Articles

Overview of Piezoelectric Impedance-Based Health Monitoring and Path Forward

Gyuhae Park, Hoon Sohn, Charles R. Farrar and Daniel J. Inman

ABSTRACT—In this paper we summarize the hardware and software issues of impedance-based structural health monitoring based on piezoelectric materials. The basic concept of the method is to use high-frequency structural excitations to monitor the local area of a structure for changes in structural impedance that would indicate imminent damage. A brief overview of research work on experimental and theoretical studies on various structures is considered and several research papers on these topics are cited. This paper concludes with a discussion of future research areas and path forward.

KEYWORDS: structural health monitoring, diagnostics, piezoelectric materials, damage prognosis

1. Introduction

Piezoelectric materials 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 direct piezoelectric effect has often been used in sensors such as piezoelectric accelerometers. With the converse effect, piezoelectric materials apply localized strains and directly influence the dynamic response of the structural elements when either embedded or surface bonded into a structure. Piezoelectric materials have been widely used in structural dynamics applications because they are lightweight, robust, inexpensive, and come in a variety of forms ranging from thin rectangular patches to complex shapes being used in microelectromechanical systems (MEMS) fabrications. The applications of piezoelectric materials in structural dynamics are too numerous to mention and are detailed in the literature (Niezrecki et al., 2001; Chopra, 2002).

The purpose of this paper is to explore the importance and effectiveness of impedance-based structural health monitoring from both hardware and software standpoints. Impedance-based structural health monitoring techniques have been developed as a promising tool for real-time structural damage assessment, and are considered as a new non-destructive evaluation (NDE) method. A key aspect of impedance-based structural health monitoring is the use of piezoceramic (PZT) materials as collocated sensors and actuators. The basis of this active sensing technology is the energy transfer between the actuator and its host mechanical system. It has been shown that the electrical impedance of the PZT material can be directly related to the mechanical impedance of a host structural component where the PZT patch is attached. Utilizing the same material for both actuation and sensing not only reduces the number of sensors and actuators, but also reduces the electrical wiring and associated hardware. Furthermore, the size and weight of the PZT patch are negligible compared to those of the host structures so that its attachment to the structure introduces no impact on dynamic characteristics of the structure. A typical deployment of a PZT on a structure being monitored is shown in Figure 1.

The first part of this paper (Sections 2 and 3) deals with the theoretical background and design considerations of the impedance-based structural health monitoring. The signal processing of the impedance method is outlined in Section 4. In Section 5, experimental studies using the impedance approaches are summarized and related previous works are listed. Section 6 presents a brief comparison of the impedance method with other NDE approaches and, finally, several future issues are outlined in Section 7.

2. Theoretical Background

The theoretical development of the application of impedance measurements to structural health monitoring was first proposed by Liang et al. (1994) and subsequently developed by Chaudhry et al. (1995, 1996), Sun et al. (1995a), Park et al. (1999a, 1999b, 2000a, 2000b, 2001), Giurgiutiu and Zagrai (2000), Giurgiutiu et al. (2002, 2003), Zagrai and Giurgiutiu (2001), Soh et al. (2000), Bhalla et al. (2002a, 2002b), and Naidu et al. (2002). The method utilizes high-frequency structural excitations, which are typically higher than 30 kHz through surface-bonded PZT patches to monitor changes in structural mechanical impedance. The PZT patches require very low-level voltage, typically less than 1 V, to produce high-frequency excitation in the host structure.

An electromechanical model which quantitatively describes the process is presented in Figure 2. Assuming that an axial PZT actuator is attached to one end of a single degree-of-freedom (DOF) mass–spring system, whereas the other end is fixed, Liang et al. (1994) show that the electrical admittance $Y(\omega)$, which is an inverse of the electrical impedance, of the PZT actuator is a combined function of the mechani-

Gyuhae Park, Hoon Sohn and Charles R. Farrar, Engineering Sciences and Applications Division, Weapon Response Group, Los Alamos National Laboratory, Los Alamos, NM 87545, USA. Daniel J. Inman, Center for Intelligent Material Systems and Structures, Virginia Polytechnic Institute of State University, 310 Durham Hall, Blacksburg, VA 24061, USA.

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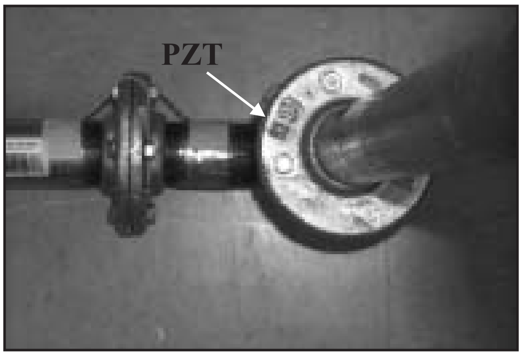

Figure 1. A piezoelectric patch attached to a bolted connection of a pipeline system

cal impedance of the PZT actuator $Z_a(\omega)$ and that of the host structure $Z(\omega)$

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

where V is the input voltage to the PZT actuator, and I is the output current from the PZT. a, d_{3x}, Y_{xx}^{E}, and $\bar{\varepsilon}_{33}^{T}$ are the geometry constant, the piezoelectric coupling constant, Young's modulus, and the complex dielectric constant of the PZT at zero stress, respectively.

Equation (1) sets the groundwork for using the PZT actuator for impedance-based structural health monitoring applications. Assuming that the mechanical property of the PZT does not change over the monitoring period of the host structure, equation (1) clearly shows that the electrical impedance of the PZT is directly related to the mechanical impedance of the host structure, allowing the monitoring of the host structure's mechanical properties using the measured electrical impedance. Consequently, any changes in the electrical impedance signature can be considered an indication of changes in the structural integrity. It should be noted that the electrical admittance $Y(\omega)$ is primarily capacitive. In other words, the imaginary part of the admittance plays a dominant role. This imaginary part is more sensitive to the temperature variation than the real part because the dielectric constant ε_{33}^{t} is temperature sensitive and it only affects the imaginary part. Therefore, the real part of the admittance (or impedance) is mainly used for monitoring in applications. The variation in the PZT electrical impedance over a range of frequencies is analogous to that of the frequency response functions (FRFs) of a structure, which contain vital information regarding the health of the structure.

Wang et al. (1996a) further extended the work carried out by Liang et al. (1994) for the PZT stack actuators connected with structures at both sides, and checked their sensing and actuation ability in detail. The dependence of the electric admittance on the structural impedance is once again observed, which confirms a possibility of monitoring structural behavior by measuring the electric admittance of the PZT. In continuous work, Wang et al. (1996b, 1997) presented a mathematical model, which describes deformation compatibility between a PZT patch and a beam or a plate. The relationship between the static capacitance of the PZT and deformation of the structure has been established and the structural deformation has been sensed from the variation of the purely electric capacitance of the PZT.

3. Parameters on the Impedance Method

3.1. Frequency Ranges

The structural health monitoring techniques based on vibration signature analyses have been investigated extensively. An extensive survey of this field can be found in Doebling et al. (1998). These methods usually involve recording vibration signatures in a "healthy" condition, and evaluating the state of the structure by comparing the vibration signatures taken at various times during the life span of the structure. Measured data are processed using a variety of signal processing techniques to look for changes in characteristics that indicate the presence of damage.

As described in the previous section, the impedance method follows the same philosophy that involves the continuous comparison of vibratory patterns measured by piezoelectric impedance sensors to evaluate the health of a structure. The foremost difference is the frequency range that is used to detect the changes in structural integrity. The sensitivity of the vibration-based NDE techniques in detecting damage is closely related to the frequency band selected. To sense incipient-type damage, 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). In order to ensure high sensitivity to incipient damage, the electrical impedance is measured at high frequencies in the range of 30–400 kHz. Under this high-frequency range, the wavelength of the excitation is small, and sensitive enough to detect minor changes in the structural integrity.

The frequency range for a given structure is commonly determined by trial-and-error and there has been little analytical work carried out regarding the vibration modes of complex structures at the ultrasonic frequency region. Sun et al. (1995a) suggested that a frequency band with high mode density is favorable as it generally contains more structural information about the condition of a structure. In the impedance-based method, multiple frequency ranges containing 20–30 peaks are usually chosen, because a higher density of modes implies that there is a greater dynamic interaction over that frequency range. A frequency range higher than 200 kHz is found to be favorable in localizing the sensing, while a frequency range lower than 70 kHz covers a larger sensing area.

3.2. The Real Part of Electric Impedance

As stated in the previous section, the real part of electric impedance is more reactive to damage or changes in the structure's integrity than the imaginary part (Sun et al. 1995a; Bhalla et al. 2002a). The change in the structure's impedance is attributed to the change in integrity of the structure due to damage. This characteristic is exhibited only in the real portion of the impedance signature, as indicated in equation (1).

