Chapter 1

INTRODUCTION

1.1 Background

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.

To date, extensive analysis and investigations have been focused on integrating smart material technology into health monitoring systems (Inman 1998). The "smart structures" or "intelligent material systems" refers to the integrated use of structures, actuators, sensors, and control systems allowing them to adaptively change or respond to external conditions. Examples of smart structures and materials are the integration of piezoceramic materials (PZT), shape memory alloys and other electomechanically coupled materials. The smart materials possess very important characteristics for fault detection and diagnostics, such as that they can serve as sensors, as well as actuators for those systems that do not contain natural exciting forces. Furthermore, they come in variety of sizes and abilities, allowing them to be placed everywhere, even in remote and inaccessible locations to actively monitor the conditions of various types of structures.

Impedance-based structural health monitoring techniques have been developed by utilizing the variety of smart material technologies (Sun, *et al*. 1995a) 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 electromechanical coupling property of piezoelectric materials. In this coupling property, the electrical impedance of piezoelectric materials 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, we 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 higher 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.

Even though the impedance-based structural health monitoring techniques has been shown promising successes in monitoring and finding minor changes in structural integrity, more fundamental research is needed before a full-scale development and commercialization can take place. Included in these is the effect of temperature changes on the impedance-based technique. Since piezoelectric materials exhibit strong temperature dependency and change in temperature results in marked changes in the structural dynamic response, any variation that is associated with a change in temperature may be confused as damage. Furthermore, the robustness of the impedance-based health monitoring technique to the presence of boundary and environmental condition changes has not yet been substantially tested.

Another problem associated with using the impedance method is that this technique is qualitative, i.e. this technique cannot precisely predict the exact nature and size of the damage. The key to the effective implementation of the impedance-based health monitoring technique is the variation of the impedance curve for a given change in the structural integrity. At this stage, however, the change in electrical impedance and the change in structural properties are not correlated. In order to assess the life expectation of structure, damage should be quantified and an appropriate model is necessary for the quantitative evaluation. Finally, the feasibility of using the impedance-based health monitoring technique under extreme environmental conditions, such as in a high temperature environment or after a severe natural disaster, is worthy of investigation.

1.2 Research Objectives

The research to be performed is towards improving the robustness of the impedance-based health monitoring technique in order to handle real-life field applications. More specifically, the goal of the dissertation is to develop a signal processing technique to minimize the effect of temperature and boundary condition changes, to provide experimental verifications of using the impedance method under extreme environmental conditions, and to integrate the impedance-based structural health monitoring technique with a model based damage detection technique or a neural networks based approach in order to establish a more rigorous and quantitative health monitoring system. The work is basically an experimental study and can be divided into several parts based on the issues to be solved.

The main objectives of this research effort can be summarized as follows:

a. To remove effects of temperature changes from the impedance-based structural health monitoring. Experiments in the laboratory have shown that the temperature change causes a line drift of electrical impedance over the frequency range. This change can easily lead to a wrong conclusion regarding the integrity of the structure in question. This problem is very important since almost all of health monitoring applications are subjected to ambient or structural temperature changes. Therefore, a theoretical and experimental investigation is performed in order to gain a better understanding of temperature effects on piezoelectric materials and structures. Finally, a software correction technique is established to eliminate the effect of temperature on the impedance-based health monitoring technique.

b. To examine the ability of the impedance-based structural health monitoring technique to detect and distinguish incipient damage from the variations due to the boundary condition changes. Contrary to most structural health monitoring techniques which are tested under the strict boundary conditions, the impedance-based health monitoring technique is tested under uncontrolled environmental conditions. The compensation technique is again applied to reduce the random and systematic noise due to boundary condition changes.

c. To investigate the feasibility of using the impedance-based health monitoring technique to the applications under extreme environmental conditions. Two proof-of-concept applications are considered. A bolted joint beam, commonly found in power plant components or aerospace structures, is to be investigated in the temperature range of 500 – 600 $^{\circ}C$, and a pipeline structure will be interrogated as an application of condition monitoring of civil critical facility after a severe natural disaster, such as an earthquake.

d. To integrate the impedance-based health monitoring technique with a model-based damage identification technique or a neural network based approach in order to establish a more rigorous and quantitative health monitoring methodology. The research will attempt to quantify the nature of damage by combining a newly developed damage identification method based on a wave propagation modeling, or by combining multiple sets of artificial neural networks, which utilize measured electrical impedance signals for input patterns.

