Quantitative Assessment of the Fastening Condition and the Crack Size with Using Piezoceramic (PZT) Sensors

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Keyword: Structural Health Monitoring; Piezoceromic (PZT) Sensors; Electro Impedance; Bolt Fastening; Crack, Damage Assessment Indices

Abstract.

We present a study on the development of a practical and quantitative technique for the assessment of the structural health condition with using piezoceramic (PZT) sensors. The electro-impedance-based technique with the PZT patches is very sensitive for evaluation of the incipient and small damage in a high frequency range, and however the commonly traditional modal analysis method is effective only for considerably larger damages in low frequency range. The paper presents the technique in detecting and characterizing real-time damage on the specimen that is an aluminum plate fastened with bolts and nuts by different torques and as well a plate with a crack. By using the special arrangement of the PZT sensors, the required longitudinal wave is generated through the specimen. A large number of experiments are conducted and the different conditions of the specimens, i.e. the location and extent of loosening bolts, and the plate with a crack are simulated, respectively. Since fixing and loosening the loosened bolt is controlled by a torque wrench, we can control exactly the experiment of the different torques. Compared with the simulated healthy condition, we can find whether or not there is a damage in the specimen with using an impedance analyzer with the PZT sensors. Several indices are discussed and used for assessing the different simulated damages. As for the location of bolt loosening, the RMSD is found to be the most appropriate index for numerical assessment and as well the RMSD shows strongly linear relationship for assessing the extent of the bolt loosening, and the frequency peak shift ΔF is used to assess the cracked plate. The possibility of repeatability of the pristine condition signatures is also presented and the appropriate frequency range and interval are uniquely selected through large numbers of experiments.

1. Introduction

The aging of large structures is a major concern for engineers and scientists, and the rapid development of the economy gives rise to much higher and stricter criteria and requirements for SHM (Structural Health Monitoring). The NDE technique (Nondestructive Evaluation) is especially a major concern. A large number of technologies for NDE have been developed, such as MA (Modal Analysis), wave propagation, time domain, eddy-current methods and ultrasonic, magnetic field methods, etc. The application ranges from aircrafts to infrastructures, i.e. pipeline systems, bridges and buildings, etc. The piezoceramic sensors (PZT) that simultaneously act as an actuator and sensor are widely used for SHM. In the high frequency range, the electro-impedance-based technique with using a PZT is very sensitive for the evaluation of the incipient and small damage, such as bolt loosening, cracks and holes.

The interaction between a PZT and its host structure can be described by using a simple 1-D model, as shown in Fig. 1. The PZT is normally bonded directly to the surface of the structure with using a high-strength adhesive to ensure a better mechanical interaction. The bonded PZT is considered as a thin bar that is undergoing axial vibration in response to an applied alternating voltage. One end of the bar is fixed and the other end is connected to the host structure, which is represented by a single-degree-of-freedom system. This assumption regarding the interaction at two discrete points is consistent with the mechanism of force transfer from the bonded PZT sensor to the structure. The model of the principle is shown as in Fig. 1 [1].

We present the performance of the electro-impedance-based technique for detecting real-time damage on the sample of a plate with bolts and nuts, and as well a plate with a crack as the simulated damage. A large amount of experiments are executed and several conditions are imposed to simulate real-time damage, i.e. the location of the loosening bolts, and the loosening extent of the bolts, the size of the crack. The different indices are discussed and executed to efficiently quantify the damage conditions. The theory behind this technique and the experimental investigations is presented in this paper. The analytical results strongly show the sensibility and reliability of this technique.

