Advanced Impedance-based Damage Detection Considering Temperature and Loading Effects

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온도 및 하중 영향을 고려한 임피던스 기반의 향상된 손상진단 기법

김 민 구

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ABSTRACT

Reliable damage detection and health monitoring of critical members are very essential for safe operation of civil infrastructures such as bridges, buildings, power plants, etc. As a promising method of structural health monitoring (SHM), impedance-based damage detection technique has been of great attention to many researchers. In this thesis, impedance-based damage detection techniques, which are further enhanced so that reliable health monitoring can be made, are presented considering environmental and operational variations. In general, conventional impedance-based damage detection techniques identify damage by comparing “current” impedance signals with “baseline” ones obtained from the pristine condition of a structure being monitored. However, structures in real field are often subjected to changing environmental and operational conditions that affect measured impedance signals and these ambient variations can often cause false-alarms.

In this study, two novelty approaches are developed to tackle the aforementioned limitations. First, a data normalization, which is a way to distinguish structural damages from undesired ambient variations, is investigated based on impedance signals. Pattern recognition technique by using unsupervised support vector machine learning method, is used for this data normalization technique and damage classification is implemented through experimental tests. Second, a new reference-free impedance technique that does not require direct comparison of current-state impedance signals with baseline data is
developed for crack detection in a plate-like structure. In Lamb wave method, a new methodology of reference-free crack detection in metallic plate-like structures is developed (Kim, et al. 2007 [1]). In this study, by adopting the fundamental concept of PZTs polarization characteristics, a reference-free technique into impedance signature utilizing a single pair of PZTs collocated on both surfaces of the structure is developed. A novelty damage classifier based on energy level of mode conversion is established and employed to various crack-induced experimental specimens. Furthermore, temperature and loading effects are investigated to verify the effectiveness of the technique through experimental tests.

The uniqueness of this study lies in (1) the development and application of a new data normalization procedure to impedance signals using support vector machine, (2) Extension of reference-free technique to impedance-based NDT method so that instantaneous damage classification can be made without using baseline impedance signals. These approaches are expected to overcome the drawbacks of the conventional impedance-based damage detection techniques and give a great attraction for reliable health monitoring in real structures.
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CHAPTER 1
INTRODUCTION

1.1 Overview and Motivation

There has been an increasing demand in using active sensing based Structural Health Monitoring (SHM) and Nondestructive Testing (NDT) techniques for continuous monitoring of civil infrastructures to detect some structural defects such as crack, bolt loosen and fatigue failure (Balageas, et al., 2006 [2]; Sohn, et al., 2003 [3]). The general process of SHM / NDT involves: (1) the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, (2) damage-sensitive features from those measurements are extracted, (3) decision boundaries are established from the analysis of damage-sensitive features and then current state of system health is determined and (4) prediction of remaining lifetime of structure from decision making. Moreover, general procedure of SHM / NDT can be categorized into the following four levels (Rytter, 1993 [4]):

Level 1. Determine the presence of damage within the structure.
Level 2. Locate the regions of damage.
Level 3. Quantify the severity of damage.
Level 4. Predict the remaining service life of the structure.

Among the several methods for SHM / NDT, impedance-based structural health monitoring has shown promising successes in monitoring and finding changes in
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structural integrity. In this technique, a piezoelectric sensor is surface-mounted to the host structure by means of a high strength adhesive and its electrical impedance is extracted across a high-frequency band. A key aspect of the impedance method is to use high-frequency structural excitations to monitor the change of the electrical impedance that is associated with the structural parameters of the structure. There are some favorable merits in the impedance method. First, by employing high-frequency excitation range, this technique is very sensitive to locally minor defects of a structure (Park, G et al. 2003 [5]). Second, it is easy to obtain impedance signals of a structure using simple devices like an impedance chip embedded low cost circuit or commercialized impedance board.

From the above mentioned advantages, impedance-based experimental implementations have been conducted in various field applications. However, there are some challenges to damage detection in conventional impedance method as follows.