While most reported studies have used the measured real part of impedance or admittance directly, Bhalla et al. (2002a) introduce a new concept of "active" signature, whereby it is

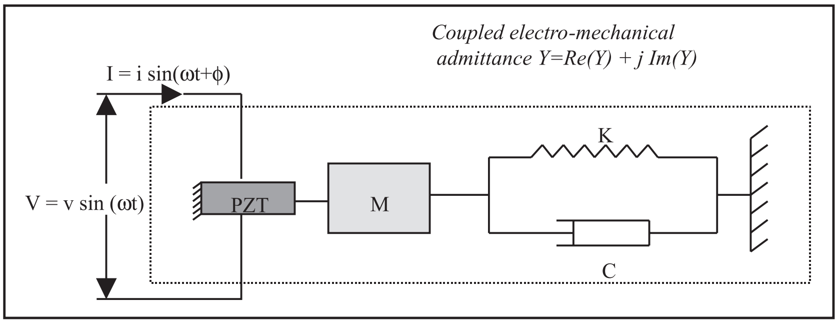

Figure 2. One-dimensional model used to represent a PZT-driven dynamic structural system

possible to utilize the direct interactive component of the signature after filtering the "inert" component. Assuming that the PZT's material properties are known, they rewrite equation (1) in the following format

$$Y = i\omega a\varepsilon_{33}^{T} - i\omega a\frac{Z_a}{(Z+Z_a)}d_{3x}^{2}\hat{Y}_{xx}^{E} = Y_p + Y_A \tag{2}$$

where the passive part of the admittance, Y_p, donates the PZT contribution and the active component, Y_A, represents the contribution from the PZT–structure interaction. Based on the fact that Y_p also has the real component and Y_A contains the imaginary part, the active component can be obtained by filtering out the passive component of the PZT with the relation of equation (3):

$$Y_A = Y - Y_p \tag{3}$$

The active component is found to be more suitable in the monitoring of a structure with superior tolerance to temperature fluctuations. In addition, the procedure makes it possible to utilize the imaginary part as well as the real part for health monitoring, which maximizes the information regarding the conditions of a structure.

3.3. Sensing Region of Impedance Sensors

Under the high-frequency ranges employed in the impedance-based method, the sensing region of the PZT is limited to an area close to the PZT sensor/actuator. The localized nature of the sensing region provides an advantage in that the impedance sensor is less sensitive to boundary condition changes or any operational vibrations, which usually affect lower-order global modes. Extensive numerical modeling based on the wave propagation theory has been performed to identify the sensing region of the impedance-based method (Esteban, 1996). Esteban's work also includes a parametric study on the sensing region of a PZT sensor/actuator by considering various factors and geometries, such as mass loading effect, discontinuities in cross-section, multi-member junctions, bolted structures, and energy absorbent interlayers. At such high-frequency ranges exact measurements and quantification of energy dissipation, however, become difficult and little additional information is obtained. In general, the sensing range of an impedance sensor is closely related to the material properties of a host structure, geometry, frequency ranges being used, and properties of PZT materials. Based on the knowledge acquired through various case studies, it has been estimated that the sensing area of a single PZT can vary anywhere from 0.4 m (sensing radius) on composite structures to 2 m on simple metal beams. The frequency ranges higher than 500 kHz have been found to be unfavorable, because the sensing region becomes extremely small and the PZT sensors show adverse sensitivity to their bonding conditions or PZT itself rather than the behavior of a structure monitored.

3.4. Hardware Components of the Impedance Method

The impedance method utilizes piezoelectric sensors/actuators to acquire dynamic responses of a structure. The PZT sensors/actuators are compact, unobtrusive, and lightweight so that they can be easily integrated into critical structural areas. With the nature of local-area excitation, the sensors/actuators consume relatively low electric power. The PZT sensor also exhibits excellent features for health monitoring, such as a large range of linearity, fast response, low-cost, high conversion efficiency, and long-term stability.

The impedance measurements are typically carried out using a HP4194A impedance analyzer. PZTs are interrogated after setting parameters in the analyzer. The data are then transferred to a computer via an I/O interface. The disadvantage of this configuration is that the equipment used is relatively bulky, expensive, and not very portable. Moreover, the impedance-based method uses a very small subset of the capabilities of this instrument. Peairs et al. (2002a) developed an operational amplifier-based turnkey device that can measure and record the electric impedance of a PZT, as shown in Figure 3. The approximated impedance of the PZT (Z_p) is given in equation (4):

$$\begin{aligned} V_o &= \frac{R_s}{Z_p + R_s}V_i \\ Z_p &= \frac{R_s(V_i - V_o)}{V_o} \end{aligned} \tag{4}$$

Depending on the PZT size, the amplification circuit might be necessary for low-frequency ranges, where the impedance of the PZT is high. The gain, G, provided by the amplification circuit is shown in equation (5):

$$G = -\frac{R_2}{R_1} \tag{5}$$

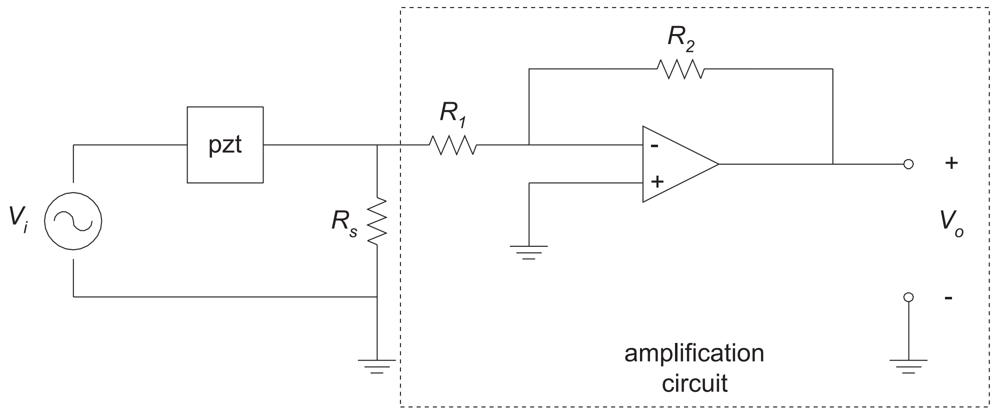

Figure 3. Impedance approximating circuit with an amplification circuit

Advantages of the new impedance-measuring device include its low cost, greater accessibility, and smaller size. The price of the parts required to make one test device was less than \$10, compared to \$40,000 of the HP 4194 system. The new method requires the use of a digital signal analyzer with a fast Fourier transform (FFT) function, which is a common piece of equipment in most research facilities. Another advantage includes the capabilities of varying the driving voltage much higher, while the impedance analyzer has an output limit at 1 V. The higher applied voltage will not generally change impedance signature, but it may improve the signal-to-noise ratio and help to identify weak modes (Sun et al., 1995a).

3.5. Parametric Studies on the Impedance Method

Raju (1998) provides extensive experimental studies on the parameters affecting the impedance-based methods, such as actuator excitation level, test wire length, multiplexing (using a single wire for accessing multiple sensors), and boundary condition changes. Raju concludes that the variations in such parameters do not significantly affect the impedance signatures. Bhalla et al. (2002b) investigate issues related to practical implementation of the impedance method. The long-term consistency of the impedance signature over two months has been investigated and excellent repeatability has been observed. Their study also includes protection of the PZT transducer against a humid environment using a silica gel layer, multiplexing of an array of PZT to optimize sensor interrogation time, and possible use of double-sided adhesive tapes to bond the PZT transducers.

Xu and Liu (2002) have investigated the effects of a bonding layer on the dynamic interaction between a PZT patch and a host structure. The study reveals that the effects of bonding conditions are remarkable, which significantly affect resonant frequency estimation of the system. The authors suggest that it is necessary to include the effects of bonding to obtain more accurate results, although it is usually difficult to measure the stiffness of the bonding layer. Ong et al. (2002a, 2002b) investigate the effects of the shear lag caused by the bonding layer on the impedance sensors. The shear lag is defined as a ratio between the effective transfer stain on the beam surface and the actuation strain of PZT transducer. The experimental and simulation results indicate that the impedance responses are generally sensitive to the shear lag effects, causing the vertical and horizontal shifts of impedance measurements. The authors suggest that high modulus adhesives should be used in order to obtain maximum repeatability and consistency of the impedance signature. Giurgiutiu et al. (2002) show that the sensor integrity and consistency can be assessed by the imaginary part of electric impedance. The well-bonded sensor shows a smooth curve, while the disbonded sensor shows a very strong resonance in the imaginary part of the impedance measurement. Thus, we can determine if the sensor is perfectly bonded to a structure or not by tracing the imaginary part, although quantitative assessment or estimation of the bonding stiffness is still not a trivial task.

4. Signal Processing and 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., 1995a), a simple statistical algorithm, which is based on frequency-by-frequency comparisons, is referred to as "root-mean-square deviation" (RMSD)

$$M = \sum_{i=1}^{n} \sqrt{\frac{[\mathrm{Re}(Z_{i,1}) - \mathrm{Re}(Z_{i,2})]^2}{[\mathrm{Re}(Z_{i,1})]^2}} \tag{6}$$

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 indicating the presence of damage in a structure. Raju et al. (1998) adopt another scalar damage metric, referred to as the "cross-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 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 severity of damage.