2. Experimental Procedures

2.1 Electro-Impedance Measuring System

Plates that have bolt connections possess an important role in all types of structures. Damage detection that is based on plates that have bolt connections is universally significant. We present the simulation of several real-

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time damages, i.e. the location of the bolt loosening and the extent of the bolt loosening. The experimental setup

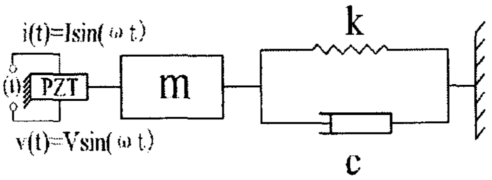


Fig. 1 Degree of freedom model of structure

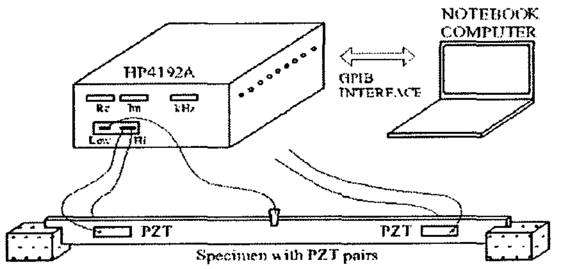


Fig. 2 The electro-impedance measurement where piezoelectric sensors attached system and the PZT sensors

is comprised of an impedance analyzer HP4192A, PZT sensors and a notebook computer with software, GPIB interface cables and a plate specimen. A 0.3mm thickness is selected for the experimental investigations to efficiently generate the longitudinal elastic wave for the rectangular PZT sensors of 25mm length and 4mm width.

In general, one PZT sensor that is bonded on the surface of the structure dominantly generates the traverse or bending wave; however, the longitudinal wave is required for the damage detection along with the plates in the experiments. Fig. 2 shows the arrangement of the PZT sensors. The PZT pair of PZT1, 1" bonded on one end of the plate is constructed. PZT1 is bonded on one side of the end of the plate, while PZT1" is bonded on the back side of the plate that corresponds to PZT1. Therefore, the transverse or bending component of the waves that are generated by PZT1 and PZT1" counteract each other; however, the longitudinal component that is generated is intensified along the plate. Correspondingly, the PZT pair of PZT2, 2" is bonded on the other end of the plate. As well, the specimen with a crack is simulated, and the PZT3, 3" are used, as shown in Fig. 4

2.2 Experiment for the Location of Bolt Loosening

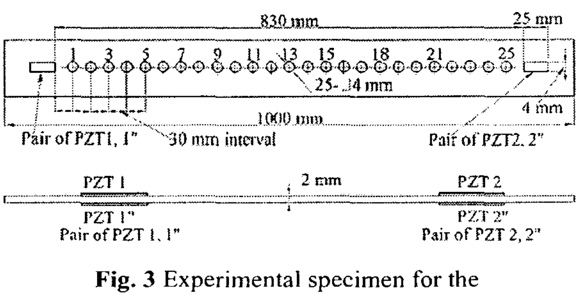


Fig. 3 Experimental specimen for the location of bolt loosening

A bolted connection is a common form in many structures. Real-time condition monitoring and active control of bolt loosening of critical bolts will improve the reliability and safety of many structures. The specimen in Fig. 3 is the aluminum plate of 1000mm length, 25mm width and 2mm thickness with twenty-five 4mm diameter holes. The holes are fastened with using twenty-five 4mm diameter bolts and nuts with gaskets. Two pairs of PZT1, 1" and PZT2, 2" are bonded to the two ends of the plate, as shown in Fig. 3. The pair of PZT1, 1" is located 85mm from one free end of the plate and the pair of PZT2, 2" is similarly placed 85mm from the other end of the plate. The first hole is drilled at a distance of 30mm from the pair of PZT1, 1" and the last one is also at 30mm distance from the pair of PZT2, 2". A total of 25 holes are drilled, which are at an equal interval of 30mm, and are numbered from 1 to 25 beginning from the first hole. All of the holes are then screwed with bolts, nuts and gaskets by a 3 N.m torque with using a torque wrench, and then the condition is treated as a healthy condition of the specimen. To simulate the damage, one bolt is loosened from 3 N.m to 1 N.m and then 0 N.m at a randomly desired location while all the rest are maintained in a tightly screwed position by 3 N.m torques. Simultaneously, the bolt is loosened from 3 N.m to 1 N.m and 0 N.m separately to simulate the extent of bolt loosening at the specific location. The admittance signatures of healthy and damaged conditions are acquired by the pairs of PZT1, 1" and PZT2, 2" for two repititions, and the healthy admittance signatures are labeled with H1, which is obtained by PZT1, 1", and H2, which is obtained by PZT2, 2". After acquiring the admittance signatures for the damaged condition, the bolt is again screwed back to 3 N.m. The single holes of 1, 3, 5, 7, 9, 11, 13, 15, 18, 21 and 25 are investigated.