1. Environmental and operational variations: One of the main obstacles is environmental and operational variations, such as temperature change and loading conditions. It has been reported that the impedance signal is greatly affected by those operational and environmental variations so that it makes difficulties for reliable online health monitoring (Park, G et al. 1999 [6], Annamda, et al. 2007 [7]) as shown in Figure 1.1.

2. Limitation of baseline-based damage detection: The basic scheme of SHM system is that ‘baseline’ data is measured so that some change of the ‘baseline’ data due to some defects of a structure can be regarded as a indication of damages. However, the baseline data constantly varies throughout the life span of the structure and changes due to other environmental factors. From the unavoidable reasons, conventional impedance method has limitations basically and it can cause undesirable false alarms.
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The aforementioned problems are the motivations of this study. In order to overcome the limitations of conventional NDT methods, data normalization technique and reference-free impedance based technique based on impedance signature are developed for reliable damage detection. In data normalization method, a technique which isolates the environmental effects including temperature and loading variations from the structural defects of a structure is proposed using unsupervised support vector machine. In reference-free impedance based crack detection technique, it is further advanced so that damage classification is performed instantaneously without any ‘baseline’ data. The verification of those proposed techniques are investigated through the experimental test.
1.2 Literature Review

In this section, relative literature studies are presented on the topics of conventional impedance based NDT technique, statistical pattern recognition technique and reference-free NDT technique.

1.2.1 Impedance-based NDT techniques

Impedance-based method for damage detection has favorable merits of being sensitivity to incipient damages and minor changes of a structural integrity as mentioned before. Because of these advantages, experimental implementation of this impedance technique for damage detection has been successfully conducted on several complex structures: truss joints (Ayres et al. 1998 [8]), a spot joint (Giurgiutiu et al. 1999 [9]), a brick wall member (Park, G et al. 2000 [10]), reinforced concrete member (Soh, et al. 2000 [11]), thin plates (Zagrai, et al. 2001 [12]) and steel bridge components(Park, S et al. 2006 [13]). Effects of environmental factors such as temperature and loading have been also reported by several researchers (Park, G et al. 1999 [6], Annamda, et al. 2007 [7]). From the study of the operational effects on impedance signature, particularly temperature changes and loading conditions significantly affect the electro-mechanical impedance signature and several techniques to compensate for the environmental variation problems have been developed (Park, G et al. 1999 [6], Koo, et al. 2007 [14]). However, these techniques have limitations because these methods rely on baseline data which constantly varies throughout the life span of structures although these compensation techniques are effective against environmental variations.
1.2.2 Statistical Pattern Recognition technique for SHM

Statistical pattern recognition is usually defined as “the act of taking in raw data and taking an action based on the category of the pattern (Fukunaga, 1990 [15])”. Pattern recognition aims to classify data or patterns based either on a priori knowledge or statistical information extracted from the patterns. By using the pattern recognition algorithms, some features which are characterized from the data is extracted and used for damage detection. Pattern recognition techniques based on impedance signal have been investigated by several researchers. Lopes, et al. (2000 [16]) have researched impedance based SHM technique by utilizing artificial neural networks to find damage and its location of bridge section. Park, S et al. (2006 [17], 2007 [18]) have reported the combination technique of impedance and Lamb wave using support vector machine (SVM) on a railroad structure. However, those studies did not consider the environmental and operational effects such as temperature and loading variations so as to have difficulties for applying to real applications. In this study, data normalization using support vector machine is investigated under temperature and loading effects on impedance signals.

1.2.3 Reference-free NDT technique

Reference-free damage detection technique is an enhanced method against the undesirable environmental effects. In conventional method, damage is often identified by comparing the “current” data obtained from a potentially damaged condition of a structure with the “past” baseline data collected at the pristine condition of the structure. Kim, et al. (2007 [1]) have proposed a Lamb wave-based reference-free technique to crack detection using PZT polarization characteristics. This reference-free technique is conceived so that cracks can be detected without direct comparison with previously
obtained baseline data. In addition, NDT techniques based on nonlinear acoustics and energy-based Lamb wave have been developed (Dutta, et al. 2007 [19]; Park, S et al. 2010 [20]). Since this approach does not rely on previously collected data, it cannot be affected by environmental and operational variations during monitoring duration the structures. In this study, impedance-based reference-free technique is developed and investigated through numerical and experimental studies.
1.3 Objectives and Scopes

The purpose of this study is to identify structural damages of the monitored structure regardless of environmental and operational variations based on impedance technique. To overcome the fundamental hurdles of the conventional impedance techniques, this study intends to tackle the problems by establishing theoretical development and conducting experimental verifications. The specific objectives of this study are listed below.

