this study. The test specimen was constructed using two 400 mm x 200 mm x 3 mm beams bolted together with 200 mm x 200 mm x 3 mm steel plates. The bolt used in this study was the M22 hexagon bolt, of which the length was 50.8 mm. A 20 mm x 20mm PZT sensor is attached to the center of the bar.

Fig. 3 shows the equipment configuration for the signal measurements. An Arbitrary Waveform Generator (AWG) that creates input signals, a high-speed signal digitizer (DIG) that measures the responses of the structures from the sensor, and a Multiplexer that automatically changes the channel for measuring signals were inserted into the slot types in the NI-PXI chassis. A controller was also inserted into the chassis to control the equipment. This experiment was performed using LabVIEW, which is software that controls and operates this DAQ system.

The joint was initially tightened to the torque of 40 Nm, representing its intact state and the impedance was measured. The joint was then loosened to 25 Nm and 15 Nm and the impedance was measured again. After the measurement of the 'loose' case, an external heater (heating film) was attached to the SMA washer to verify that the SMA washer can restore the lost torque of the bolted joint, as shown in Fig. 4. In this paper, it is focused on how the impedance signatures are changed according to the SMA actuation on the washer of a bolt-jointed system and hence the details on the washer are referred from (Park 2001).

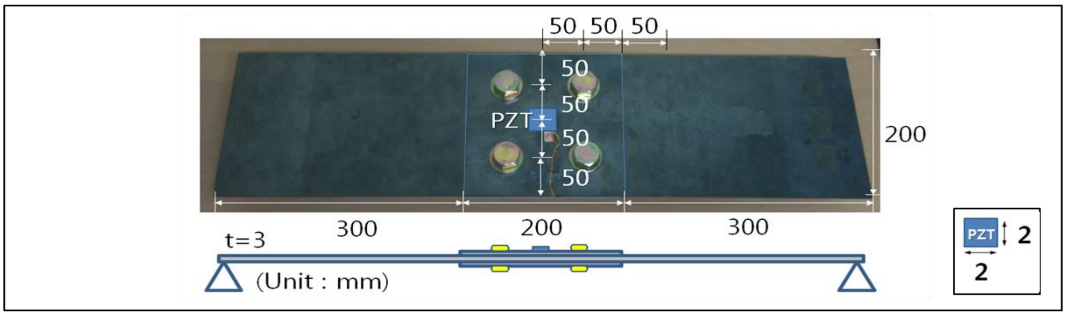



Fig. 2 Test specimen

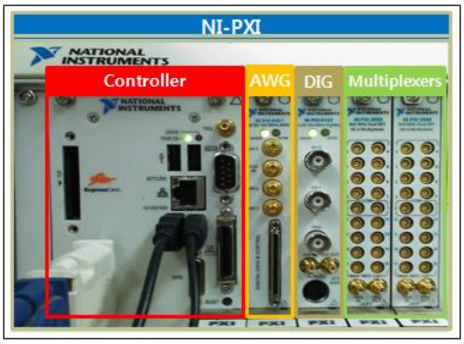



Fig. 3 DAQ system for the experiment

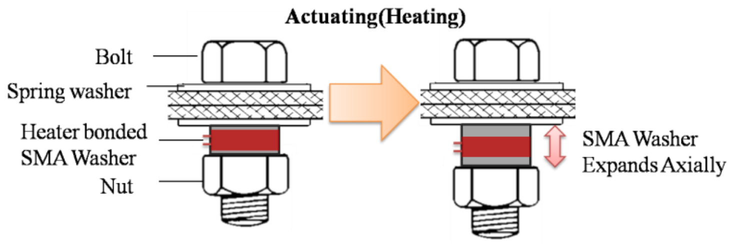



Fig. 4 Smart Self-healing Bolted Joint

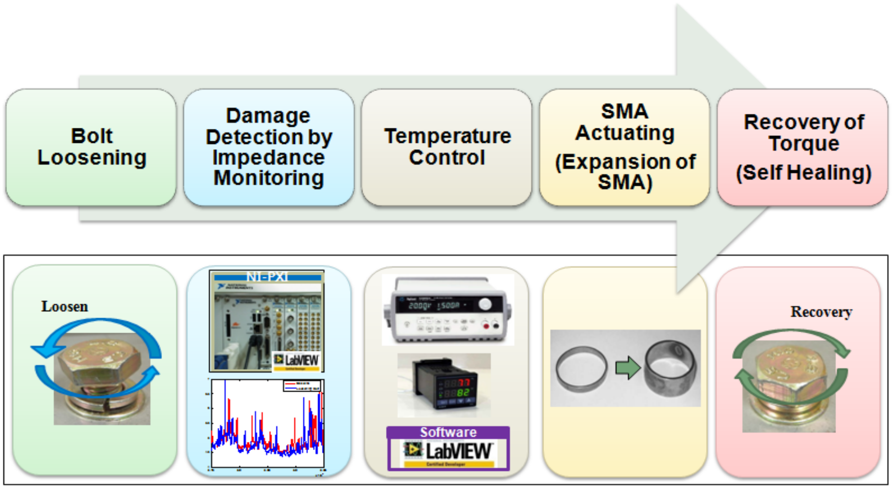



Fig. 5 Process of the Self Monitoring and Self Healing Bolted Joints System

Fig. 5 shows the entire process of the proposed 'Self Monitoring and Self Healing Bolted Joints System'. The basic principle of this technique is that the temporary adjustment of the decreased torque can be achieved using a shape memory alloy actuator around the axis of the bolt shaft. To heat the SMA washer, an external heater is bonded to the SMA washer and the SMA washer is inserted between the bolt and the nut. When the bolted joint is loosened, the PZT sensor detects the damage using the impedance based monitoring technique. Then, the system orders the power controller to actuate (heat) the SMA washer, and the heated SMA washer expands axially. As a result, the bolted joint restores the lost torque.

