

IMPEDANCE-BASED STRUCTURAL HEALTH MONITORING

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1. Introduction

The development of a real-time, in-service structural health monitoring and damage detection technique has recently attracted a large number of academic and industrial researchers. The goal of this research is to allow systems and structures to monitor their own integrity while in operation and throughout their lives in order to prevent catastrophic failures and to reduce the costs by minimizing explicit preemptory maintenance and inspection tasks.

Impedance-based structural health monitoring techniques have been developed by utilizing the electromechanical coupling property of piezoelectric materials (Sun, *et al.* 1995) and form a new nondestructive evaluation (NDE) method. The basic concept of this approach is to monitor the variations in structural mechanical impedance caused by the presence of damage. Since structural mechanical impedance measurements are difficult to obtain, impedance methods utilize the electrical impedance of piezoelectric materials, which is directly related to the mechanical impedance of the host structure, and will be affected by the presence of structural damage. Through monitoring the measured electrical impedance and comparing it to a baseline measurement, one can qualitatively determine that structural damage has occurred or is imminent. In order to ensure high sensitivity to incipient damage, the electrical impedance is measured at high frequencies (typically greater than 30 kHz). At such high frequencies, the wavelength of the excitation is small and is sensitive enough to detect minor changes in the structural integrity. More importantly, high-frequency (kilohertz) signals require very low voltage (less than 1 volt at micro Watts) to produce a useful impedance excitation in the host structure. By integrating the impedance technique with self-sensing smart materials (Dosch *et al.* 1992), it has been demonstrated that the impedance-based method is suitable for use in a wide variety of structural health monitoring applications.

2. Electro-Mechanical Principle

The health monitoring method utilizes impedance sensors to monitor changes in structural stiffness, damping and mass. The impedance sensors consist of small piezoelectric patches, usually smaller than 25x25x0.1 mm, that are used to directly measure the local dynamic response.

Piezoceramic transducers acting in the 'direct' manner produce an electrical charge when stressed mechanically. Conversely, a mechanical strain is produced when an electrical field is applied. The process to be used with the impedance-based monitoring method utilizes both the direct and converse versions of the piezoelectric effect simultaneously to obtain an impedance signature. When a PZT patch attached to a structure, and is driven by a fixed alternating electric field, a small deformation is produced in the PZT wafer and the attached structure. Since the frequency of the excitation is very high, the dynamic response of the structure reflects only a very local area to the sensor. The response of that local area to the mechanical vibration is transferred back to the PZT wafer in the form of an electrical response. When a crack or damage causes the mechanical dynamic response to change (a frequency phase shift or magnitude change in the mechanical dynamic response), it is manifested in the electrical response of the PZT wafer.

The electromechanical modeling which quantitatively describes the process is presented in Figure.1. The PZT is normally bonded directly to the surface of the structure by a high-strength adhesive to ensure a better electromechanical coupling. The surface-bonded PZT is considered to be a thin bar in axial vibration due to an applied alternating voltage. One end of the bar is considered fixed, whereas the other end is connected to the external structure. This assumption regarding the interaction at two discrete points is consistent with the mechanism of force transfer from the bonded PZT transducer to the structure.

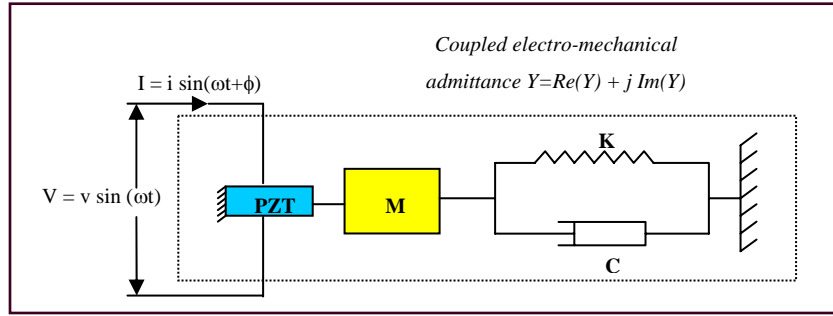


Figure 1 1-D model used to represent a PZT-driven dynamic structural system

The solution of the wave equation for the PZT bar connected to the structure leads to the following equation for a frequency-dependent electrical admittance (Liang *et al.* 1994):

$$Y(\omega) = i\omega a \left(\bar{\epsilon}_{33}^T (1 - i\delta) - \frac{Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)} d_{3x}^2 \hat{Y}_{xx}^E \right) \quad (1)$$

In equation (1), Y is the electrical admittance (inverse of impedance), Z_a and Z_s are the PZT material's and the structure's mechanical impedances, respectively, \hat{Y}_{xx}^E is the complex Young's modulus of the PZT with zero electric field, d_{3x} is the piezoelectric coupling constant in the arbitrary x direction at zero stress, $\bar{\epsilon}_{33}^T$ is the dielectric constant at zero stress, δ is the dielectric loss tangent of the PZT, and a is a geometric constant of the PZT. This equation indicates that the electrical impedance of the PZT bonded onto the structure is directly related to the mechanical impedance of a host structure. The variation in the PZT electrical impedance over a range of frequencies is analogous to that of the frequency response functions (FRF) of a structure, which contains vital information regarding the health of the structure.