1. Application of data normalization method to impedance-based damage detection technique: The data normalization technique utilizing unsupervised support vector machine will be employed to resolve the weaknesses of the previous conventional impedance method against temperature changing and static & external loading.

2. Development of impedance based reference-free technique: Reference-free technique based on impedance signature will be developed and investigated to detect crack damage through numerical and experimental tests. It makes a great contribution to instantaneous damage classification without any previously-obtained ‘baseline’ data.

3. Investigation of environmental effects through experimental tests: In order to verify the effectiveness of the proposed impedance-based reference-free technique, temperature and loading effects will be investigated on various crack-induced plate specimens.
1.4 Contribution and Uniqueness

This study offers great potentials to impedance-based damage detection. As removing the undesirable environmental effects, impedance based technique will have attractions to real-structure applications since this technique is very sensitive to minor changes of the monitored structure. The uniqueness of this study is listed below.

1. Application of a new data normalization procedure based on support vector machine to impedance signature and development of a novelty damage classification using generalized extreme value statistics: There are some attempts to develop a damage detection technique based on impedance signal using the pattern recognition approach, but it is the first time to take account for environmental effects, which are needed to be separated from damages using data normalization technique on impedance signature.

2. Extension of reference-free technique to impedance-based NDT technique: Establishment of impedance based reference-free technique using a single of collocated PZTs is developed in terms of the intimate relationship between Lamb wave and impedance. In addition, instantaneous damage classification is implemented based on an energy-based damage classifier. It is the first time to utilize the reference-free technique, which does not rely on baseline data, on impedance signals.
1.5 Organization

This thesis consists of total 5 chapters. The organization of this thesis is summarized as follows:

- In Chapter 2, the data normalization technique including theoretical background and experimental studies is described. Overall procedures of data normalization are explained and two experimental example tests are investigated. In addition, the limitations of this technique are represented.

- In Chapter 3, the reference-free impedance-based damage diagnosis using a single pair of collocated PZTs is explored. It contains theoretical development and experimental verification as well as numerical simulation. In experimental verification, self-sensing circuit for measuring electrical impedance is illustrated.

- In Chapter 4, the environmental effects on the reference-free technique are represented. Especially, the effects of temperature variation and external loading conditions on the reference-free impedance method are investigated and verified to demonstrate the effectiveness of the proposed technique.

- In Chapter 5, the summary and conclusion of this study are represented. Furthermore, suggestions for the future studies are represented.
CHAPTER 2
DATA NORMALIZATION
FOR IMPEDANCE-BASED SHM

2.1 Introduction

The primary goal of structural health monitoring is to provide reliable information regarding damage classification, damage localization, and damage severity. The basic premise is that damages alter the dynamic characteristics of the structure when damage occurs. However, in reality, time-varying environmental and operational conditions such as temperature variation and traffic loadings affect the measured signals and it makes hard to detect damages of the structure (Sohn, 2007 [21]). From these problems for damage diagnosis, the most important thing which should be concerned is how to extract reliable damage-sensitive features from the response data. These features are needed to be sensitive to small severities of damage yet insensitive to other undesirable effects including environmental and operational effects. Especially, in impedance-based SHM, feature extraction is quite importance because the measured impedance signals are vulnerable to those temperature and loading variations (Park et al., 2003 [5]).