1.3 Research Contributions

The research included in this dissertation provides an extensive body of knowledge on the use of the impedance-based structural health monitoring to the various applications, including mechanical, civil, and aerospace structural components. It is anticipated that this knowledge will have many practical and experimental implications in the smart structures and nod-destructive evaluation field, and will provide valuable information and validity of the potential benefits of this technique.

The results reported here make two major contributions to the area of impedance based health monitoring. The first contribution is to provide a solution to the practical problem of performing health monitoring in the presence of temperature changes. These often ignored but ever-present extreme environmental effects are firmly addressed here and a method for accounting for such changes is presented. Secondly, the spectral element method and neural network approaches are adapted for use with the impedance method to enable the method to examine the severity of the damage and the nature of the damage. Hence, the results reported here, greatly improve the practical use of impedance based health monitoring.

1.4 Vibration-Based Non-Destructive Evaluation Techniques

There are many approaches available to monitor the structural integrity. The literature related to damage diagnostics is quite extensive and therefore this section is not intended to be a complete literature survey on the field. Instead, a brief description of the types of method employed will be given, and the discussions on the practical limitations of the methods will follow.

To date, the techniques that examine changes in modal parameters to detect and locate damage have been investigated extensively. The basis for these techniques is that damage produces a change in measurable structural modal parameters, such as natural frequencies, damping ratios and mode shapes. An extensive survey of this field can be found in the literatures (Dimarogonas 1996; Salawu 1997; Doebling *et al.* 1998). The use of vibration pattern information for nondestructive evaluation (NDE) is a field of very increasing interest. For instance, it was the main theme of the 1997 annual International Modal Analysis Conference with more than 400 papers presented, and became a recurrent topic for sections in technical conferences and symposiums, such as the SPIE conference and the Structural health Monitoring Workshop (Chang, 1997; 1999) at Stanford University.

The vibration-based damage diagnosis methods can be categorized based upon the dynamic quantity used in the identification procedure (Doebling *et al*. 1998):

- **Natural Frequency Changes:** Adams *et al*. (1978) and Cawley and Adams (1979) used sensitivity analysis to detect damage in a plate. This work derived the fact that a state of damage could be identified by a reduction in resonant frequencies and an increase in damping, which has been used for the basis of numerous modal methods for the damage detection and health monitoring. Salawu (1997) published a summary of methods based on tracking the natural frequency changes. It should be noted, however, that frequency shifts have significant practical limitations for several applications (Farrar *et al*. 1994; Friswell and Penny, 1997). Since modal frequencies are a global property of the structure, this parameter is somewhat insensitive to the small levels of damage, or requires very precise measurements.

- **Mode Shape Changes:** West (1984) uses the modal assurance criteria (MAC), which correlates mode shapes of the damaged and undamaged structures, for the location of structural damage without the use of a prior finite element model (FEM). A number of researchers have proposed damage detection algorithms, which bypass FEM model and rely directly on the measured data to identify damage. The measured data include, mode shapes (Rickles and Kosmatka 1992; Lin 1994), mode shape curvatures (Pandey *et al*. 1991; Pabst and Hagendorn 1993), and strain modes shapes (Chance *et al*. 1994; Chen and Swamidas 1997). Simulation results shows that the changes in mode shapes are more sensitive to changes in resonant frequencies, but experimentally identification became very difficult because this scheme requires a large number of sensors to identify mode shapes, and experimentally identified modes lack the necessary accuracy demanded by this procedure (Osegueda *et al*. 1992; Ko *et al*. 1994). Mode shapes are more difficult to obtain than resonant frequencies, as shown in Doebling *et al*. (1997)

- **Flexibility/Dynamic Matrix Changes:** Another way to estimate damage in structures is based on the modifications of flexibility or structural model matrices such as mass, stiffness, and damping to reproduce as closely as possible the measured experimental data. Several different methods have been proposed. They are based on the comparison of the flexibility changes (Pandey and Biswas 1994; Peterson, *et al*. 1995), classical optimal matrix update (Berman and Nagy, 1983; Lindner *et al*. 1993; Liu 1995), minimum rank perturbation theory (Zimmerman and Kaouk 1994; 1995), and eigenstructure assignment (Zimmerman and Kaouk 1992, Lim 1995). One of the major problems with this approach is that the resulting matrices are not always positive definite or ensure the connectivity of structures. Furthermore, for error location in model updating, all elements in the matrices tend to be changed rather than a small number of elements changed substantially, imposing difficulties to localize the damage.