Damage to a structure causes direct changes in the structural stiffness and/or damping and alters the local dynamic characteristics. In other words, the mechanical impedance is modified by structural damage. Since all other PZT properties remain constant, it is Z_s , the external structure's impedance, that uniquely determines the overall admittance. Therefore, any change in the electrical impedance signature is considered an indication of a change in the structural integrity.

An experimental modal testing using the electrical impedance of PZT patches (as co-located actuators and sensors) is presented by Sun *et al.* (1996). In this paper, the authors discuss that both the point frequency response functions of a single location and the transfer frequency response function between two locations on a structure can be obtained by measured electrical impedance. This work provides a critical insight into the impedance-based structural health monitoring technique, which the electrical impedance of piezoceramic materials constitutes a unique signature of the dynamic behavior of the structures.

Experimental implementation of the impedance-based structural health monitoring technique has been successfully conducted on several complex structures; a four bay space truss (Sun *et al.* 1995), an aircraft structure (Chaudhry *et al.* 1995), complex precision parts (Lalande *et al.* 1996), temperature varying applications (Park *et al.* 1999), a spot-welded structural joints (Giurgiutiu *et al.* 1999), civil structural components (Park *et al.*, 2000a), a reinforced concrete bridge (Soh *et al.* 2000), and civil pipelines (Park *et*

al. 2001). A complete review summarizing both hardware and software issues of the impedance methods can be found in the reference (Park *et al.*, 2003b)

3. Parameters of the Technique

Frequency Range

The sensitivity of NDE techniques in detecting damage is closely related to the frequency band selected. To sense incipient-type damage which does not result in any measurable change in the structure's global stiffness properties, it is necessary for the wavelength of excitation to be smaller than the characteristic length of the damage to be detected (Stokes and Clouds 1993). Hence, the frequency range typically used in the impedance methods is in the range of 30 kHz to 250 kHz. The range for a given structure is determined by a trial and error method. There is little analytical work done about the vibration modes of complex structures at these ultrasonic frequencies. It has been found that a frequency range with a high mode density exhibits a higher sensitivity since it generally covers more structural dynamic information (Sun *et al* 1995). In the impedance-based method, multiple numbers (usually two or three) of a frequency range containing 20-30 numbers of peaks are usually chosen, since a number of peaks implies that there is a greater dynamic interaction over that frequency range. A higher frequency range (higher than 150 kHz) is found to be favorable in localizing the sensing, while a lower frequency range (lower than 70 kHz) covers more sensing areas. This is due to the fact that damping became more dominant at high frequency. It must be noted that there are two different kinds of peaks on measured electrical impedance. One reflects the structural resonant frequencies and the other is the PZT's resonant frequencies. For lightweight structures, it is advisable to avoid PZT's resonances when selecting frequency bands because they are much greater in magnitudes compared to structural resonances.

Sensing Region

Under the high frequency ranges used in this impedance-based method, the sensing region of the PZT is localized to a region close to the sensor/actuator. Extensive theoretical modeling efforts based on the wave propagation approach have been performed to identify the sensing region of the impedance-based method (Esteban 1996). Esteban's work also included a parametric study on the sensing region of a PZT sensor/actuator by considering the various factors, such as mass loading effect, discontinuities in cross-section, multi-member junctions, bolted structures, and energy absorbent interlayers. At such high frequency ranges, however, exact measurements and quantification of energy losses became very difficult and very little additional information was obtained. Based on the knowledge acquired through various case studies, it has been estimated that (depending on the material and density of the structure) the sensing area of a single PZT can vary anywhere from 0.4 m (sensing radius) on composite reinforced concrete structures, to 2 m on simple metal beams. Castanien and Liang (1996), and Kabeya (1998) used transfer impedance or transfer admittance to interrogate the structure in order to extend the sensing region of the impedance-based health monitoring technique.

Damage Assessment

While the impedance response plots provide a qualitative approach for damage identification, the quantitative assessment of damage is traditionally made by the use of a scalar damage metric. In the earlier work (Sun *et al.* 1995), a simple statistical algorithm, which is based on frequency-by-frequency comparisons, referred to as 'Root Mean Square Deviation' (RMSD),

$$M = \sum_{i=1}^n \sqrt{\frac{[\text{Re}(Z_{i,1}) - \text{Re}(Z_{i,2})]^2}{[\text{Re}(Z_{i,1})]^2}} \quad (2)$$

where M represents the damage metric, $Z_{i,1}$ is the impedance of the PZT measured at healthy conditions, and $Z_{i,2}$ is the impedance for the comparison with the baseline measurement at frequency interval i . In a RMSD damage metric chart, the greater numerical value of the metric, the larger the difference between the baseline reading and the subsequent reading indicates the presence of damage in a structure. Raju (1998) adopt

another scalar damage metric, referred to as the ‘Correlation’ metric, which can be used to interpret and quantify the information from different data sets. The correlation coefficient between two data sets determines the degree of linear relationship between two impedance signatures, and provides an aesthetic metric chart. In most cases, the results with the correlating metric are consistent with those of RMSD, in which the metric values increase when there is an increase in the severity of damage.

The damage metric simplifies the interpretation of impedance variations and provides a summary of the information obtained from the impedance response curves. Using this damage metric in conjunction with a damage threshold value, this technique can warn inspectors in a green/red light form, whether or not the threshold value has been reached.