The separation of the structural defects in the structure from the undesirable variations can be addressed thorough a procedure known as data normalization. Data normalization is a process of normalizing data sets so that signal changes caused by operational and environmental variations of the system can be separated from structural changes of interest, such as structural deterioration or degradation (Sohn et al., 2009 [22]). In order
to achieve successful structural health monitoring goals, it is necessary to develop data normalization techniques for robust damage detection. In this study, nonlinear principal component analysis based on unsupervised support vector machine is introduced and verified.

Data normalization based on pattern recognition techniques has been investigated by several researchers. Lopes et al. (2000 [16]) has reported impedance based NDT technique utilizing the artificial neural networks to find damage and its location of bridge section. Park et al. (2006 [17]) has investigated conventional impedance based method and wavelet analysis for damage diagnosis of steel bridge and railroad structures using support vector machine. However, those studies did not consider the environmental and operational effects which affect significantly impedance signatures. It means that reliable damage detection based on impedance signals by using those techniques is difficult unless some novelty techniques considering those environmental and operational variations are made.

In this study, data normalization using unsupervised support vector machine is investigated under temperature and loading variations on impedance signals. Support vector machine (SVM) is an automated learning system that uses a hypothesis space of linear functions in a high dimensional feature space (Vapnik, 1995 [23]). Using this state-of-the-art method, the nonlinear classification based on impedance signals is made. This data normalization technique based on impedance signature in this study is a new approach and it can lead to a successful achievement for damage detection against the operational and environmental variations.
2.2 Theoretical Backgrounds

In this section, a main concept of linear principal component analysis as well as kernel principal component analysis is briefly explained. Principal component analysis (PCA) is one of pattern recognition analysis and is mathematically defined as an orthogonal linear transformation that transforms the data to a new coordinate system that maximizes the variance of the original variables. This new transformed orthogonal coordinate system is called principal components (Jolliffe, 1986 [24]). Principal component analysis is known as an efficient way in reducing dimensionality of data, since a small fraction of the entire principal components can often account for most the data structure. Moreover, PCA is an efficient way to isolate the effect of damage from that of environmental variations. In this study, the data normalization technique using Kernel principal component analysis (KPCA) is utilized. Expanding the data set into higher dimension using Gaussian Kernel function, the principal component analysis is conducted without the nonlinearity of data set.

2.2.1 Linear Principal Component Analysis

Linear principal component analysis aims to search for a transformed coordinate in the form of straight lines in such a way that maximizes the variance of original variables. Linear principal component analysis is realized by eigenvector decomposition of the data covariance matrix. The first eigenvector corresponding to the largest eigenvalue of the covariance matrix represents the direction which the variance of the projected variable is maximized. These new variables projected onto the first eigenvector are called the first principal component, and the subsequent principal components associated with the remaining eigenvalues can be computed by projecting the data onto the successive eigenvectors.
Let \( x_j \in \mathbb{R}^{m\times 1}, \quad j = 1, ..., N \), denote a set of \( N \) number of centered, i.e., \( \sum_j \varphi(x_j) = 0 \), \( m \)-dimensional feature vectors extracted from measurements. Then LPCA is performed by constructing of the covariance matrix \( C_1 \in \mathbb{R}^{N\times N} \).

\[
C_1 = \frac{1}{N} \sum_{j=1}^{N} x_j x_j^T
\]

Which it gives an eigenvalue-decomposition of the covariance matrix:

\[
\lambda^* \omega = C_1 \omega \tag{2-2}
\]

where \( \lambda^* \) and \( \omega \) are eigenvalues and corresponding eigenvectors of the corresponding covariance matrix \( C_1 \), respectively. From calculation of Equation (2-2), \( m \) number of eigenvalues and corresponding eigenvectors can be computed, and the \( k^{th} \) principal component of a feature vector \( x_j \) is obtained as an inner product between \( x_j \) and the corresponding \( k^{th} \) eigenvector \( \omega_k \):

\[
PC_k(x_j) = \omega_k^T x_j \tag{2.3}
\]

However, LPAC can be utilized under an assumption that the data set is linear. If there is a guarantee that data set is not linear, LPCA does not work in the problem. So, LPCA should be generalized into nonlinear principal component analysis (NLPCA) to reveal nonlinear correlations immanent in the original variables. In this study, NLPCA is realized by using KPCA. This method employs a kernel method and solves a simple eigenvalue problem in a nonlinearly transformed space.
2.2.2 Support Vector Machine