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 and strain constant, are strongly dependent on temperature (Piezo Systems Inc., 2002). Generally speaking, the increase in temperature causes the decrease in the magnitude of electric impedance, and leftward shifting of the real part of the electric impedances. The RMSD and cross-correlation based damage metrics do not account for these variations. Krishnamurthy et al. (1996) have developed a software-based correction technique, which eliminates the effects of temperature on the PZT while not eliminating the effects on the structures. This method, however, requires prior measurements of the temperature to obtain the temperature coefficient of the PZT, which is not trivial in some cases. Park et al. (1999a) 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 have 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 then 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 and Naidu (2002) also investigate the performance of RMSD, MAPD, covariance and correlation coefficients as indicators of damage. The RMSD and the MAPD are 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.

5. Applications of Impedance-Based Structural Health Monitoring

5.1. Experimental Modal Analysis using Electrical Impedance Measurements

An experimental modal testing using the electrical impedance of PZT patches as collocated actuators and sensors is presented by Sun et al. (1995b). This work provides a critical insight into the impedance-based structural health monitoring technique, where the electrical impedance of piezoelectric materials constitutes a unique signature of the dynamic behavior of the structures. The authors discuss that both the point FRF of a single location and the transfer FRF between two locations can be obtained by measured electrical impedance. Two algorithms of modal parameter extraction are proposed: one is the electric impedance half-power bandwidth method, and the other employs the inverse Nyquist plane curve fitting. Both algorithms successfully extract modal parameters, such as resonant frequencies, modal damping, and mode shapes. Giurgiutiu and Zagrai (2000, 2002) extended the work of Sun et al. (1995b) to one-dimensional structures considering both axial and flexural vibrations. The electric impedance spectrum has accurately represented the mechanical response of a structure, and the sensor's non-invasive characteristic has been proved. Peairs et al. (2002b) reconstructed the FRFs of a bolted joint with the measured electric impedance for diagnostics. The FRFs from both modal testing and impedance measurements were analyzed using the rational fraction polynomial method to estimate modal parameters. Changes in a specific natural frequency versus the torque level of the joint confirmed that the two analyses gave approximately the same results.

5.2. Structural Health Monitoring

Experimental implementation of the impedance-based structural health monitoring technique has been successfully conducted on several complex structures. The detection of cracks, loose connections, corrosion in metallic structures, and debonds and delaminations in composites structures are reported.

Sun et al. (1995a) pioneered the application of the impedance method to structural health monitoring by testing the truss structures. A simple statistic algorithm, which uses the RMSD damage index, as an indication of structure integrity, is proposed for damage assessment. The effects of the frequency range and the excitation level are also investigated.

Chaudhry et al. (1995) monitor the integrity of the tail section of a Piper Model 601P airplane. Two types of joint damage were induced in the structure: local and distant damage. The local damage refers to alterations in the main brackets, whereas the distant damage refers to alterations elsewhere in the structure. The impedance sensors showed extreme sensitivity to the extent of damage for local area (Figure 4), and demonstrated insensitivity to far-field changes.

Lalande et al. (1996) have investigated two most common types of wear in precision gears: abrasive wear and tooth bending fatigue. In both cases, the damage was successfully detected in a qualitative manner by impedance sensors.

Monitoring of a massive built-in bridge structure has been performed by Ayres et al. (1998). The bridge model consists of steel angles, channels, plates, and joints connected by over 200 bolts, as shown in Figure 5. The size of this structure is 1.8 m tall and has a weight of over 250 kg. The same structure has been investigated by Park et al. (2000a) under uncontrolled environmental conditions, which have varying mass loading, temperature, and operational vibrations. The ability of the impedance method to detect and distinguish incipient damage from these variations has been demonstrated.

A composite repair patch has become a popular remedy for repairing incipient crack damage in airplanes. Consequently, the growth monitoring of a crack, which is hidden by the composite repair patch, and the monitoring of the bonding between the host structure and the high strength composite patch have become a critical issue. Therefore, several researchers applied the impedance method to the crack and bonding monitoring of a structure repaired by

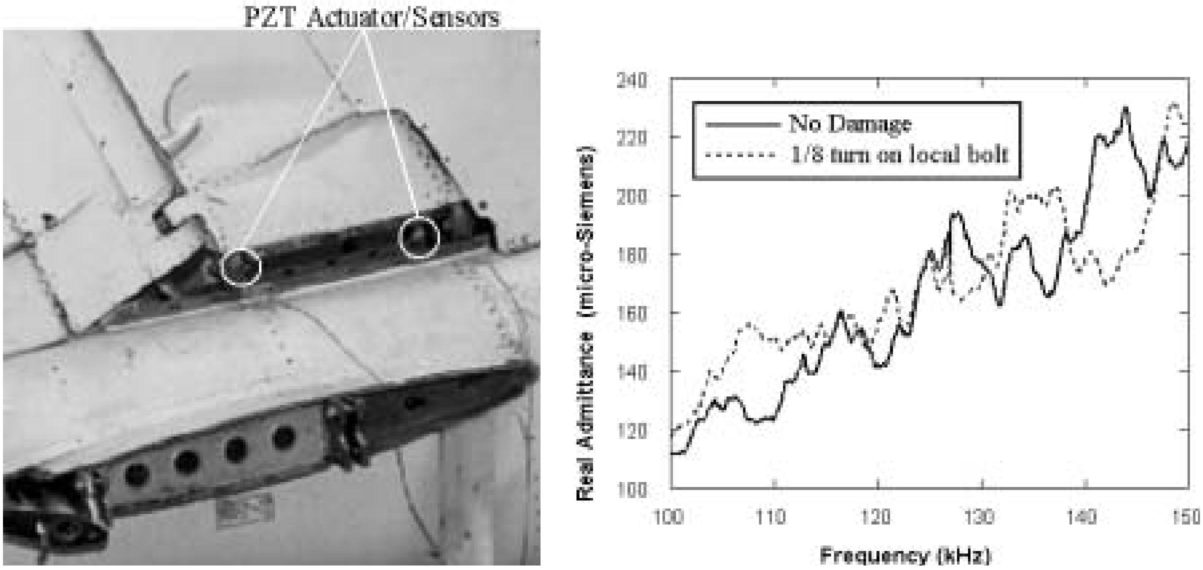

Figure 4. The integrity of the two main brackets which connect the rear fuselage to the vertical tail of a Piper Model 601P airplane were monitored (Chaudhry et al., 1995). The change in the real electrical admittance caused by loosening of the securing bolt was easily detected

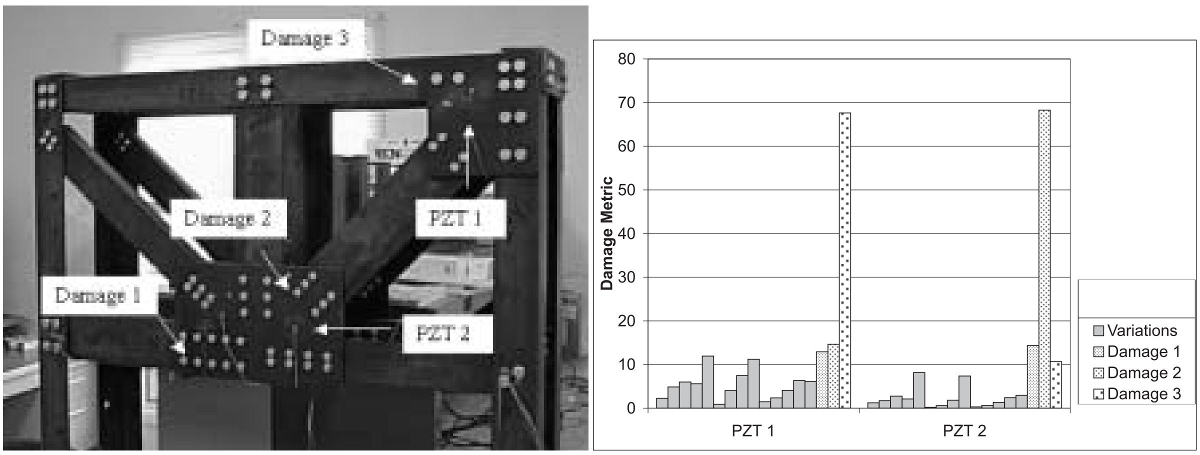

Figure 5. A quarter-scale steel bridge section (Park et al., 2000a). The damage metric shows the localized effect of the impedance method

composite patches (Chaudhry et al., 1996) and composite reinforced concrete walls (Raju et al., 1998). These structures, in turn, provide an excellent opportunity to demonstrate the capability of the impedance approach in detecting delamination and debondings typical in composite structures. Twice during the tests on four walls (Raju et al., 1998), a PZT sensor picked up the damage to the structure even before the cracks would be physically visible, demonstrating the extreme sensitivity of the method. Multiple cracks in different areas at different periods of time are picked up accurately. Furthermore, relatively large sensing regions of each PZT sensor were observed, compared to ultrasonic or strain-gage based damage detection methods.