Temperature changes, among all other ambient conditions, significantly affect the electric impedance signatures measured by a PZT. Some of PZT material parameters, such as the dielectric constant, are strongly dependent on temperature. Generally speaking, the increase in temperature causes the decrease in the magnitude, and leftward shifting of the real part of the electric impedances. The RMSD and correlation based damage metrics do not account for these variations. Park et al. (1999) use a modified RMSD metric, which compensates for horizontal and vertical shifts of the impedance in order to minimize the impedance signature drifts caused by the temperature or normal variations.

Lopes et al. (2000) incorporate neural network features with the impedance method for somewhat quantitative damage analysis. The authors proposed a two-step damage identification scheme. In the first step, the impedance-based method detects and locates structural damage and provides damage indication in a green/red light form with the use of the modified RMSD. When damage is identified, the neural networks, which are trained for each specific damage, are used to estimate the severity of damage. Zagrai and Giurgiutiu (2001) investigate several statistics-based damage metrics, including RMSD, mean absolute percentage deviation (MAPD), covariance change, and correlation coefficient deviation. It has been found that the third power of the correlation coefficient deviation, $(1-R^2)^3$, is the most successful damage indicator, which tends to linearly decrease as the crack in a thin plate moves away from the sensor. Tseng et al. (2002) also investigate the performance of RMSD, MAPD, covariance and correlation coefficients as indicators of damage. The RMSD and the MAPD were found to be suitable for characterizing the growth and the location of damage, whereas the covariance and the correlation coefficient are efficient in quantifying the increase in damage size at a fixed location.

The main limitation of the use of the aforementioned damage metrics in impedance methods is how to set appropriate decision limits or thresholds values. The decision is typically made based on arbitrary values, i.e., “small variations” for undamaged cases and “large variations” for damaged cases. In order to diagnose damage with levels of statistical confidence, the impedance-based monitoring is cast in the context of an outlier detection framework (Park et al. 2003, Fasel et al. 2003). An auto-regressive model with exogenous inputs (AR-ARX) in the frequency domain (Adams 2001) is incorporated into the impedance methods for nonlinear damage discrimination (Fasel et al. 2003). Because nonlinear feature identification requires separate input and output measurement, which is not possible with the traditional impedance analyzers, a modified frequency AR-ARX model is proposed (Park et al. 2003a). The damage sensitive feature is computed by differentiating the measured impedance and the output of the ARX model. Furthermore, because of the non-Gaussian nature of the feature distribution tails, extreme value statistics (EVS) is employed to develop a robust damage classifier (Sohn et al. 2003).

4. Comparisons with Other Damage Identification Approaches

Traditional NDE techniques include ultrasonic technology, acoustic emission, magnetic field analysis, penetrant testing, eddy current techniques, X-ray analysis, impact-echo testing, global structural response analysis, and visual inspections. Each of these various techniques has their positive and negative virtues. For instance, the ultrasonic method is useful in providing details of damage in a structure, however, this method requires the knowledge of damage location a priori and render the structure unavailable throughout the length of the test. Many traditional NDE methods are required out of service periods, or can be applied only a certain intervals, while the impedance-based method provides continuous, on-line monitoring with the potential for autonomous use.

Comparison to Global Structural Vibration-Based Methods

Like the global structural methods, the impedance-based approach involves the comparison of vibratory patterns (“signatures”) taken at various times during the life of the structure. The major difference, however, deals with the frequency range used to detect the changes in structural integrity. Relying on the lower-order global modes, the low-frequency global techniques are not sensitive to damage that has occurred at a very early stage. It has been shown (Bank et al. 1996) that high frequency responses are not very sensitive to changes in the structural integrity. By employing a high frequency range, the impedance-based method provides an alternative procedure that can identify local, minor changes in structural integrity.

Impedance Signature vs. Ultrasonic Testing

In ultrasonic testing of structural components, a piezo-transducer is used to produce an acoustic wave in the component. Based on the time delay of the wave transmission, the change in length (strain), length and/or density of the component is determined. Usually the mechanical nature of the component must be fairly well known before testing so that the frequency of the ultrasonic signal can be chosen to correlate with the mechanical response of the component. Typically, a single frequency wave or only a few different frequencies are used in ultrasonic methods. A broad-band signal is not obtained as in the impedance signature method. The ultrasonic method is useful in some structures for obtaining a picture of various embedded components or material anomalies. This method however does not lend itself to autonomous use as does the impedance method and experienced technicians are required to review the ultrasonic data to discern detail.

Impedance Signature vs. Acoustic Emission

The Acoustic Emission (AE) method uses the elastic waves generated by crack initiation, moving dislocations, and disbands for detection and analysis of structures. The AE method is suitable for long-term, in-service monitoring like the impedance method. Both methods are ideal for monitoring critical sections where high structural integrity should be maintained. However, the AE method requires stress or chemical activity to generate the acoustic emission, while the impedance method can easily solve the problems associating with ‘how to excite structures’ by using the concept of self-sensing actuation (Dosch, *et al.* 1992). The advantage of the self-sensing actuator is more obvious in the sense that, in the AE method, the existence of multiple numbers of travel paths from the source to the sensor can make signal identification difficult (Bray and McBride 1992). In addition, the AE method needs to filter out the electrical interference and ambient noise from the emission signals, whereas the limited sensing area of the impedance method helps in isolating changes in the impedance signature due to other far-field changes such as mass loading and normal operational vibrations.