The support vector machine (SVM) is an automated learning system that uses a hypothesis space of linear functions in a high dimensional feature space (Vapnik, 2000 [23]). The simplest model is called as the linear SVM (LSVM), and it works for data that are linearly separable in the original feature space only. In the early 1990s, nonlinear classification in the similar procedure as in the linear SVM became possible by introducing nonlinear functions called kernel functions without being conscious of actual mapping space. This extended technique of nonlinear feature spaces is called nonlinear SVM (NSVM) shown in Figure 4.1 (Mita and Taniguchi, 2004, [25]). Assume the training sample \( S \) consisting of vectors \( x_i \in R^n \) with \( i = 1,...,N \), and each vector \( x_i \) belongs to either of two classes thus is given a label \( y_i \in \{-1,1\} \). The pair of \((w,b)\) defines a separating hyper-plane of equation as follows:

\[
S = \{(x_1,y_1),...,(x_N,y_N)\}
\]

\[
(w\cdot x) + b = 0
\]

where \( w \) and \( b \) are arbitrary constants.

Figure 2.1 Scheme of nonlinear support vector machine
However, Equation (2-5) can possibly separate any part of the feature space, therefore one needs to establish an optimal separating hyper-plane (OSH) that divides $S$ leaving all the points of the same class on the same side, while maximizing the margin which is the distance of the closest point of $S$. The closest vector $x_i$ is called support vector and the OSH $(w', b')$ can be determined by solving an optimization problem. The resulting SVM is called as the maximal margin SVM. In order to relax the situation, the maximal margin SVM is generalized by introducing non-negative slack variables $\xi = (\xi_1, \xi_2, \ldots, \xi_N)$ as follows:

$$
\begin{align*}
\text{minimize} & \quad d(w') = \frac{1}{2} (w' \cdot w') + C \sum \xi_i, \\
\text{subject to} & \quad y_i \left( (w' \cdot X_i) + b' \right) \geq 1 - \xi_i, \quad i = 1, 2, \ldots, N, \quad \xi \geq 0.
\end{align*}
$$

(2-6)

The purpose of the extra term $C \sum \xi_i$, where $i = 1, \ldots, N$ is to keep under control the number of misclassified vectors. The parameter $C$ can be regarded as a regularization parameter. The OSH tends to maximize the minimum distance of $1/w$ with small $C$, and minimize the number of misclassified vectors with large $C$. To solve the case of nonlinear decision surfaces, the OSH is carried out by nonlinearly transforming a set of original feature vectors $x_i$ into a high-dimensional feature space by mapping $\Phi: x_i \mapsto z_i$ and then performing the linear separation. However, it requires an enormous computation of inner products $(\Phi(x) \cdot \Phi(x_i))$ in the high-dimensional feature space. Therefore, using a Kernel function which satisfies the Mercer’s theorem given in Equation (2-7) significantly reduce the calculations to solve the nonlinear problems. Equation (2-8) is the widely used kernel functions for nonlinear SVM.

$$
(\Phi(x) \cdot \Phi(x_i)) = K(x, x_i)
$$

(2-7)
\[ K(x, x_i) = (x \cdot x_i + 1)^d \]  
\[ K(x, x_i) = \tanh(\alpha (x \cdot x_i) + \beta) \]  
\[ K(x, x_i) = \exp\left(-\frac{\|x - x_i\|^2}{2\sigma^2}\right) \]  
\[ K(x, x_i) = \frac{\sin(N + 0.5)(x - x_i)}{\sin(0.5(x - x_i))} \]

where \( d, \alpha, \beta, \) and \( \sigma \) are parameters.