Pohl et al. (2001) performed an experimental and theoretical investigation to show the effectiveness of the impedance method in monitoring carbon fiber reinforced polymer (CFRP) composites. Damage, which is introduced by the low-speed impact, is detected by changes in the impedance peaks. The finite element model (FEM) provides a useful tool to confirm the experimental results. Bois and Hochard (2002) present experimental and simulation results on the use of the impedance method to detect delamination of composite structures. They provide a possibility of defining the size and the position of delamination with the modeling based on the three-dimensional electromechanical constitutive laws of the PZT materials. A debonding detection method for composite patches is proposed based on the coupled use of the impedance method and hybrid genetic algorithms (Xu and Liu, 2002). The model consists of infinitesimal length springs in the joint layer between repair patches and a host

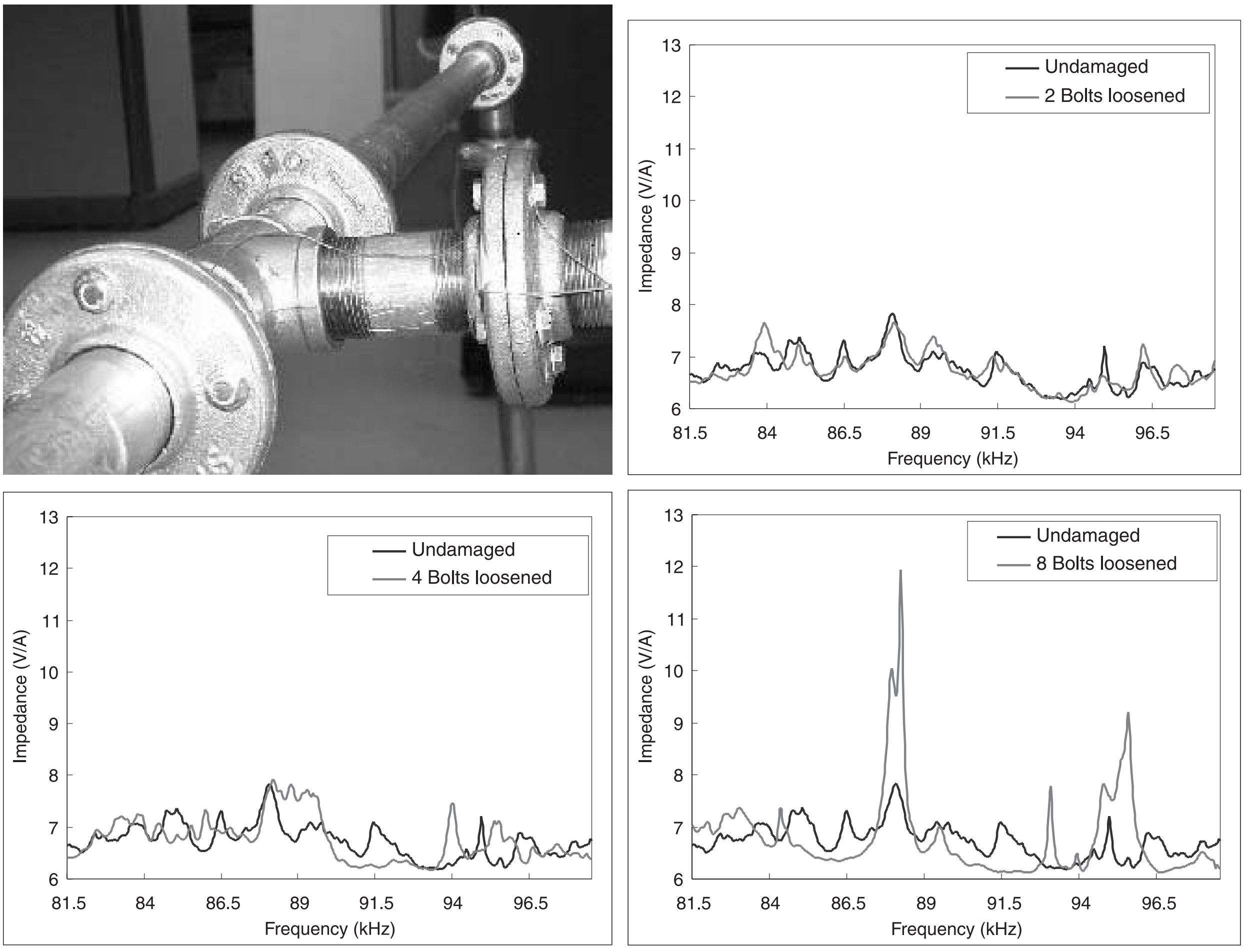

Figure 6. A pipeline experiment performed by Park et al. (2001). The impedance variation became more pronounced with increases in damage extent

structure. A numerical study shows that the debonding is effectively identified with reasonable accuracy.

Giurgiutiu et al. (1999) present health monitoring results of spot-welded structural joints. The impedance signature was recorded up to the 1100 kHz frequency range. The initiation and propagation of damage were successfully correlated with the impedance measurements. In addition, through the use of multi-site impedance measurements, the sensitivity to minor cracks, localization of damage, and rejection properties to far-field changes have been observed.

Park et al. (1999b) discuss the application of impedance monitoring as a means of damage detection for high-temperature structures. The authors tested a bolted joint structure subject to a temperature range of 482–593 °C using high-temperature piezoelectric sensors. The baseline impedance measurements varied much more at these high temperatures than the authors had seen in previous room temperature tests. However, these variations were small compared to the variations caused by damage, which was induced by loosening the bolt slightly. Although the investigation shows that impedance monitoring is a candidate for damage detection for high-temperature applications, the long-term reliability of bonding between the PZT and a host structure under extreme temperature has not been fully tested.

Soh et al. (2000) have used the impedance method for monitoring of a prototype reinforced concrete (RC) bridge. The test structure, consisting of two longitudinal beams ($5 \times 0.25 \times 1$ m^3) supporting a deck slap with 0.1 m thickness and made up of cement–concrete reinforced with steel rods, was subjected to three load cycles to introduce crack damage. The signatures of the impedance sensors located in the vicinity of the damage were found to have undergone drastic changes, while those further away were less affected. This study also provides a procedure to interpret a signal from debonding or breakdown of the PZT sensors. If there is any damage to the patch itself or to the bonding layer, the signature may show an abrupt shift or unstable trend without distinct peaks in the frequency responses.

A built-in pipeline structure has been investigated by Park et al. (2001), as shown in Figure 6. The objective of this investigation is to utilize the impedance method in identifying structural damage in areas where rapid condition monitoring is urgently needed, such as in a post-earthquake analysis. The time necessary to take the impedance measurements from more than 20 impedance sensors and to construct the damage metric chart is less than 5 min. This rapid assessment demonstrates the feasibility of on-line implementation of this technique.

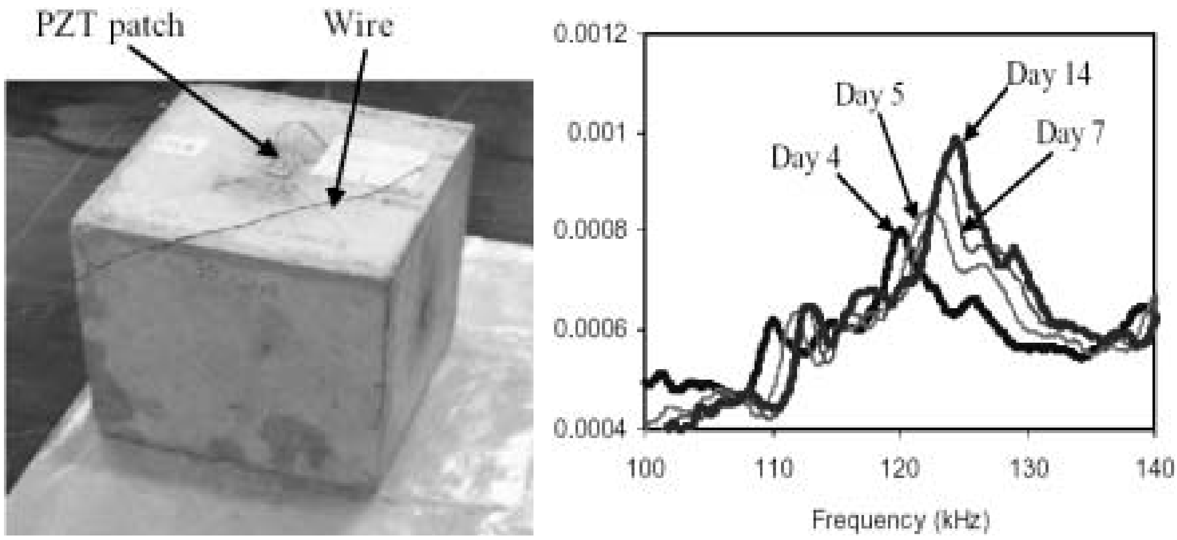

Figure 7. Bhalla et al. (2002a) show the possibility of monitoring the curing process of concrete structures. The peak shifts rightwards and becomes sharper progressively with time, which suggests the stiffness is increasing

Tseng and Naidu (2002) investigated several aluminum specimens with the impedance method. Their study includes the possibility of replicating the pristine state impedance signature of different transducers at similar geometrical locations. The experimental results suggest that such signature replications could be achieved up to 150 kHz ranges, which will be useful for effective health monitoring using an array of transducers in similar geometrical locations. The study also observes a relatively large sensing range of the impedance sensors. For instance, a 5 mm hole or half-turn of a screw was detected from the sensor more than 1 m away from the damage location. Tseng et al. (2002) also present numerical studies in which surface-bonded impedance sensors can be used to monitor two types of damage, void and crack, in a concrete structure. Commercialized FEM software, ANSYS, was used to model a concrete square specimen and the mechanical impedance of a structure. The electric impedance of a PZT was then obtained at each frequency.