Impedance Signature vs. Impact-Echo testing

For the Impact-Echo (IE) testing, a stress pulse is introduced into the structure from an impact source and resulting stress waves are measured and analyzed by a transducer. The pulse propagates into the structure and is reflected by cracks or disbands of the structures. The IE testing has been used to assess the conditions of various civil structures, including concrete, wood, and masonry materials. However, the IE testing requires an external source to excite a pulse and does not lend itself for autonomous use like the impedance method. The IE testing technique has been shown to be fairly effective for detecting and locating large scale voids and delaminations, but is not sensitive to the presence of small cracks and discontinuities due to the relatively low frequencies involved.

The principal advantages of the impedance approach compared to other techniques are as follows;

- The technique is not based on any model, and thus can be easily applied to complex structures;
- The technique uses small non-intrusive actuators to monitor inaccessible locations;
- The sensor (PZT) exhibits excellent features under normal working conditions, has a large range of linearity, fast response, light weight, high conversion efficiency, and long term stability
- The technique, because of high frequency, is very sensitive to local minor changes

- The measured data can be easily interpreted
- The technique can be implemented for on-line health monitoring
- The continuous monitoring provides a better assessment of the current status of the structure, which can eliminate scheduled base inspections.

The impedance-based structural health monitoring could provide a comprise interface between the global structural methods and the traditional high frequency NDE techniques. With a limited number of sensors and actuators, critical areas of a structure can be monitored, which is one of the advantages of the global structural methods. Damage in an incipient stage can be accurately identified, which only the local inspection techniques, such as ultrasonics, can possibly detect.

5. Proof-of-Concept Applications

The impedance-based health monitoring technique has been successfully applied to several structural components. Damage detection on two structures, including a pipeline structure and a quarter-scale bridge section, is presented to illustrate the potential of the impedance-based method for locating local damage in civil applications.

Health Assessment of Pipeline Structures

Pipelines convey natural gas, oil, and water, and some pipelines contain communication and power cables, all of which are very important to maintain functional residential and industrial facilities. Pipelines are also required for economic and community recovery after natural disasters. However, pipelines are severely damaged by shaking, liquefaction, and landslides during earthquakes (O'Rourke, and Palmer, 1996; Koseki *et al.*, 1998) and the immediate assessment of pipeline facilities is critical to prevent fires, explosions, and pollution from broken gas or sewage lines. Although extensive research efforts have been focused on assessing the conditions of pipelines after earthquakes (Hwang *et al.*, 1998; Kitaura *et al.*, 1998), the condition monitoring of these structures is still based on limited information. Therefore, the possibility of implementing the impedance-based health monitoring technique for pipeline structural damage assessment has been investigated and its ability to immediately detect and locate damage has been demonstrated.

Experimental Setup

Bolted joints are frequently used to connect segmented pipelines in building piping systems. This interface can be the most critical source of failure of the pipelines, since significant seismic loadings can stress the joint beyond its yield or buckling capacity, while the main body of the pipe remains elastic (Eidinger, 1999). Therefore, the conditions of these joints need to be monitored to ensure the integrity of entire pipelines.

A model of a pipeline with bolted joints is shown in figure 2. This model consists of segmented pipes (d=40 mm), flanges, elbows, and joints connected by more than 100 bolts. The size of this structure is 2 m wide and 1.3 m tall. One PZT sensor/actuator (15 x 15 x 0.2 mm) is bonded on each joint to monitor the conditions of this structure. The HP4194 electrical impedance analyzer was used for the measurement of PZT's electrical impedance in the frequency range of 80-100 kHz. The total impedance of each junction (2 or 3 joints), labeled A to I in figure 2, was utilized to track the damage. The total impedance refers to 'a single impedance signal acquiring from distributed PZTs'; the leads from the several distributed PZTs are physically connected together and this single lead is then connected to the terminal on the impedance analyzer. This procedure may reduce the sensitivity to structural damage due to the multiplexing nature of measurements; however it drastically reduces the interrogation time as compared to that of analyzing each PZT separately. After measuring the baseline impedance signature, damage was introduced by slightly loosening the bolts over several joints on this structure.

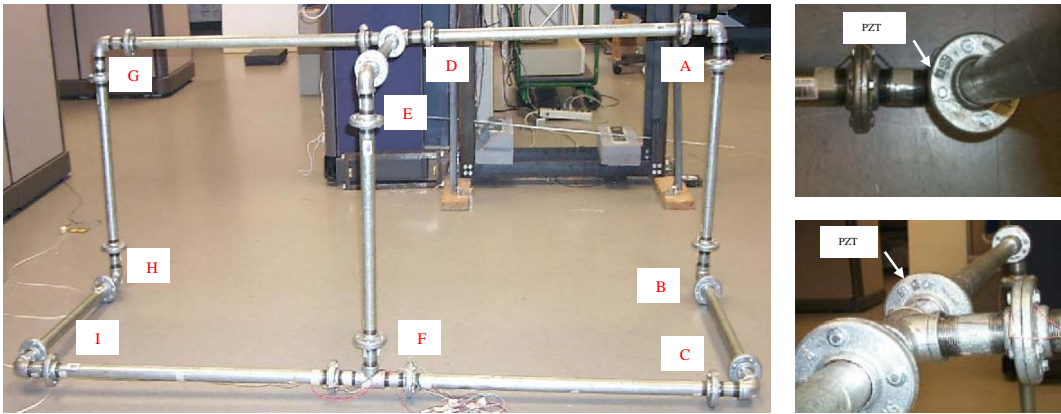


Figure 2. A pipeline used in the experiment

Observations and Analysis

The impedance measurements (real part) of PZTs at Junction D with 4 levels of local damage are shown in figure 3. Only the real portion of the electrical impedance is analyzed to predict damage because it is more sensitive to change than the imaginary part or magnitude. The damage was simulated by completely loosening bolts at Junction D, as shown in the labels. It can be seen from the figure that, with increasing damage, the impedance signature shows a relatively large change in shape and is clearly indicative of imminent damage.