### 2.2.3 Kernel Principal Component Analysis

In this study, NLPCA is realized by using KPCA, also known as unsupervised least-squares support vector machine (Oh and Sohn, 2009 [26]). The mathematical formulation for linear principal component analysis can be easily extended to nonlinear principal component analysis by using kernel method and a nonlinear mapping \( \varphi(\bullet) : \mathbb{R}^m \rightarrow \mathbb{R}^h \) where \( m < h \). The input data set is transformed into a higher-dimensional space by the nonlinear mapping so that LPCA can be performed in the higher dimensional space. Here, \( \varphi(x_j) \) represents the nonlinearly-transformed feature vector of \( x_j \) satisfying \( \sum_j \varphi(x_j) = 0 \) which is called ‘centering’. The covariance matrix \( C_2 \) can be constructed using this centered and transformed data set \( \varphi(x_j) \) in a similar manner with LPCA.

\[ C_2 = \frac{1}{N} \sum_{j=1}^{N} \varphi(x_j)\varphi(x_j)^T \]  
(2-9)

This equation becomes simple eigenvalue problem as the same in LPCA:

\[ \lambda \nu = C_2 \nu \]  
(2-10)
Here, \( v \) can be expressed as a linear summation of \( \varphi(x_i) \), \( i = 1, \ldots, N \)

\[
v = \sum_{i=1}^{N} \alpha_i \varphi(x_i)
\]  

(2.11)

where \( \alpha_i \) is an unknown coefficient. Multiplying both sides of equation Eq. (2.11) with \( \varphi(x_j)^T \), it gives to another eigenvalue problem:

\[
N \lambda \alpha = K \alpha
\]

(2-12)

where \( \alpha = [\alpha_1 \alpha_2 \ldots \alpha_N]^T \in \mathbb{R}^{N \times 1} \). The \( ij^{th} \) entity of \( K \in \mathbb{R}^{N \times N} \), \( K_{ij} \), is defined as:

\[
K_{ij} = \varphi(x_i)^T \varphi(x_j) = k(x_i, x_j)
\]

(2-13)

From Equation (2-12), \( N \) number of \( \lambda \) and \( \alpha \), i.e. \( \alpha_k, k = 1, \ldots, N \) can be obtained. In Equation (2-13), the inner product between \( \varphi(x_i) \) and \( \varphi(x_j) \), is simply replaced with a simple problem of kernel function, \( k(x_i, x_j) \) (Suykens et al., 2002 [27]). Therefore, the inner product of two nonlinearly-transformed features is simply obtained by computing kernel function without any evaluations of the data in that space. The commonly used kernel functions are polynomial, radial basis function, and sigmoid kernels. In this study, a Gaussian kernel \( k(x_i, x_j) = \exp(-\|x_i - x_j\|^2 / \rho^2) \) is utilized. Here, \( \rho \) is called a Gaussian width. Since \( K \) matrix is positive-semidefinite, all eigenvalues \( \lambda_k, k = 1, \ldots, N \), are non-negative. Then, for the first \( p(\leq N) \) non-zero eigenvalues and the corresponding eigenvectors are normalized.

\[
(v_k^T v_k) = 1 \rightarrow N \lambda_k (\alpha_k^T \alpha_k) = 1, k = 1, \ldots, p
\]

(2-14)

where \( \lambda_k \) and \( \alpha_k \) are the \( k^{th} \) eigenvalue and eigenvector obtained from Eq. (2-14), respectively.
Finally, the $k^{th}$ nonlinear principal component of the feature vector $x_j$ can be computed from the process of the projection of the feature vector $x_j$ onto the corresponding $k^{th}$ eigenvector:

$$K_{PC(k)}(x_j) = v_k^T \varphi(x_j) = \sum_{i=1}^{N} (\alpha_k)_i k(x_i, x_j)$$  \hspace{2em} (2-15)

where $K_{PC(k)}(x_j)$, $(\alpha_k)_i$, and $v_k$ are the $k^{th}$ nonlinear principal component of the feature vector $x_j$ obtained by KPCA, the $i^{th}$ component of the $k^{th}$ eigenvector $\alpha_k$, and $k^{th}$ eigenvector, respectively. In practice, centering, i.e., $\sum_j \varphi(x_j) = 0$, is not trivial, since the nonlinear mapping $\varphi(\bullet)$ is not explicitly computed. To overcome this difficulty, a centered kernel matrix $K^*$ is obtained by subtracting the mean of transformed features as follows:

$$K^*_{ij} = \left[ \varphi(x_i) - \frac{1}{N} \sum_{k=1}^{N} \varphi(x_k) \right]^T \left[ \varphi(x_j) - \frac{1}{N} \sum_{k=1}^{N} \varphi(x_k) \right]$$  \hspace{2em} (2-16)