Naidu and Bhalla (2002) characterize damage in concrete structures, and demonstrate the capability of the impedance method to detect incipient damage, which may not be visible to the naked eye. The extent of damage was well correlated by the corresponding rise of the damage metric using RMSD. Bhalla et al. (2002b) also investigate the possibility of monitoring the concrete strength gain during its curing process. The stiffness of the concrete is well co-related with variations in impedance peaks, as shown in Figure 7.

Dugnani and Chang (2002) use the impedance method for bio-medical devices. The impedance method is used to characterize unstable atherosclerotic plaque. A balloon is inserted in the artery and inflated at low pressure to make contact with the plaque. Upon contact, the impedance of plaque can be obtained. Research is underway to perform clinical tests on tissues utilizing a miniaturized version of a "SMART" balloon.

As described in this section, the impedance-based health monitoring technique has been successfully applied to various structures ranging from aerospace to civil structures. Because of the high frequency employed, the method is very sensitive to minor defects in a structure and not affected by any far-field changes. Recognizing that damage is a local phenomenon and that we often know where to expect damage (either from previous testing or from geometry, such as joints), the impedance method is ideal for tracking and online monitoring of critical sections in various structures.

6. Comparison with Other Approaches

6.1. Comparisons between Conventional Self-Sensing Actuators and Impedance Sensors

With the direct and converse effect that exists in PZT materials, they can be used for both actuation and sensing simultaneously, referred to as the self-sensing actuator (Dosch et al., 1992), which has been a recurrent research topic in the area of vibration control. To the best of our knowledge, the impedance-based method is the first formulation that utilizes the self-sensing actuation concept for structural health monitoring. The process to be used to achieve the self-sensing is, however, significantly different between the impedance method and traditional approaches (Dosch et al., 1992; Anderson et al., 1992; Cole and Clark, 1994).

Traditionally, in order to achieve the self-sensing actuation, the sensing signal from the PZT is separated from the applied input signal by a special electric circuit referred to as a bridge circuit (Dosch et al., 1992), as shown in Figure 8. This method is based on the assumption that the PZT is equivalent to a pure capacitor in the electric circuit analysis. When an actuation signal is applied, the PZT and the matched capacitance will receive an equal voltage. At the same time, vibration is induced in the structure and a sensing voltage will be added to the PZT patch. Each branch of the circuit is then fed through an op-amp, which cancels the actuation signal and leaves only the sensor signal out. However, because the magnitude of the applied voltage is usually much larger

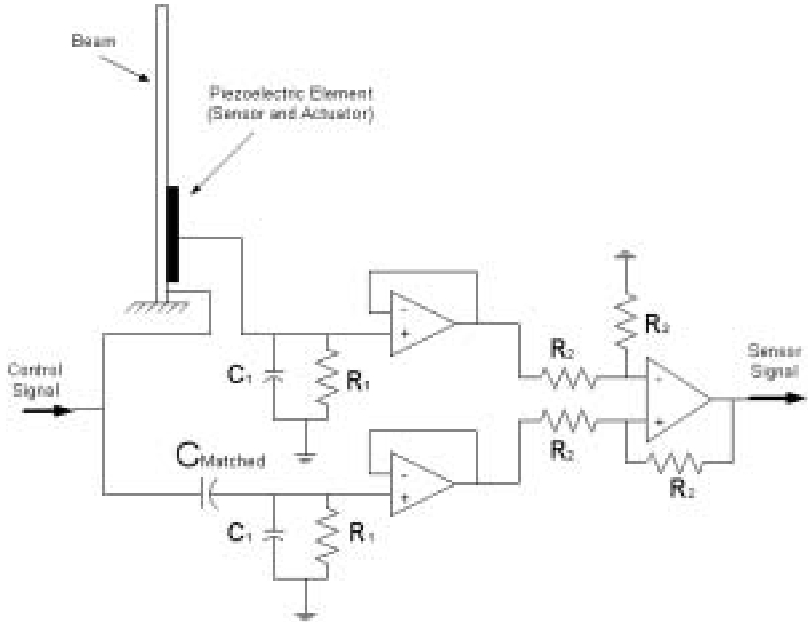

Figure 8. A schematic diagram of the self-sensing bridge circuit

than that of the sensor signal, and the capacitance of the PZT is significantly influenced by temperature changes, the signal is easily mixed with input voltage, making physical realization of self-sensing actuation extremely difficult (Tani et al., 1997).

The process used in the impedance method is significantly different from the previous self-sensing actuation approaches. When a PZT is bonded to a structure, it excites and induces vibrations in the structure by applying the electric field. Meanwhile, the resultant vibrational response, which is characteristic of the particular structure, modulates the current flowing through the PZT. If the variation of the current can be measured, the electric impedance can be obtained, which contains the same information and serves the same purpose as the conventionally known transfer function between force and velocity (Chaudhry et al., 1995). This procedure greatly simplifies the whole process in realizing self-sensing actuation, and does not require the balance of the bridge circuit, which is the most essential and difficult part of the self-sensing actuation.

Conventional self-sensing actuators have been recently used for structural health monitoring. Pardo de Vera and Guemes (1999) use embedded self-sensing piezoelectric actuators for monitoring crack growth in glass fiber reinforced plastic (GFRP) plates. It was, however, extremely important to maintain a precise equilibrium of the bridge circuit to prevent any of the exciting signal from filtrating to the sensing results. Vipperman (2001) uses adaptive self-sensing actuators to qualitatively monitor the conditions of a structure by measuring the piezoelectric permittivity, which is implicitly measured by the adaptive self-sensing actuator (Cole and Clark, 1994). This method is somewhat similar to the impedance method by implicitly identifying the capacitance of the PZT element, but operates in a much lower bandwidth and directly measures a single scalar damage parameter in the time domain, possibly making the techniques complementary.

6.2. Comparisons with Other NDE Approaches

Structural health monitoring is a subject that has received considerable attention and remains an active research area. 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. Brief comparisons between the impedance method and other NDE approaches can be found in the literature (Park et al., 2000a; Giurgiutiu et al., 2002).

As described in the previous section, the impedance method tracks changes in the dynamic properties or response of structures as in global structural response methods. While these methods propose many different algorithms for identifying and localizing damage, the majority of these methods rely on global vibrational responses or the FEM process for damage diagnosis. For practical applications, these techniques have not been shown to be effective in detecting damage at an early stage. To avoid these shortcomings, the impedance-based methods employ high-frequency structural excitations, which provide several advantages described in the previous sections. In addition, by utilizing the same PZT for actuation and sensing, the data acquisition of the impedance method is much more convenient than traditional accelerometer–shaker combinations typically used for global vibration response methods.

The ultrasonic methods, acoustic emission, or any other high-frequency analysis methods may provide detailed information on anomalies in some structures, but these methods usually require complicated instruments and comprehensive skills to interpret the measured data. In addition, most of these methods require out-of-service periods, or can be applied only at certain time intervals, which may not be suitable for autonomous on-line structural health monitoring. The sensitivity of the impedance method to minor defects is comparable to that of ultrasonic methods, but the method does not require experienced technicians to discern details. The costs of the required hardware and sensors/actuators are much lower than those of the ultrasonic or any other high-frequency NDE techniques. The sensing regions of the impedance sensors are much larger than those of local ultrasonic or eddy current sensors, which are usually moved to scan over certain areas to detect anomalies in a structure.

The impedance-based structural health monitoring provides a comprise interface between the global structural methods and the traditional ultrasonic 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 local inspection techniques, such as ultrasonics, can possibly detect.