For the first level of damage (loosening two bolts), only a small variation along the original signal (undamaged curve) was observed. This is because the first level of damage can be categorized as the incipient stage. When four bolts have been loosened, the impedance showed more pronounced variations as compared to previous readings, and finally, when six and eight bolts have been loosened, it showed a distinct change in the signature pattern, i.e. new peaks and valleys appear in the entire frequency range. This change occurs because the damage modifies the apparent stiffness and damping of the joint. This variation shows the extreme sensitivity of the impedance-based method to the presence of damage in the sensing area.

A damage metric chart is illustrated in figure 4. The damage metric chart based on RMSD is constructed after each measurement has been taken. As can be seen in the figure, with an increase in extent of damage, there is a corresponding increase in the damage metric values. Although the impedance method cannot precisely predict the exact nature and size of the damage, the method provides somewhat quantitative information on the conditions of a structure by showing an increasing damage metric with increased severity of damage.

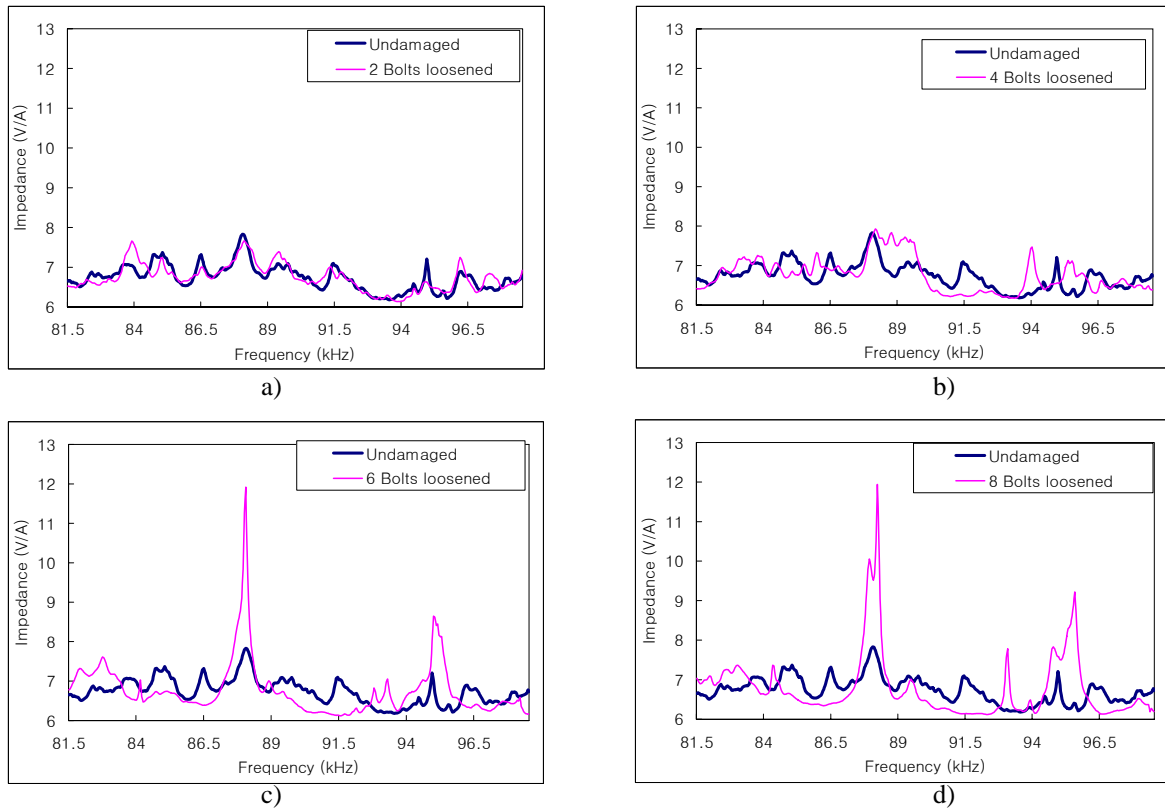


Figure 3. The electrical impedance measurements of PZTs at Junction D. The variation in the impedance is increased as the level of damage is increased.

a) 2 bolts loosened; b) 4 bolts loosened ; c) 6 bolts loosened; d) 8 bolts loosened