Therefore, the $k$th nonlinear principal components of a feature vector $x_j$ using the centered kernel matrix can be computed.
2.2.4 Procedure of Data Normalization

Figure 2.2 shows the procedure of data normalization used in this study. To realize the proposed data normalization technique for impedance-based SHM, baseline data measured from the pristine of the structure is collected as a first step. This baseline data have to include the expected environmental variations which the structure would be subjected to. The collected baseline data is used for training data sets. Then, some distinguishing features are extracted and input data set for KPCA is selected. In this study, as the features, five properties of the measured impedance data from the pristine condition of the structure are chosen in each real and imaginary part. Then, KPCA is performed to find the optimal Gaussian width. This optimization is to find the width value which the difference of the first eigenvalue and successive eigenvalue is the maximum. It means that the difference of the first principal component and second principal component represents how well the separation level is performed in KPCA. After
determining the optimal width, KPCA is performed again to project the transformed input data sets in higher dimension to the computed principal axis. Same procedures of transforming and projecting are also implemented for the test data sets which are compared with the training data sets. As the next step, finding the closest distance of each data set in high-dimension is followed. In this stage, the difference between both the training and test data sets is calculated. To determine the threshold value, statistical modeling is conducted using the training data. The threshold value is obtained by parameter estimation of GEV (Generalized Extreme value) distribution and calculating confidence level of the distribution. Finally, damage can be detected by comparing the estimated damage index with the threshold value.

2.2.5 Outlier Analysis using Extreme Value Statistics

For the next step, the damage index, which is called “Novelty Index” can be determined by calculating the minimum distance of each data set. Novelty index represents the degree of deviation of each data set. Specifically, the novelty index is defined by measuring the degree of deviation of new data from the baseline data.

\[ \text{Novelty Index}(y) = \|x - y\| \]  \hspace{1cm} (2-17)

where \( y \) is test data and \( x \) is baseline data, respectively. It is understandable from the estimation of novelty index that how the recent obtained data set \( y \) is far from the baseline data \( x \). If a new data set is obtained from an abnormal condition, the value of the novelty index would increase. This characteristic of the novelty index is utilized to classify the damage in the study. The statistical model of the novelty index is established by adopting extreme value statistics and a threshold value is determined in terms of confidence level of the selected extreme value statistic.
In damage classification process, establishing a threshold value is an important issue. In general, the features associated with damage can be classified as outliers deviating from the normal condition and these outliers usually occupy the tails of a distribution. Since the main problem is to estimate the tails of distribution accurately, it is doubtful that commonly used Gaussian assumption to the underlying distribution for novelty index is reasonable. To overcome this limitation of extreme values, statistical model using the extreme value theory is established in this study.

Suppose that the given data are divided into $n$ numbers of subsets $\{x_1, x_2, ..., x_n\}$. Then, the most relevant statistic for the tail distribution is the maximum operator, i.e. $\max(\{x_1, x_2, ..., x_n\})$, or the minimum operator, i.e. $\min(\{x_1, x_2, ..., x_n\})$, that selects the maximum (or minimum) values from each subset. If a large number of data are independent and identically distributed and generated from a single probability distribution, the maximum of each subset could be modeled using probability distribution, the maximum of each subset could be modeled using the following three distributions (Park et al., 2006 [28]).