7. Extensions of the Impedance Method

7.1. Transfer Impedance

While the impedance method traditionally uses self-impedance or point-impedance to assess damage, there have been several attempts to use an array of PZTs to measure the transfer-impedance, which is governed primarily by the mechanical transfer function between the two PZT patches. Castanien and Liang (1996) and Kabeya (1998) use the transfer-impedance in order to obtain more global information regarding the conditions of a structure and to extend the sensing region of the impedance method. Castanien and Liang (1996) have interrogated a section of aircraft fuselage using both self-impedance and transfer-impedance, and were able to detect two types of damage: cracking and attaching large weights. Kabeya (1998) successfully demonstrated that the transfer-impedance could extend the sensing area of the impedance-based method and possibly reduce the number of PZT sensor–actuators by conducting experiments on a bridge joint model and a pipeline connection. Peairs et al. (2002b) also utilize the self-impedance and transfer-impedance to construct FRFs of a bolted joint.

The response of the transfer-impedance is, however, much smaller in magnitude than that of the self-impedance because excitation waves have to travel much longer distances, and the response magnitude is closer to the noise level. In order to effectively utilize the transfer-impedance, the excitation level must be kept much higher, which is not possible with traditional impedance analyzers.

7.2. Integration with Other NDE Techniques

Koh et al. (1999) use surface-mounted PZT sensors/actuators for detecting damage in a bonded composite structure using both electrical impedance and structural FRF measured by PZT elements. They claim that the impedance method offers real-time local inspection of critical sections, while the transfer function method provides a better alternative in cases where far-field sensing is required. Park et al. (2000b) combine the impedance method with a model-based damage identification technique for one-dimensional structures. Once the location of damage was identified with the impedance method, the FRF data were utilized to characterize structural damage. Naidu et al. (2002) utilize the changes in the resonant frequencies of a structure, which is measured by the impedance signature, to identify locations of damage. The localization scheme requires a FEM of the structural member to track the natural frequency shifts and corresponding mode shapes. In the model-based approaches (Park et al., 2001; Naidu et al., 2002), the authors assume that the structural properties such as mass and stiffness matrices of the intact structure are known, and the damage detection problem is cast in the context of structural reanalysis with small perturbation. In real-world applications, it would be extremely difficult to obtain a numerical model of the baseline structure, which is accurate enough to properly represent the actual structure. Another difficulty arises from the fact that there is a great difference in sensitivity to minor defects between the impedance method and traditional model-based NDE techniques. It is possible that, even with the significant changes in impedance signature at higher frequencies, we may not see any noticeable changes in global modes, which most of model-based NDE techniques rely on.

Several wave propagation based NDE techniques have been researched for detecting structural damage. These methods measure the reflections and transmissions of a wave using a single patch (referred to as a pulse-echo) or arrays of sensors and actuators. Most of these methods utilize the sensing and actuation capability of the PZT patches, which can be nicely integrated with the impedance method. In addition, the waves usually travel long distances and cover a relatively large area, which can be supplementary to the impedance-based health monitoring.

Kabeya et al. (1998) first combined the impedance method with the wave propagation approaches. They proposed a damage location technique based on the time domain pulse-echo method. A longitudinal wave was generated by a PZT patch and a reflective wave was recorded by the same PZT patch, which in turn located the source of reflection by calculating the travel time of the wave. This concept was extended by Li et al. (1998) and Jiang et al. (1999). The supplementary combination of the impedance method and the wave propagation approaches was substantially investigated by Giurgiutiu (2003) and Giurgiutiu et al. (2002, 2003). A simple geometry was used to analyze the pulse-echo technique and changes in wave phase and velocity were used to identify locations of damage. They conclude that, while the impedance-based approach is more suitable for near-field damage detection, the wave propagation based approach is more applicable for far-field damage detection. When a network of sensors is deployed, each individual PZT patch is activated as an actuator in turn, and the rest of the PZTs act as sensors scanning a large area. They also provide a conceptual design and suggestions for a health monitoring system for aging aircraft structures using both the impedance and the wave propagation based methods.

The impedance method has been extended to pre-stress monitoring of thin structural members (Abe et al., 2000). It has been found that the pre-stress is directly related to measured wavenumbers in flexural wave equations, and the wave numbers can be estimated by electric impedance measurements. The frequency band appropriate for the stress monitoring is dependent on the dimensions and pre-stress level of the structure. Test results demonstrate the feasibility of the impedance method in monitoring the pre-stress in structural members. Ong et al. (2002c) also investigate the effect of pre-stress on the shifts of the admittance peaks. The identification of pre-stress was recognized as an inverse problem, and the use of genetic algorithms was proposed as one possible means for monitoring the pre-stress values Peairs et al. (2000b) use the impedance method as part of the self-monitoring and self-repairing bolted joint concept. In their study, the self-repairing of a joint is achieved by the activations of shape memory alloy washers inserted between bolts and nuts. The impedance method has been used to monitor the conditions of the joint in question before and after the actuation of the SMA washers. Inman et al. (2001) integrate the impedance-based damage detection method with the vibration control of smart structural systems. This technique allows a single piece of PZT material to concurrently control the vibration of a structure and detect structural damage. The first six or seven lowest vibration modes of the structure were controlled by the feedback control force generated from the PZT materials. Monitoring of the structural condition was achieved by the impedance method in a much higher frequency range of kHz to avoid interference with the structural control force. The results from the proof-of-concept tests illustrate that simultaneous structural health monitoring and vibration control is feasible across a range of frequencies.

8. Future Issues

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 technique, and damage prognosis algorithms, the impedance methods will continue to attract the attention of researchers and field engineers. In this section, future issues of the impedance method are summarized from hardware and software standpoints.

To date, only the traditional PZT sensors have been used with the impedance method, but brittle PZT can withstand very small bending. This brittleness of the PZT imposes difficulties in handling and bonding of the sensor into the structure monitored. In addition, the conformability to curved surface is extremely poor so as to require extra treatment of the surfaces. Recently, active PZT composite actuators have been developed, namely 1–3 composites by Smart Materials Corp, active fiber composite developed by MIT, and macro-fiber composite (MFC) actuators at NASA Langley Center. These piezo-composites are capable of being repeatedly manufactured at low cost, are tolerant to damage, capable of conforming to complex or curved surfaces, and embeddable into structures. The uses of piezo-fiber composite actuators need to be investigated, and would provide the advantages of being robust, reliable, and easily adaptable for impedance-based health monitoring.

As stated, the impedance analyzers typically used in the experiments are bulky and expensive, not suitable for real-field applications. Peairs et al. (2002b) has used a simplified circuit to obtain impedance signatures, but the method still requires external FFT analyzers. Stamp-sized digital signal processing (DSP) chips, which are equipped with input, output, and FFT functions, are commercially available and can be used for acquiring the electrical impedance from the PZT. The development of standalone, miniaturized impedance measurements system should be pursued.

The application of the impedance method to large-scale complex structures demands the deployment of a dense array of sensors up to hundreds and thousands in quantity. This increase in sensor numbers potentially produces difficulties and complexities in data acquisition and processing. The efficient management of data from a largely distributed sensing system is an important and challenging issue. Another drawback in using multiple sensors is the wiring harnesses needed to connect the sensors to signal processing and computers for obtaining the required information regarding the health of the host systems. Therefore, the integration of wireless telemetry systems into the impedance-measuring unit is imperative to manage and operate the sensing devices. Recognizing the fact that it takes much more energy to transmit data than to perform the local computation, it is important to embed local processing capabilities at the sensors and use a telemetry system to send only essential data. Data processing and storage equivalent to 486 PCs are now available on 2.5 cm^2 chips, and these chips consume power in a fraction of W, which makes it feasible to develop such an on-board processing devices.

Another important issue in designing such a system is the management of the power consumption. While great strides have been made in battery and fuel-cell technologies, they still have to be periodically replaced or recharged. To solve this problem, some researchers (Sodano et al., 2002) propose to use the voltages generated by natural or ambient vibration in a system. The proposed device is coupled with the PZT, stores the electric energy in a capacitor (or recharges a battery), regenerates it through discharge in a controlled signal for diagnostics and runs the telemetry of the wireless sensing system. The use of transducer materials to harness ambient motion and hence energy for use in sensor systems as a replacement for batteries is not only a potential cost saving but may be imposed requirements in many cases. Because sensors and hardware need to operate for a long period of time, the development of a low-power protocol sensor unit would be necessary (Farrar et al., 2002).

A device, which incorporates algorithms in the areas of impedance acquisitions, embedded signal processing, telemetry, and power management mentioned above into one package, will provide significant potential in structural health monitoring and damage prognosis efforts. This device would have a network of sensors in control and can act as a station between sensor networks and the central health monitoring station.

Another issue in deploying a PZT patch for impedance-based monitoring is to estimate the sensing range of the PZT. In general, the sensing range of the PZT is highly constrained to its immediate vicinity, but the actual sensing range is heavily dependent on the material properties and geometry of the host structure. A proper estimate of this sensing range can affect the number of sensors to be implemented and the location and configuration of these sensors. A high-fidelity modeling technique would be necessary to model the dynamic interaction between the PZT and the host structure at higher frequency ranges.