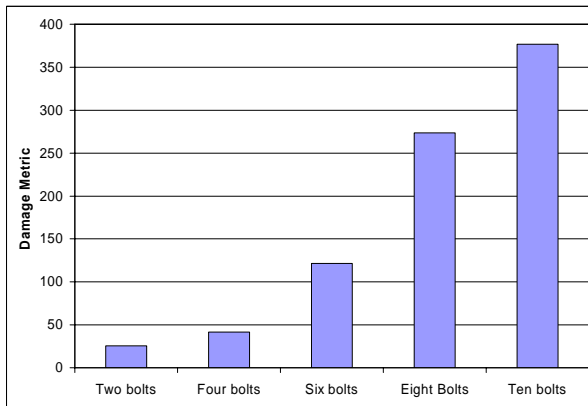


Figure 4. Damage Metric Chart. Comparison of metric values with induced damage.

the remaining curves followed the same pattern as that of the second reading, since those are well out of sensing range of PZTs at Junction A. Other impedance measurements of junction G are shown in figure 6. The location of Damage 1 was out of the sensing range of PZTs, hence almost no change in impedance curve was observed. However, when Damage 2 was introduced, the impedance measurement was significantly

Another experiment was performed on the global scale. Three conditions were imposed on this structure in sequence, as shown below;

- Damage 1 : loosening 3 bolts at Junctions A and B, respectively
- Damage 2 : loosening 2 bolts at Junctions E and G, respectively
- Damage 3 : loosening 4 bolts at Junctions F, G, and H, respectively

The impedance measurements (real part) of PZTs located at junction A are shown in figure 5. For junction A, when Damage 1 was introduced, the measurement was significantly different from the baseline measurement, which is indicative of damage. However, when the other two damage conditions were imposed, the

different from the previous readings and was affected by the presence of damage. When damage 3 was introduced, the measurements indicated another complete change in the signature pattern.

The damage metric chart demonstrates the results more clearly, as can be seen in figure 7. It can be seen that at Damage 1, there is a large increase in the damage metric value for PZTs at A and B. The other PZTs show a very small change in the damage metric, because they are distant from the damage. Similar results are obtained when damage 2 and 3 were induced. Each PZT shows an increase in the damage metric value, if damage is induced close to the sensors. By looking for variations in the impedance measurement and in the damage metric value, structural damage can be detected and the integrity of the structure can be monitored throughout its service life or immediately after the natural disaster, as shown in this example.

The use of the damage metric charts in providing a quick, accurate summary of the health of the structure became obvious during the testing. The time necessary to take the impedance measurements and to construct the damage metric is less than 5 minutes, which is quick enough for an on-line implementation of this technique

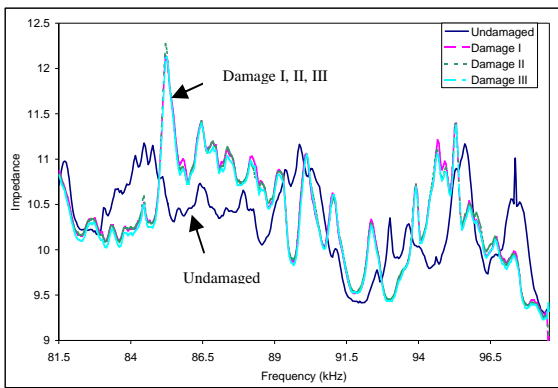


Figure 5. The electrical impedance measurements of PZTs at Junction A.

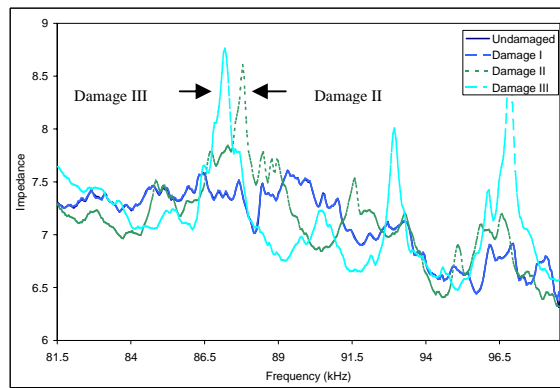


Figure 6. The electrical impedance measurements of PZTs at Junction G

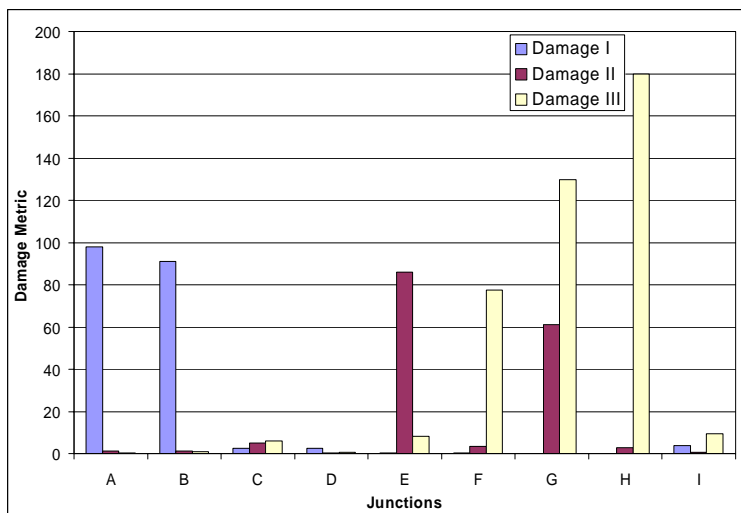


Figure 7. Damage metric chart over the different locations.