### *3.2 Experimental results*

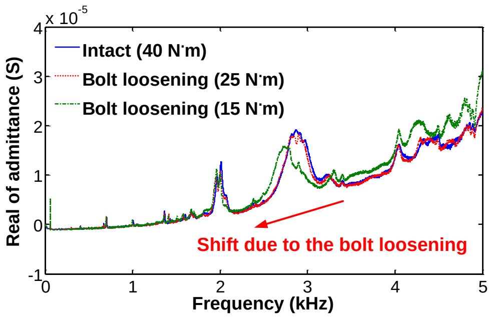
#### *3.2.1 Results of impedance based bolt loosening damage detection*

The piezoelectric impedance-based health-monitoring method was used to detect bolt loosening damage. The impedance was monitored over a frequency range from 0.1 kHz to 5 kHz and impedance was measured 20 times at each torque step. First, to represent the intact case, we tightened the joints initially to 40 Nm using the torque wrench, and then loosened the joints to 25

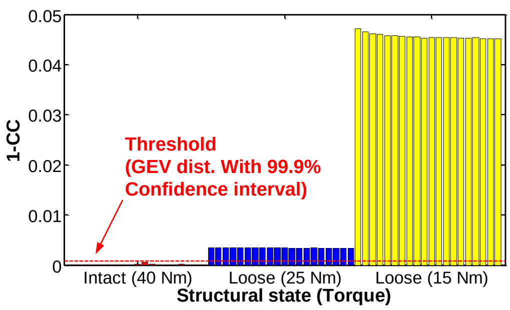
Nm and 15 Nm which represents the loose damaged case. Fig. 6(a) shows the shift of the impedance signature from 0.1~5 kHz. As shown in Fig. 6 (a), as the torque reduces from 40 Nm to 25 Nm and to 15 Nm, the peak of the resonant frequency shifted leftward upon loosening, indicating a reduction in stiffness. The damage metric was calculated to quantify the change in the impedance signal caused by damage. Fig. 6(b) shows the 1-CC (cross-correlation coefficient) of each loose damage condition. The observed 1-CC of each damage case increased with the level of bolt loosening damages, and all 1-CC values under the damage conditions were higher than the threshold calculated under the intact condition. Overall, the suggested impedance-based health-monitoring method can be used effectively to monitor the bolt loosening damage to the structure.

### *3.2.2 Results of self-healing the loosened bolt by actuating the SMA*

The basic principle of the self-healing technique is that the temporary adjustment of the decreased torque can be achieved using a shape memory alloy actuator around the axis of the bolt shaft. As shown in Fig. 7, a ThermofoilTM heater from Minco Products, Inc. was bonded to the SMA washer. The flexible heater was approximately 79 mm x 7.6 mm x 1 mm and it had a resistance of 6.4 ohms. It was powered with a maximum 22 V and current of 2.5 A DC power supply.