2.3 Experiment for the size of a crack

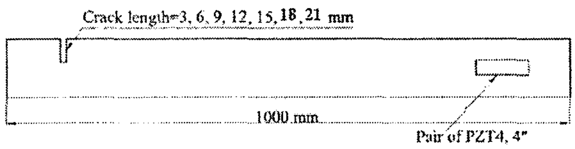


Fig. 4 Experimental specimen with a crack

Fig. 4 shows that the specimen is the aluminum plate of 1000mm length, 25mm width and 2mm thickness with a crack. The pair of PZT 3, 3" is located at the right end of the plate. The plate without a crack is considered to be the healthy condition and the crack is 100mm away from the left end of the plate. To simulate the damage, the damage is simulated as a crack with different length, i. e. 3, 6, 9, 12, 15, 18, 21mm, respectively. For each step, the admittance of the healthy and damaged conditions are measured by using the impedance analyzer HP4192A, respectively.

3. Results Analyses

3.1 Consideration of Frequency Range and Repeatability

The electro-impedance-based technique demonstrates high sensibility in the high frequency range. To obtain the most appropriate range to acquire the admittance signatures, the pair of PZT1, 1" is scanned through a wide range from 10kHz to 1,000kHz. The real part of the admittance that corresponds to 100~150 kHz includes 20~30 dominant peaks. According to the literature, the signatures, which include several peaks, indicate high sensibility to the change that is caused by a small amount of damage. Except for those that are relative to 100~150kHz, the admittance signatures that are relative to 10~40kHz show random irregular variations and those that are relative to 160~1,000kHz show ordinary signals without dominant peaks. Several sampling intervals, i.e. 5Hz, 10Hz, 20Hz, 50Hz, are investigated to obtain the admittance signatures. The smaller the interval is, the more accurate the signature is without distortion over a longer period of time. By comparing the fidelity of the signatures with the time cost, the interval of 20Hz is found to be the optimal choice for the experiments [2].

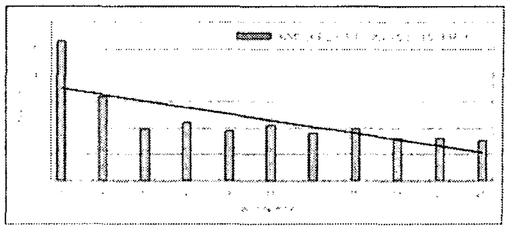
3.2 Analysis of Simulated Damages for the Location of Bolt Loosening

The experiments are conducted with using the specimen in Fig. 3 over 100~150 kHz, and the data is processed by displaying the real part of the electro-impedance. Several damage indices are tried: Root Mean Square Deviation (RMSD), Mean Absolute Percentage Deviation (MAPD), Covariance (Cov) and Correlation Coefficient (CC) [3, 4]. For the damages, i.e. the location of bolt loosening and the extent of bolt loosening at the same location, the RMSD is found to have a strongly linear relation between the damaged and healthy conditions. In this section, the damaged conditions of the specimen in Fig. 3 are analyzed with using the index of the RMSD. For each stage of damage, the admittance signatures are obtained by the pairs of PZT1, 1" and PZT2, 2". Eleven arbitrarily selected damages, which are located at the holes that are numbered 1, 3, 5, 7, 9, 11, 13, 15, 18, 21 and 25, are investigated.