Analysis of a quarter scale Bridge Section

In almost all practical field applications, the structure being monitored is constantly undergoing changes due to external boundary conditions, such as loading, low-frequency vibrations of the structure, and changes in the ambient temperature. These effects make it difficult to detect and locate structural damage because such ambient changes also modify the response of a structure. However, a compensation technique was developed to minimize the effects of temperature and normal variations, making the impedance-based structural health monitoring technique stable under all types of environmental conditions (Park et al. 1999).

Experimental Setup

An investigation on a massive quarter scale model of a steel truss bridge joint is presented. A model of a steel bridge joint is shown in figure 8. The bridge model consists of steel angles, channels, plates, and joints connected by over 200 bolts. The size of this structure is 1.8 m tall and has a mass of over 250 kg. Four PZT sensor/actuators are bonded on the critical sections to actively monitor the conditions of this typical high-strength civil structure. The purpose of the experiment presented here is to examine the effect of external boundary conditions on the impedance signature and obtain a better understanding of practical issues that are a result of monitoring the health of structures in an uncontrolled field environment.

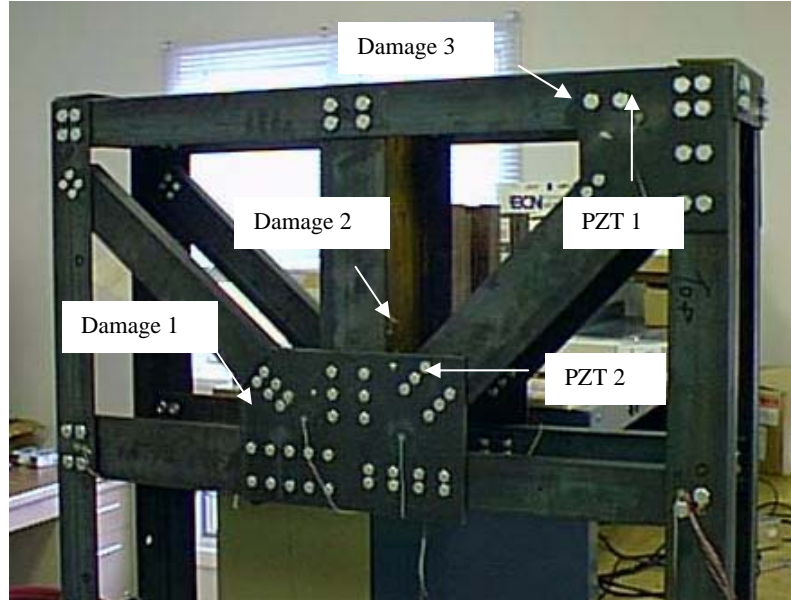


Figure 8. A ¼ scale steel bridge section

The following three ambient boundary conditions were imposed on the structure in an attempt to simulate real-life variation;

- repeatability - variations of the signal over a given time period is monitored.
- vibrations - structure is manually hammered while the measurements are being taken
- loading - a load of 15 kg. mass is added to the structure. The weight is placed on the vicinity of PZT sensors, so that it induces the stresses on bolted connections within the sensing range of PZT sensor/actuators.

These sets of readings from four PZTs are repeated over a period of three weeks. After identifying the range of the impedance signature variations due to the boundary condition changes, damage was induced by loosening the bolts over several locations on the structure. The HP 4194 impedance analyzer is used to interrogate each PZT. Throughout the analysis, the compensation technique (Park et al. 1999) to minimize the effects of any boundary condition changes was applied.

Test Observations and Analysis

The impedance measurements of two PZTs are presented in figure 9, with two different frequency ranges. Each plot shows the variations of the impedance signature with three ambient condition changes imposed on the structure. Only fourteen measurements, which show the largest variations, are shown without the labels. As can be seen, the variations remained relatively small and would be considered as minor changes. The vibration produced the largest variations, however it was expected as the structures were being hammered while measurements were being taken. As compared to the modal analysis experiments, which a small orientation change results in marked changes in resonant frequencies, mode shapes, and modal damping, the impedance signature patterns shows relatively small variations. The measurements were found to be repeatable and no noticeable degradation with time was observed.

The damage metric chart is presented in figure 10. The first fourteen variations are those from the changes in boundary conditions. Those pronounced ones are the damage metric due to the vibration. As depicted, the values are very small and hence, negligible. The location of damage 1, 2 and 3 are shown in figure 8. Damage is simulated by loosening a bolt (1/8 turn) in that location. The exact sensing range of each PZT sensor was difficult to predict, since a number of bolts were presented in this structure. Consistent with the results of others (Esteban, 1996), the bolted joints are the major contributors of energy dissipation in the structures.