Combining the impedance method with wave propagation approaches should be continuously pursued. These techniques share the same PZT patches for sensors and actuators, and will be complementary to each other. Integration with well-known NDE techniques, such as ultrasonics, and acoustic emission, will result in significant advancements for some applications. The combined approach would be very effective in the sense that most existing NDE methods can provide details of damage in a structure, but require knowledge of damage location a priori.

The signal processing of the impedance method is probably the least explored area to date. Impedance-based health monitoring is still heavily based on the variations of the impedance response charts. Damage metric charts are used only when a qualitative comparison between data sets needs to be made. Because the impedance-based method relies on experimental data with inherent uncertainties, statistical analysis procedures are inevitable if we are to state in a quantifiable manner that changes in the impedance of a structural system are indicative of damage as opposed to operational and environmental variability. Statistically rigorous algorithms need to be employed to assess the variation of the signature patterns caused by certain types of damage. A primitive application of statistical pattern recognition to vibration signals that has led to documented success can be found in the literature (Sohn and Farrar, 2001). Similar to their essential feature extraction or statistical pattern recognition techniques, the future approach may be directed to investigate the use of pattern recognition methods that will capitalize on the features of the impedance signal for more successful damage detection and structural health monitoring.

9. Concluding Remarks

In this paper we have reviewed the development and applications of the impedance-based structural health monitoring technique. The impedance method provides several advantages over traditional NDE approaches. First, because of the high-frequency range employed, the method is very sensitive to incipient damage in a structure and unaffected by changes in boundary conditions, loading, or operational vibrations. The method is very suitable for an autonomous continuous monitoring system because the data acquisition procedure can be automated and requires minimal user interference. An analytical model of the structure is not required, making the method attractive for use on complex structures. Furthermore, piezoelectric sensors possess several ideal characteristics for structural health monitoring sensors. However, it should be pointed out that the impedance method has been tested only under laboratory conditions. No study has been established as to how effective the impedance method can be in applications subjected to a wide range of operational and environmental condition changes. Future research must be focused more on the testing of real structures in their operational conditions rather than laboratory tests of representative structures.

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References

Abe, M., Park, G., and Inman, D.J., 2000, "Impedance-Based Monitoring of Stress in Thin Structural Members," in *Proceedings of the 11th International Conference on Adaptive Structures and Technologies*, October 23–26, Nagoya, Japan, 285–292.

Anderson, E.H., Hagood, N.W., and Goodliffe, J.M., 1992, "Self-Sensing Piezoelectric Actuator. Analysis and Application to Collocated Structures," in *Proceedings of the 33rd Structural Dynamics and Materials Conference*, 2141–2155.

Ayres, J.W., Lalande, F., Chaudhry, Z., and Rogers, C.A., 1998, "Qualitative Impedance-Based Health Monitoring of Civil Infrastructures," *Smart Materials and Structures*, Vol. 7, 599–605.

Bhalla, S., Naidu, A. S. K., and Soh, C. K., 2002a, "Influence of Structure–Actuator Interactions and Temperature on Piezoelectric Mechatronic Signatures for NDE," in *Proceedings of ISSS-SPIE 2002 International Conference on Smart Materials Structures and Systems*, December 12–14, Bangalore, India (paper no ISSS-SA-502).

Bhalla, S., Naidu, A.S.K, Ong, C.W., and Soh, C.K., 2002b, "Practical Issues in the Implementation of Electromechanical Impedance Technique for NDE," in *Proceedings of the SPIE International Symposium on Smart Materials, Nano-, and Micro-Smart Systems*, December 16–18, Melbourne, Australia (paper no 4935-77).

Bois, C., and Hochard, C., 2002, "Measurement and Modeling for the Monitoring of Damaged Laminate Composite Structures," in *Proceedings of the 1st European Workshop on Structural Health Monitoring*, 425–432.

Castanien, K.E., and Liang, C., 1996, "Application of Active Structural Health Monitoring Technique to Aircraft Fuselage Structures," in *Proceeding of SPIE Smart Structure Conference*, Vol. 2721, 38–50.

Chaudhry, Z., Joseph, T., Sun, F., and Rogers, C., 1995, "Local-Area Health Monitoring of Aircraft via Piezoelectric Actuator/Sensor Patches," in Smart Structures and Integrated Systems, SPIE Conference, San Diego, CA, *Proceedings of the SPIE*, Vol. 2443.

Chaudhry, Z., Lalande, F., Ganino, A., and Rogers, C., 1996, "Monitoring the Integrity of Composite Patch Structural Repair via Piezoelectric Actuators/Sensors," AIAA-1996-1074-CP.

Chopra, I., 2002, "Review of the State of the Art of Smart Structures and Integrated Systems," *AIAA Journal*, Vol. 20, No. 11, 2145–2187.

Cole, D.G., and Clark, R.L., 1994, "Adaptive Compensation of Piezoelectric Sensoriactuators," *Journal of Intelligent Material Systems and Structures*, Vol. 5, 665–672.

Doebling, S.W., Farrar, C.R., and Prime, M.B., 1998, "A Summary Review of Vibration-Based Damage Identification Methods," *Shock and Vibration Digest*, Vol. 30, 91–105.

Dugnani, R., and Chang, F.K., 2002, "A Novel Impedance-Based Sensor Technique for Real Time, In Vivo, Unstable Plaque Characterization," in *Proceedings of the 1st European Workshop on Structural Health Monitoring*, 458–465.

Dosch, J.J., Inman, D.J., and Garcia, E., 1992, "A Self-Sensing Piezoelectric Actuator for Collocated Control," *Journal of Intelligent Material Systems and Structures*, Vol. 3, 166–185.

Esteban, J., 1996, "Modeling of the Sensing Region of a Piezoelectric Actuator/Sensor," Ph.D. Dissertation, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Farrar, C.R., Hemez, F., and Sohn, H., 2002, "Developing Damage Prognosis Solutions," in *Proceedings of the 1st European Workshop on Structural Health Monitoring*, 31–45.

Giurgiutiu, V., 2003, "Embedded NDE with Piezoelectric Wafer Active Sensors in Aerospace Applications," *Journal of Materials (JOM-e), Special Issue on NDE,* Vol. 55, No. 1. See http://www.tms.org/pubs/journals/JOM/0301/Giurgiutiu/Giurgiutiu-0301.html.

Giurgiutiu, V., and Zagrai, A., 2000, "Characterization of Piezoelectric Wafer Active Sensors," *Journal of Intelligent Material Systems and Structures*, Vol. 11, 959–976.

Giurgiutiu, V., and Zagrai, A. N., 2002, "Embedded Self-Sensing Piezoelectric Active Sensors for Online Structural Identification," *ASME Journal of Vibration and Acoustics*, Vol. 124, 116–125.

Giurgiutiu, V., Reynolds, A.N., and Rogers, C.A., 1999, "Experimental Investigation of E/M Impedance Health Monitoring of Spot-Welded Structural Joints," *Journal of Intelligent Material Systems and Structures*, Vol. 10, 802–812.

Giurgiutiu, V, Zagrai, A., and Bao, J.J., 2002, "Piezoelectric Wafer Embedded Active Sensors for Aging Aircraft Structural Health Monitoring," *International Journal of Structural Health Monitoring*, Vol. 1, 41–61.

Giurgiutiu, V., Zagrai, A. N., Bao, J., Redmond, J., Roach, D., Rackow, K., 2003, "Active Sensors for Health Monitoring of Aging Aerospace

Structures," *International Journal of the Condition Monitoring and Diagnostic Engineering Management*, Vol. 6, No. 1, 3–21.

Inman, D.J., Ahmadihan, M., and Claus, R.O., 2001, "Simultaneous Active Damping and Health Monitoring of Aircraft Panels," *Journal of Intelligent Material Systems and Structures*, Vol. 12, 775–783.

Jiang, Z., Kabeya, K., and Chonan, S., 1999, "Longitudinal Wave Propagation Measuring Technique for Structural Health Monitoring," in *Proceedings of 4th SPIE Conference on Smart Structures and Integrated Systems*, March 17–21.

Kabeya, K., 1998, "Structural Health Monitoring Using Multiple Piezoelectric Sensors and Actuators," Master's thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Kabeya, K., Jiang, Z., and Cudney, H., 1998, "Structural Health Monitoring by Impedance and Wave Propagation Measurements," in *Proceedings of International Motion and Vibration Control*, August 25–28, Switzerland, 207–212.

Koh, Y.L., Rajic, N., Chiu, W.K., and Galea, S., 1999, "Smart Structures for Composite Repair," *Composite Structures*, Vol. 47, No. 1, 745–752.

Krishnamurthy, K., Lalande, F., and Rogers, C.A., 1996, "Effects of Temperature on the Electrical Impedance of Piezoelectric Sensors," in Smart Structures and Materials: Smart Structures and Integrated Systems, *Proceeding of the SPIE,* Vol. 2717, 302–310.

Lalande, F., Childs, B., Chaudhry, Z., and Rogers, C.A., 1996, "High-Frequency Impedance Analysis for NDE of Complex Precision Parts," in Conference on Smart Structures and Materials, February 26–29, San Diego, CA, SPIE Publishing, Bellingham, WA, *Proceedings of the SPIE,* Vol. 2717, 237–245.