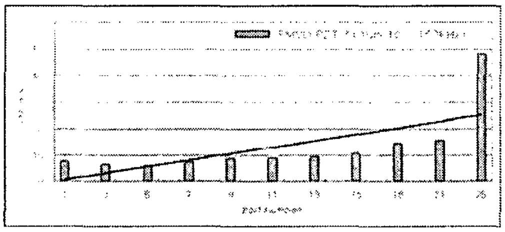
Fig. 5 (a), (b) presents the RMSD values for the damaged signatures that are obtained by PZT1, 1" and PZT2, 2", respectively, for the bolt loosening by 0 N.m in the frequency range of 100~150kHz. It's observed from Fig. 5 (a) that even when the farthest bolt, number 25, is subjected to a small bolt loosening damage, the RMSD value reaches a relatively high value of 10%. The result efficiently verifies that PZT sensors have a high sensitivity to detect a small damage that is located at a far distance. Fig. 5 (b) also provides similar verification for the high sensitivity of PZT sensors. Fig. 5 (a) shows that the RMSD values gradually decrease when the simulated damage moves away from the pair of PZT1, 1", and Fig. 5 (b) indicates that the RMSD values gradually increase when the simulated damage approaches the pair of PZT2, 2" with each step.

The trends of increase and decrease of the RMSD show a considerably uniform linear relation.

Fig. 6 (a), (b) presents the RMSD values for the damaged signatures with the bolt loosening by 1 N.m in the frequency range of 100~150kHz. Fig. 6 (a), (b)



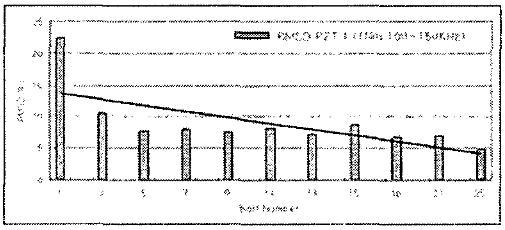
(a) RMSD(%) of PZT 1, 1"



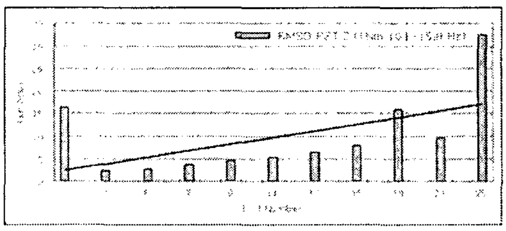
(b) RMSD(%) of PZT 2, 2"

Fig. 5 RMSD versus damage distance with 0 $N \cdot m$ torque

indicates that the RMSD values have the same variation trend as that of Fig. 6 (a), (b), however, the magnitude is relatively smaller. For example, the farthest bolt, number 25, is subjected to a small bolt loosening damage by 0N.m and the RMSD value reaches a value of 5%, but Fig. 6 (a) has a value of 10% at the same location. The theory behind this phenomenon is that the different torques of 1N.m and 0N.m apply different normal stresses to the vicinity of the bolts. Therefore the elastic wave propagation along the plate that is generated by the PZT sensors is influenced and the energy dissipation of the wave is presented in different extents. It can be said again that the gentle variation of the bolt loosening conditions between 1N.m and 0N.m can be efficiently detected, and therefore the sensitivity and reliability of PZT sensors for such an incipient damage are validated once again.



(a) RMSD(%) of PZT 1, 1"



(b) RMSD(%) of PZT 2, 2"

Fig. 6 RMSD versus damage distance with 1 $N \cdot m$ torque

From all of the figures above, it is shown that the closest bolt, that is, bolt 1 that is relative to PZT1, 1" and bolt 25 that is relative to PZT2,2", has a much greater RMSD value than all of the other bolts. This phenomenon reflects the energy dissipation of the wave propagation along the plate.