The practical limitations of damage diagnostics using vibration measurements are summarized.

First, relying on the lower-order global modes, these technique are not sensitive to a damage occurred at a very early stage. Detecting damage at the incipient level, before the global structural integrity is compromised, is most useful as it can give a warning before actual failure occurs. However, damage must generally be of a global scale to cause an experimentally measurable change in lower order global frequencies and modes. The other serious limitation of modal analysis methods is the extreme sensitivity of the frequencies and modes to the boundary conditions. For civil infrastructures, changes in the mass and loading are part of the normal operation. Simulation of all possible normal usage changes and their effect on the modal parameters is impossible to store so as to distinguish them from damage.

In addition, many algorithms presume that an accurate FEM of the structures or very precise measurements are available. However, there are always modeling errors and measurement errors in real-field applications. Modeling errors are from manufacturing defects, variations of member properties, assumptions about the structural damping, neglecting nonlinearities, and errors in modeling boundary conditions (Juneja, 1996). In most cases however, these errors should be expected and this will undoubtedly impose difficulties to damage identification. Furthermore, due to constraints on the instruments and structures, the number of sensors and actuators available for damage detection is severely limited. For large space structures, the percentage of degrees of freedom that can be equipped with sensors rarely exceeds 10%. In order to overcome this difficulty, either the measured degrees of freedom are expanded or the number of degree of freedom of the model is reduced, and this procedure inevitably introduces additional error into the damage identification procedure.

On the other hand, several methods have been proposed to utilize the time responses, rather than modal data, to identify structural damage (Banks *et al* 1996; Seibold and Weinert 1996; Cattarius and Inman 1997; Carneiro 2000). One advantage of time domain approaches is that these methods can avoid the model expansion or model reduction of the structures mainly encountered in the modal-domain approaches. However these methods usually require intensive computations and are based on a very high fidelity of model of structures. It should be noted that, for the linear system, the loss of information contained in measured data is negligible, when we transfer the data from the time domain into the frequency domain using a conventional Fourier transformation procedure.

Recently, artificial neural networks (ANN) have been extensively used to predict the extent and location of damage. To identify structural damage, neural networks have been trained by modal data (Tsou *et al*. 1993; Kirkegaard and Rytter, 1994; Schwarz *et al*. 1996), time history (Barga *et al*. 1990; spillman *et al*. 1993; Barai and Pandey 1995), static strain data (Kudva, *et al*. 1991; Worden, et al. 1993), frequency response functions (Povich and Lim 1994), or transfer functions (Rhim and Lee, 1995). ANN is well suited for solving inverse variational problems in the context of monitoring and fault detection because of their pattern recognition and interpolation capabilities. However, one of the major problems in the ANN based damage identification methods is that it requires training data containing all the essential features of damage mechanism. This requires considerable computation efforts. In addition, the robustness of ANN, in the case when damage is not contained in the training data, has not yet been fully verified. Another problem associated with using ANN is that it is extremely difficult to train ANN for all possible combinations of multiple damage in different areas, if global structural responses are utilized to identify structural damage.

As mentioned above, there are considerable difficulties in identifying structural damage using measured vibration data. Current and future research may help resolve these difficulties. For instance, Farrar and Doebling (1998) has investigated statistical variations in modal parameters due to the environmental changes in order to establish the bounds of these parameters, so that damage must cause changes in modal parameters that are outside these bounds. Bianchi and Ricci (1999) proposed an integrated approach by combining the methods using the frequency shifts, the frequency response functions, and the mode shape curvatures data, respectively. Neural networks and fuzzy systems are also introduced to Bianchi's analysis as an interface between the damage detection methods and the users. In addition, a number of researchers have used Wavelet transformation for damage identification. Wavelets shows the potential for on-line damage detection when combined with other techniques such as pattern recognition, as detailed in Staszewski (1999). Furthermore, the use of laser doppler vibrometer has enhanced the accuracy required by modal-analysis damage detection schemes (Nokes and Cloud 1993; Lalande *et al* 1996; Castellini and Tomasini 1999). By increasing the excitation frequency used to evaluate the dynamics of the monitored structures, the laser vibrometer enhances the ability of the techniques to localize internal damage. An efficient method for qualitative health monitoring of structures, that uses piezoceramic actuators/sensors to detect incipient level damage (Sun *et al*., 1995a), has been developed at the Center of Intelligent Material Systems and Structures, and will be detailed in the next section.