Li, Y., Jiang, Z., Chonan, S., Feng, G., and Wen, B., 1998, "Impedance-Based Technique and Wave Propagation Measurement for Non-Destructive Evaluation," in *Proceedings of International Conference on Vibration Engineering*, 476–481.

Liang, C., Sun, F.P., and Rogers, C.A., 1994, "Coupled Electromechanical Analysis of Adaptive Material Systems – Determination of the Actuator Power Consumption and System Energy Transfer," *Journal of Intelligent Material Systems and Structures*, Vol. 5, 12–20.

Lopes, V., Park, G., Cudney, H., and Inman, D.J., 2000, "A Structural Health Monitoring Technique Using Artificial Neural Network and Structural Impedance Sensors," *Journal of Intelligent Material Systems and Structures*, Vol. 11, No. 3, 206–214.

Naidu, A., and Bhalla, S., 2002, "Damage Detection in Concrete Structures with Smart Piezoceramic Transducers," in *Proceedings of ISSS-SPIE2002, International Conference on Smart Materials Structures and Systems*, July 17–19, Bangalore, India, ISSS2002/SA-538.

Naidu, A. Bhalla, S., and Soh, C.K., 2002, "Incipient Damage Localization with Smart Piezoelectric Transducers using High-Frequency Actuation," in *Proceedings of SPIE International Symposium on Smart Materials, Nano-, and Micro-Smart Systems*, December 16–18, Melbourne, Australia.

Niezrecki, C., Brei, D., Balakrishnan, S., and Moskalik, A., 2001, "Piezoelectric Actuation: State of the Art," *Shock and Vibration Digest*, Vol. 33, No. 4, 269–280.

Ong, C.W., Lu, Y., and Soh, C.K., 2002a, "The Influence of Adhesive Bond on the Electromechanical Admittance Response of a PZT Patch Coupled Smart Structure," in *Proceedings of the 2nd International Conference on Structural Stability and Dynamics,* December 16–18, Singapore.

Ong, C.W., Yang, Y., Wong, Y.T., Bhalla, S., Lu, Y., and Soh, C.K., 2002b, "The Effects of Adhesive on the Electromechanical Response of a Piezoceramic Transducer Coupled Smart System," in *Proceedings of ISSS-SPIE 2002 International Conference on Smart Materials Structures and Systems*, December 12–14, Bangalore, India (ISSS2002/SA-592).

Ong, C.W., Yang, Y., Naidu, A.S.K., Lu, Y., and Soh, C.K., 2002c, "Application of the Electromechanical Impedance Method for the Identification of In-Situ Stress in Structures," in *Proceedings of SPIE International Symposium on Smart Materials, Nano-, and Micro-Smart Systems*, December 16–18, Melbourne, Australia, paper no. 4935-79.

Pardo de Vera, C., and Guemes, J. A., 1999, "Embedded Self-Sensing Piezoelectric for Damage Detection," *Journal of Intelligent Material Systems and Structures*, Vol. 9, No. 11, 876–882.

Park, G., Kabeya, K., Cudney, H. H., and Inman, D. J., 1999a, "Impedance-Based Structural Health Monitoring for Temperature Varying Applications," *JSME International Journal*, Series A, Vol. 42, No. 2, 249–258.

Park, G., Cudney, H., and Inman, D., 1999b, "Impedance-Based Health Monitoring Technique for Massive Structures and High-Temperature Structures," in Smart Structures and Materials 1999: Sensory Phenomena and Measurement Instrumentation for Smart Structures and Materials, *Proceedings of the SPIE*, Vol. 3670, 461–469.

Park, G., Cudney, H., and Inman, D. J., 2000a, "Impedance-Based Health Monitoring of Civil Structural Components," *ASCE Journal of Infrastructure Systems*, Vol. 6, No. 4, 153–160.

Park, G., Cudney, H., and Inman, D.J., 2000b, "An Integrated Health Monitoring Technique Using Structural Impedance Sensors," *Journal of Intelligent Material Systems and Structures*, Vol. 11, No. 6, 448–455.

Park, G., Cudney, H., and Inman, D.J., 2001, "Feasibility of Using Impedance-Based Damage Assessment for Pipeline Systems," *Earthquake Engineering and Structural Dynamics Journal*, Vol. 30, No. 10, 1463–1474.

Peairs, D., Park, G., and Inman, D.J., 2002a, "Improving Accessibility of the Impedance-Based Structural Health Monitoring Method," *Journal of Intelligent Material Systems and Structures*, in press.

Peairs, D., Park, G., and Inman, D.J., 2002b, "Self-Healing Bolted Joint Analysis," in *Proceedings of the 20th International Modal Analysis Conference*, February 4–7, Los Angles, CA.

Piezo Systems Inc., 2002, Piezoelectric Product Catalog, http://www.piezo.com.

Pohl, J., Herold, S., Mook, G., and Michel, F., 2001, "Damage Detection in Smart CFRP Composites Using Impedance Spectroscopy," *Smart Materials and Structures*, Vol. 10, 834–842.

Raju, V., 1998, "Implementing Impedance-Based Health Monitoring Technique," Master's thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Raju, V., Park, G., and Cudney, H., 1998, "Impedance-Based Health Monitoring Technique of Composite Reinforced Structures," in *Proceedings of the 9th International Conference on Adaptive Structures and Technologies*, October 14–16, Cambridge, MA, 448–457.

Sodano, H., Magliula, E.A., Park, G., and Inman, D.J., 2002, "Electric Power Generation Using Piezoelectric Devices," in *Proceedings of the 13th International Conference on Adaptive Structures and Technologies*, October 7–9, Berlin, Germany.

Soh, C.K., Tseng, K, Bhalla, S., and Gupta, A., 2000, "Performance of Smart Piezoceramic Patches in Health Monitoring of a RC Bridge," *Smart Materials and Structures*, Vol. 9, 533–542.

Sohn, H., and Farrar, C. R., 2001, "Damage Diagnosis Using Time Series Analysis of Vibration Signals," *Smart Materials and Structures*, Vol. 10, 446–451.

Stokes, J. P., and Cloud, G. L., 1993, "The Application of Interferometric Techniques to the Nondestructive Inspection of Fiber-Reinforced Materials," *Experimental Mechanics*, Vol. 33, 314–319.

Sun, F.P., Chaudhry, Z., Liang, C., and Rogers, C.A., 1995a, "Truss Structure Integrity Identification Using PZT Sensor–Actuator," *Journal of Intelligent Material Systems and Structures*, Vol. 6, 134–139.

Sun, F., Roger, C.A., and Liang, C., 1995b, "Structural Frequency Response Function Acquisition via Electric Impedance Measurement of Surface-Bonded Piezoelectric Sensor/Actuator," in *Proceedings of the 36th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, 3450–3461.

Tani, J., Cheng, G.G., and Qiu, J., 1997, "Effectiveness and Limits of Self-Sensing Piezoelectric Actuators," in *Proceedings of International Workshop on Structural Health Monitoring*, Stanford, CA, 502–514.

Tseng, K., and Naidu, A., 2002, "Non-Parametric Damage Detection and Characterization Using Smart Piezoceramic Materials," *Smart Materials and Structures*, Vol. 11, 317–329.

Tseng, K., Basu, P.K., and Wang, L., 2002, "Damage Identification of Civil Infrastructures Using Smart Piezoceramic Sensors," in *Proceedings of the 1st European Workshop on Structural Health Monitoring*, 450–457.

Vipperman, J.S., 2001, "Simultaneous Qualitative Health Monitoring and Adaptive Piezoelectric Sensoriactuation," *AIAA Journal*, Vol. 39, No. 9, 1822–1825.

Wang X.M., Ehlers, C., and Neitzel, M., 1996a, "Electromechanical Dynamic Analysis of the Piezoelectric Stack," *Smart Materials and Structures*, Vol. 5, 492–500.

Wang, X.M., Ehlers, C., and Neitzel, M., 1996b, "Dynamic Analysis of Piezoelectric Actuator Bonded on Beam," in Proceedings of the 3rd International Conference on Intelligent Materials, *Proceedings of the SPIE*, Vol. 2779, 883–890.

Wang, X.M., Ehlers, C., and Neitzel, M., 1997, "An Analytical Investigation of Static Models of Piezoelectric Patches Attached to Beams and Plates," *Smart Materials and Structures*, Vol. 6, 204–213.

Xu, Y.G., and Liu, G.R., 2002, "A Modified Electromechanical Impedance Model of Piezoelectric Actuator–Sensors for Debonding Detection of Composite Repair Patches," *Journal of Intelligent Material Systems and Structures*, Vol. 13, No. 6, 389–405.

Zagrai, A.N., and Giurgiutiu, V., 2001, "Electromechanical Impedance Method for Crack Detection in Thin Plates," *Journal of Intelligent Material Systems and Structures*, Vol. 12, 709–718.