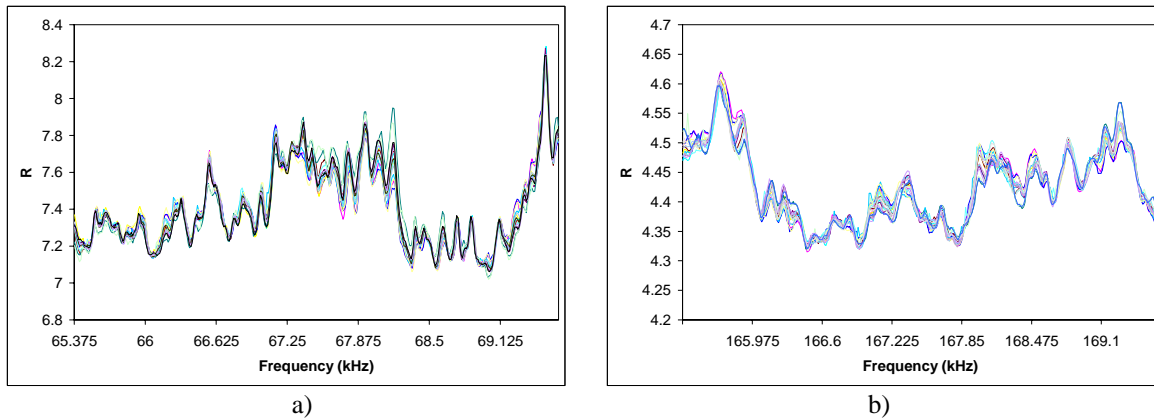


Figure 9. Impedance (real) vs. Frequency plots for a) PZT 1, b) PZT 2

Damage 1 is believed to be well out of sensing range of both PZT 1 and PZT 2. Hence, only a small increase in damage metric is shown for both PZTs. However, PZT 2 shows an increase in metric value (due to damage 1) over that of any of the increase caused by the normal variations. This small increase cannot be used to signal the presence of damage, however does provide evidence of the sensitivity of this method in relatively large ranges. Damage 2 is located closed to the PZT 2 and Damage 3 is within sensing region of the PZT 1, hence the increase in damage metric values are the highest for both PZTs. Note that the effect of loosening a single bolt on the entire structure is minor, thus damage can be detected in its early stage. The impedance measurements of PZT 2 for the case of both damage 2 and damage 3 are shown in figure 11, for visual comparison. It can be seen that, when damage 2 was introduced, the impedance measurement is significantly different from the previous readings. However, in the case of damage 3, only a small variation in the impedance measurement was observed, since damage is distant from this PZT sensor/actuator.

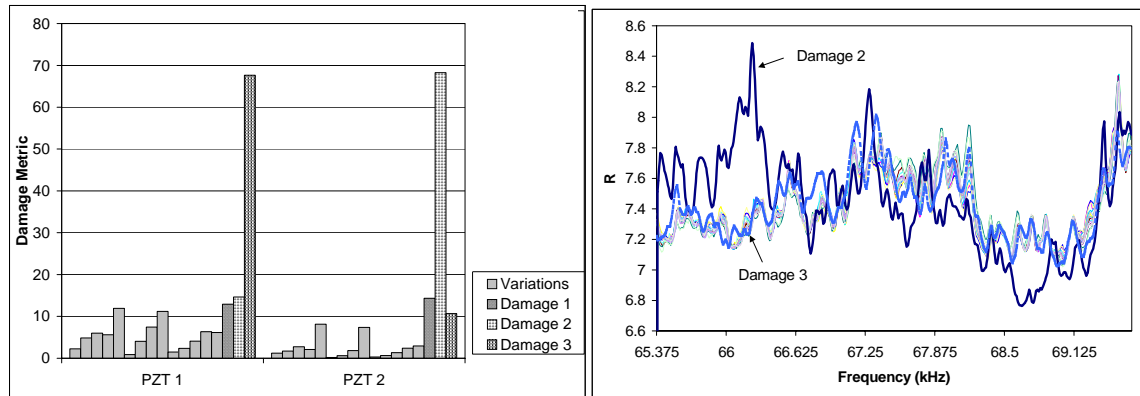


Figure 10. Damage metric chart for PZTs. **Figure 11.** Impedance vs. Frequency plots for PZT 2

An important problem associating with monitoring large-scale civil structures is that they possess very low natural frequencies and are difficult to excite, leading to difficulties in picking up very small frequency changes for the damage detection technique using low frequency vibration data. (Friswell and Penny, 1997). However, as demonstrated in this example, the impedance-based structural health monitoring technique can be easily applied to relatively large, massive civil structures by employing a very high frequency local excitation.

Bolted and riveted connections are commonly found in civil structures. These connections invariably promote damage growth due to the nature of the geometry and the local stress concentrations. It has been estimated that approximately 70% of all mechanical failure occurs due to fastener failure (Simmons, 1986). However, these connections are often difficult to inspect due to the geometry and/or the location in the structure. Various types of bolt failures that occur include tensile overload, shear overload, hydrogen embrittlement, and fatigue failure. Although only the changes in joint stiffness are used to simulate real-time damage, the results of this experiment supports the effectiveness of the impedance-based technique in monitoring the condition of various civil applications, which are subjected to either adverse environments that can degrade the connections, or strenuous loading cycles causing bolt cracking and fatigue damage. It should be noted that the damage considered in this article contains bolted joint failures only; this is mainly because they are easy to simulate, control, and enable repeatable tests. There is ample evidence in the references (Park et al. 2003b) that the impedance method can successfully detect and locate any possible types of damage in structures.

6. Summary

The experimental investigations of impedance-based health monitoring techniques on various components typical of civil infrastructures were presented. The basic concept of this health monitoring technique is to monitor the variations in the structural mechanical impedance caused by the presence of damage at high frequency range (typically higher than 30 kHz), utilizing the electromechanical coupling properties of piezoelectric materials.

Impedance-based structural health monitoring is slowly coming into full view of the structural NDE community. With continual advances in sensor/actuator technology, signal processing techniques, and damage prognosis algorithms, the methods will continue to attract the attentions of researchers and field engineers for monitoring of various structural applications.

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