1.5 Piezoelectric Impedance-based Structural Health Monitoring

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.

1.5.1 Electromechanical Principle

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. For a linear piezoelectric material, the relation between the electrical and mechanical variables can be described by linear relations (Crawley and Anderson 1990):

$$\begin{aligned} S_i &= s_{ij}^E T_j + d_{mi} E_m \\ D_m &= d_{mi} T_i + \varepsilon_{mk}^T E_k \end{aligned} \tag{1.1}$$

or

$$\begin{bmatrix} S \\ D \end{bmatrix} = \begin{bmatrix} s^E & d_t \\ d & \varepsilon^T \end{bmatrix} \begin{bmatrix} T \\ E \end{bmatrix} \tag{1.2}$$

where S is the mechanical strain, T is the mechanical stress, E is the electric field, D is the charge density, s is the mechanical compliance, d is the piezoelectric strain constant, ε is the permittivity, and the subscripts i, j, m and k indicate the direction of stress, strain or electric field. The superscripts E and T indicate that those quantities are measured with electrodes connected together and zero stress, respectively and the subscript t indicates transpose. The first equation describes the converse piezoelectric effect and the second one describes the direct piezoelectric effect.

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 for the structure. When a PZT patch attached to a structure 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 Fig 1.1. The PZT is normally bonded directly to the surface of the structure by a high-strength adhesive to ensure a better mechanical interaction. 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.

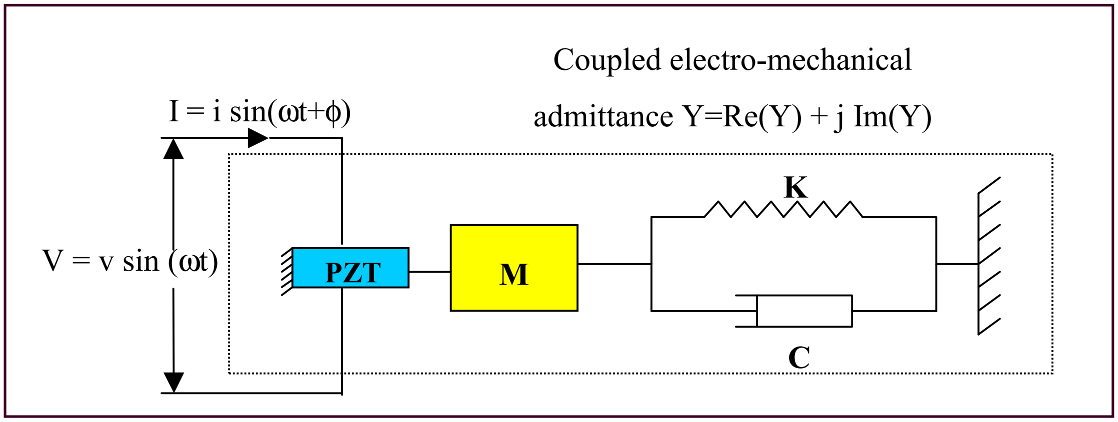

Figure 1.1 1-D model used to represent a PZT-driven dynamic structural system

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):

$$Y(\omega) = i\omega\, a\left(\bar{\varepsilon}_{33}{}^{T}(1 - i\delta) - \frac{Z_s(\omega)}{Z_s(\omega) + Z_a(\omega)} d_{3x}{}^{2} \hat{Y}_{xx}{}^{E} \right) \tag{1.3}$$

In equation (1.3), 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, $\varepsilon_{33}{}^{T}$ 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 electrical impedance of a PZT bonded to the structure, over a frequency range, is analogous to the frequency response functions but has much higher resolution and is more easily obtained.

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. A more complete description of this technique can be found in the literature (Sun *et al.* 1995a).