3.3 Analysis of Simulated Damages for the specimen with a crack

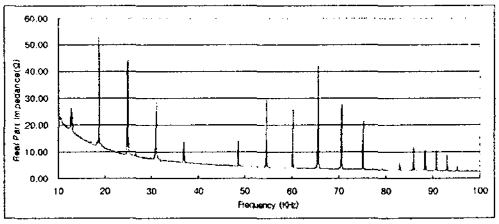


Fig. 7 Peak frequency shift of the plate with a crack

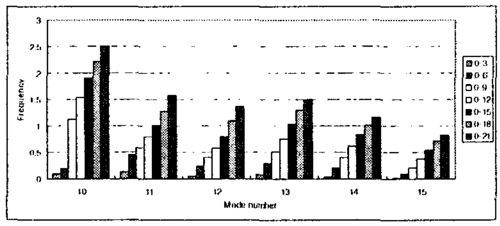


Fig. 8 Peak frequency shift of the plate with a crack

With respect to simulated damage, i.e. the size of the crack, the peak frequency shift is used to numerically estimate the damaged conditions. Fig. 7 shows the impedance response of the healthy plate. And therefore the impedance response over 100 kHz is excluded, because the response has non-uniform tendency relative to that indicated below 100 kHz. By comparison, the 10, 11, 12, 13, 14, 15 modes are selected to provide the reference for the frequency peak shift ΔF .

$$\Delta F = f_H - f_D \qquad (1)$$

In Eq. 1, f_H represents the peak frequency for the health status of the beam, and f_D the peak frequency for the damaged status. Now we compare normal peak frequency by f_H and peak frequency by f_D after damage. And then the difference of the peak frequency relative to the two conditions is called ΔF .

Fig. 8 (a) presents the ΔF values that are obtained with the cracks located at the distances of 100mm away from the left end of the plate, as shown in Fig. 4. Fig. 8 shows that with respect to the same mode number when the damage, i.e. the length of the crack increases, the ΔF values strongly linearly increase. However, with respect to the same damage, when the mode number increases, the ΔF values decrease almost linearly.

4. Conclusions

The experimental investigations of the electro-impedance-based heath monitoring technique on two aluminum plates are presented. The remarkable advantage of this technique versus the other modal analysis techniques is that the electro-impedance based technique is not based any model, and thus can be easily applied to complex structures. The PZT sensors exhibits excellent features under normal working conditions, and has a large range of linearity, fast response, light weight and long-term stability. It also shows the feasibility to monitor inaccessible locations. The simulation of damages, i.e. the location and also the extent of the bolt loosening and the size of the crack, mainly indicates the sensibility and reliability of this method. The repeatability of the admittance signatures under health conditions obtained by different PZT pairs is verified to be considerably consistent through the experiment. Additionally, the PZT sensor shows a much higher sensitivity for small damages, i.e. the small bolt loosening with 1N.m and 0N.m, even though the damage is far from the PZT sensor at a distance of nearly one meter or above.

The quantification for the evaluation of the damages is also presented. With respect to the different damages, the RMSD shows a strong linear relation between the damage and the locations of the bolt loosening. When the bolt loosening moves away from or approaches the PZT pairs, the RMSD correspondingly decreases or increases. When the bolt loosening at the same location is simulated with different torques of 1N.m and 0N.m, respectively, the RMSD with respect to 1N.m has the same trend as that of 0N.m; however, the RMSD is relatively smaller with respect to 1N.m. Additionally, with respect to the quantitative assessment of the size of the crack, the frequency peak shift ΔF shows linear relationship quite well between the mode number, the size of the crack and the shift values.

Acknowledge

This study was supported by NRL (National Research Laboratory) Program and by Management International Joint Research Project of MOST (Ministry of Science and Technology), Republic of Korea.

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