(a) Variation of the impedance signature due to damage




(b) Damage metric of the impedance signature

Fig. 6 Impedance measurements from 0.1~5 kHz and 1-CC damage metric

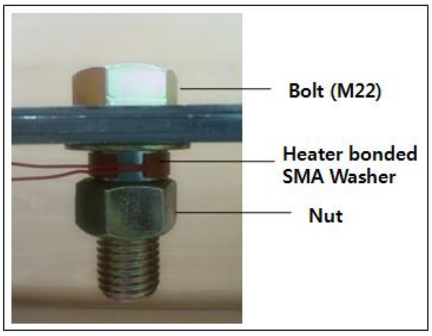



Fig. 7 SMA washer with the bonded heater

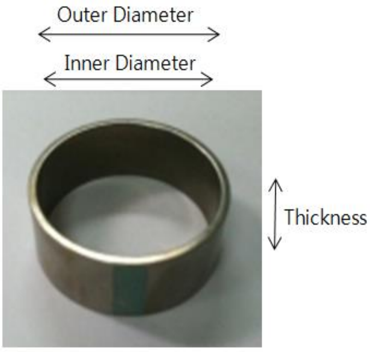



Fig. 8 SMA washer

Table 1 SMA washer properties

| | |
|---|---|
| Resistance | 0.0018 ohms |
| Mass | 6.778g |
| Length | 9.7mm |
| Inner Diameter | 24.4mm |
| Outer Diameter | 26.8mm |
| Inner Diameter Maximum Recovered | 23.3mm |
| Minimum Substrate Diameter | 23.65mm |
| Nominal Clamping Force | 13920N |
| Thermal Conductivity | 18W/m K |

The SMA washer used in this study is shown in Fig. 8 and the properties of the washer are shown in Table 1. As shown, the inner diameter was 24.2 mm, the outer diameter was 26.85 mm and the thickness was 9.7 mm.

After a series of experiments for detecting damage as described in the previous section, the SMA was actuated by controlling the temperature. The temperature control step (SMA actuating step) was divided into 5 steps - actuating for 30sec, 3min, 6min, 20min and 40min. In addition, we measured the temperature of the SMA washer, and the impedance changed 20 times at each step. Each impedance measurement was performed after completely cooling the SMA to 25℃ to exclude the impedance change caused by the temperature rise.

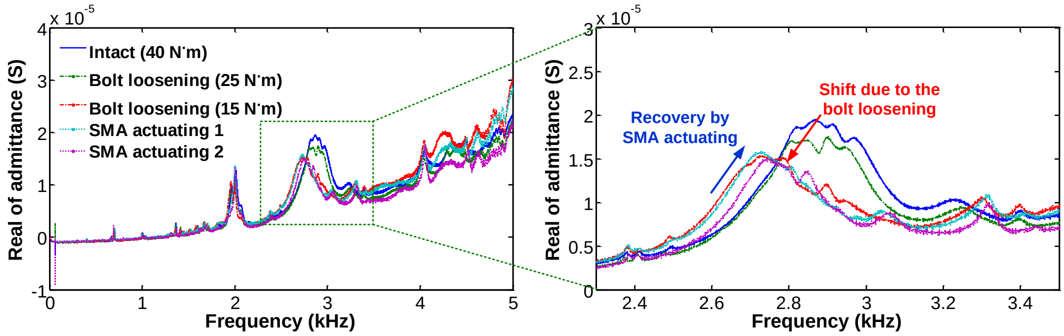



Fig. 9 Impedance measurements from 0.1~5 kHz after actuating the SMA washer

The change in bolt torque caused a change in the impedance. Analysis of the impedance signatures after the SMA actuating showed almost no change from the 1st step to the 2nd step. The impedance measurement started to change at the 3rd step - actuating for 6min. Therefore, the impedance signatures from the 3rd step and the last step are used to show the impedance change in Fig. 9. In the legend, 'SMA Actuating 1' refers to the impedance curve of the 3rd step, and the temperature of the SMA was 170℃ before cooling. 'SMA Actuating 2' refers to the impedance curve of the last step, and the temperature of the SMA was 220℃ at the hottest moment. As can be seen in Fig 9, loosening the bolt torque from 40Nm to 15Nm caused a shift of the peak of the curve. The peak was shifted leftward and downward upon loosening, indicating a reduction in stiffness; but after actuating for 40min, the peak of the resonant frequency shifted rightward and upward. It showed that the peak had a tendency to shift back to the intact condition after actuating the SMA washer using the external heating film.

As shown in Fig. 10, as the torque of the bolted joint reduced, the 1-CC increased. After actuating the SMA washer, the 1-CC bar chart showed a tendency to reduce, which means that the bolted joint restored the lost torque.