1.5.2 Related Previous Work

Liang *et al.* (1994) provide an analytical work to illustrate the dynamic characteristics and elecro-mechanical coupling properties of the PZT driven active material systems. An experimental modal testing using the electrical impedance of PZT patches (as co-located actuators and sensors) is presented by Sun *et al*. (1995). 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), a massive steel bridge joint (Ayres *et al.* 1996), complex precision parts (Lalande *et al.* 1996), a composite-reinforced concrete masonry wall (Raju *et al*. 1998). An overview of the impedance-based technique with related examples and proof-of-concept demonstrations is summarized by Rogers and Lalande (1996). Vinod (1998) provide an extensive experimental study on the parameters affecting on the impedance-based methods, such as actuator excitation level, test wire length, multiplexing (acquiring a single signal from distributed actuators), and boundary condition changes.

1.5.3 Impedance-based Structural Health Monitoring Technique Parameters

1.5.3.1 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 sensing region of the impedance-based health monitoring technique.

1.5.3.2 Frequency Range

The sensitivity of the technique 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 this technique 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* 1995a). 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 is more efficient 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 electrical resonant frequency. The magnitude of PZT's electrical resonant frequencies is much greater than that of structural resonant frequencies, and must be eliminated during the frequency range selection process, since those are insensitive to the presence of structural damage.

1.5.3.2 Damage Assessment

While the impedance response plots serve to give a qualitative approach to the analysis, the assessment of damage is made by the use of a scalar damage metric, defined as the sum of the squared differences of the real impedance changes at each frequency step, as shown in equation (1.4).

$$M = \sum_{i=1}^{n} \left[\mathrm{Re}(Y_{i,1}) - \mathrm{Re}(Y_{i,2})\right]^2 \tag{1.4}$$

where *M* represents the damage metric, $Y_{i,1}$, is the impedance of the PZT when measured at healthy conditions, $Y_{i,2}$ is the impedance of the structure for the comparison with the base line measurement at frequency interval *i*.

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.

1.5.4 Comparisons with other Damage Identification approaches

Traditional non-destructive evaluation 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 method is prevalent for various applications. For instance, visual inspection is used in the analysis of offshore oil platforms. Acoustic emissions techniques may be used in the remote inspection of nuclear reactor core secondary structures. 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, this method however 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. 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 disbonds 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, 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 self-sensing actuator concept (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 number of travel paths from the source to 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 disbonds 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.

1.5.5 Summary

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 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.

In summary, the impedance-based technique is able to provide an effective means to qualitatively detect incipient damage in the complex structures. While each of the current damage identification technique has value and merit, the impedance method is proposed (Sun *et al*. 1995) and further investigated in this dissertation because of its potential to develop into a completely autonomous monitoring system.

1.6 Dissertation Organization

This dissertation is a collection of papers presented, published, and to be submitted, at various conferences and journals focusing on smart structure systems and non-destructive evaluation field. Because of this layout, the reader will find some repetitions on the content of this dissertation. It should be noted that several test structures considered in this dissertation contain bolted joint failure; this is mainly because they are easy to simulate, control, and enable repeatable tests. The impedance method can successfully identify any possible type of damage in structures.

The temperature effect on the impedance-based structural health monitoring is discussed in chapter 2. At first, temperature effects on piezoelectric materials and structures are investigated theoretically and experimentally. Next, an empirical temperature compensation method is developed. Three proof-of-concept applications, including a bolted pipe joint, a gear, and a composite reinforced aluminum plate, are provided to verify the effectiveness of the compensation technique. In chapter 3, the effects of external boundary conditions and other structural variations on the impedance-based health monitoring technique are considered. Experimental verifications on a quarter-scale model of a bridge section and a cylinder header structure are presented. Experiments conducted under a high temperature environment are presented in chapter 4. In addition, the condition monitoring of a pipeline structure using impedance method is described. A wave propagation model to determine the nature of damage is developed and is combined with the impedance method in chapter 5. Simulation and experimental results are also presented. In chapter 6, the neural-network based damage identification approach, which uses measured electric impedance for input patterns, is described and the simulation and experimental verifications are presented. Chapter 8, finally, presents some general conclusions and provides recommendations for future research regarding the impedance-based structural health monitoring technique.