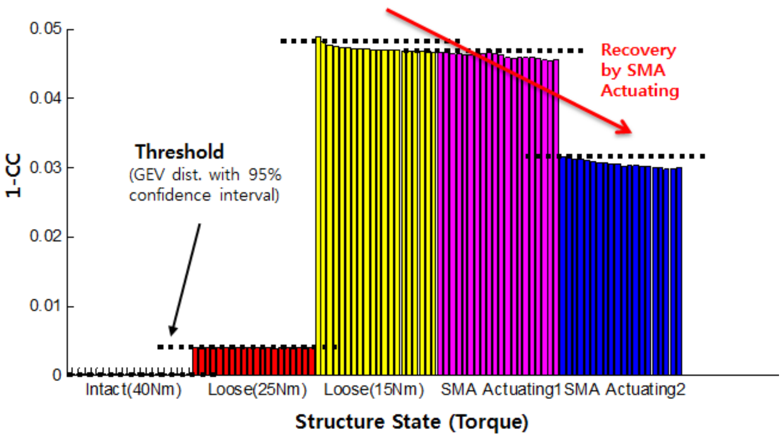



Fig. 10 1-CC and threshold level shift occurred by bolt loosening and after actuating the SMA washer

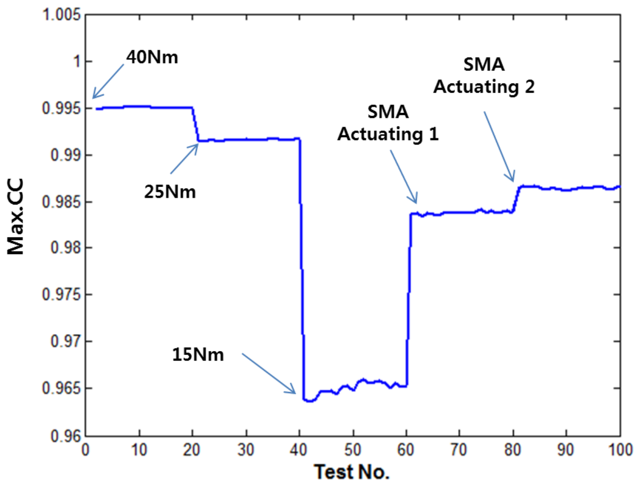



Fig. 11 Cross-correlation coefficient after the effective frequency shift

The optimal threshold values for more systematic damage detection considering the fluctuations in the 1-CC values were estimated with a statistical confidence level (C.L.) of 95% for the outlier analysis as mentioned in chapter 2.3.2. First, all of 1-CC values after damage exceeded threshold obtained from the intact data. Then, threshold values were calculated at each experimental step. As expected, the threshold values increased as the torque decreased. On the other hand, the threshold values decreased after SMA actuating. From these observations, we could confirm that the self-healing bolted joint had a tendency to recover the lost torque.

As mentioned previously, effective frequency shift (EFS) by means of the cross-correlation analysis was used to compensate the impedance variation due to the temperature change in this experiment. As shown in Fig. 11, as the torque of the bolted joint reduced, the cross-correlation coefficient, after the effective frequency shift (max. CC), was reduced. After actuating the SMA washer, the max.CC bar chart showed a tendency to increase, which means that the bolted joint restored the lost torque.

This experimental study shows the basic concept of an automated control system which monitors the bolted joints and controls the joints by actuating the SMA washers as the threshold level is updated. There was an artificial intervention at this experiment. However, the automated system will operate by itself in the field application.

## 4. Conclusions

The self-monitoring and self-healing bolted joint system is an automated smart system used to repair in a self-healing manner bolt-loosening defects using SMA washers. This study evaluated the proposed system.

- The experimental study has shown the capability of the impedance based SHM method to detect bolt loosening damage using a self-sensing circuit and piezoelectric sensors.
- A calculation of the damage metrics showed that the 1-CC increased in steps with an increasing level of damage and was over the determined optimal threshold, using the generalized extreme value distribution.
- The SMA washer with an external heater is effective to restore the lost torque of the bolted joint.
- Temperature variation due to the heated SMA washer was compensated by applying the EFS algorithm and hence the performance of the diagnostic results was improved.

In this study, the self-monitoring and self-healing bolted joint system was evaluated using piezoelectric sensors and an SMA washer. However, these results were obtained by artificial intervention; reducing the torque using the torque wrench and actuating the SMA washer by turning on the DC power supply. Therefore, additional extensive efforts are currently devoted to studying several implementation issues to handle real-world structures associated with bolted joints automatically.

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