\[
Gumbel: F_G(x|k, \delta) = \exp \left[ -\frac{x-k}{\delta} \right], \quad -\infty < x < \infty \text{ and } \delta > 0
\]

\[
Weibull: F_W(x|k, \delta, \beta) = \begin{cases} 
1, & x \geq k \\
\exp \left[ -\left(\frac{x-k}{\delta}\right)^\beta \right], & \text{otherwise}
\end{cases}
\] (2-18)

\[
Frechet: F_F(x|k, \delta, \beta) = \begin{cases} 
\exp \left[ -\left(\frac{\delta}{x-k}\right)^\beta \right], & x \geq k \\
0, & \text{otherwise}
\end{cases}
\]

where $k$, $\delta$ and $\beta$ are location, scale and shape parameters of each distribution, respectively. Jenkinson shows that the previous three extreme value distributions can be
unified into a single distribution called generalized extreme value (GEV) distribution (Jenkinson, 1955 [29]).

\[
F_{GEV}(x\mid \mu, \sigma, \gamma) = \exp \left\{ - \left[ 1 + \gamma \left( \frac{x-u}{\delta} \right) \right]^{-\frac{1}{\gamma}} \right\}, \quad -\sigma - \gamma(x-u) \leq 0, \sigma > 0
\]

(2-19)

where \( u, \sigma \) and \( \gamma \) are location, scale and shape parameters of GEV distribution, respectively. It can be readily shown that each of Gumbel, Frechet or Weibull distributions is a specific case of the GEV distribution:

\[
F_{GEV}(x\mid u, \sigma, \gamma) = F_G(x\mid k, \delta) \text{ when } \gamma \to 0, u = k, \text{ and } \sigma = \delta;
\]
\[
F_{GEV}(x\mid u, \sigma, \gamma) = F_f(x\mid k, \delta, \beta) \text{ when } \gamma > 0, u = k + \delta, \sigma = \delta, \text{ and } \gamma = 1/ \beta;
\]
\[
F_{GEV}(x\mid u, \sigma, \gamma) = F_W(x\mid k, \delta, \beta) \text{ when } \gamma < 0, u = k - \delta, \sigma = \delta, \text{ and } \gamma = -1/ \beta.
\]

(2-20)

### 2.2.6 Damage Classification

As the last step, the damage classification is performed. After the parameters are determined from the estimation of GEV distribution for novelty index of baseline data, the threshold value can be computed by using the confidence level of the cumulative density function of this estimated distribution. Therefore, if the novelty index obtained from test data is over the estimated threshold value, the condition of the structure can be classified to be damaged.
2.3 Experimental Studies

In this section, verification of the data normalization technique is investigated through two example studies. The investigated two specimens are subject to temperature variation and loading conditions for simulating the real situation which structures would face. The process and results of the test are presented in this section.

2.3.1 Example I : Loose bolt detection on a plate

The first experimental study was carried out to detect bolts loose under temperature variation and loading conditions using data normalization technique on a plate. In real structures, such as steel components, bolts are commonly used to connect each component of the structure as shown in Figure 2.3 (a). In this study, in order to simulate a similar situation like real structures, a small bolts-connected specimen made of steel was investigated to detect bolts loose. PZT patch was used as the actuator and sensor to detect the presence and growth of artificial bolts loose on the plate as shown in Figure 2.3 (b). The plate consists of 6 bolts on the part of connection between the two steel component parts.

(a)  
(b)

Figure 2.3 Experimental specimen: (a) An example of bolt connection part in bridge; (b) The investigated test specimen
Its overall configuration is shown in Figure 2.4. The specimen (800 * 200 * 3 mm) was connected with two steel plates (400 * 200 * 3 mm) jointed with six steel bolts. One PZT patch (20 * 20 * 0.508 mm) was placed near the end of the plate. The dimension of the PZT patch is determined to detect bolt loosen properly considering properties of the specimen. Based on the knowledge acquired through various 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 (Park et al. 2003 [5]). The distance between the PZT patch and the end of the plate was 150 mm.

Figure 2.4 Specification of the investigated bolts-connected steel plate

Figure 2.5 Impedance measurement device: (a) AD5933 evaluation board; (b) Block diagram
As an impedance measurement device, the commercialized AD5933 evaluation board supplied by Analog Device Inc. was used as shown in Figure 2.5 (a). This device is a high precision impedance converter system which combines an on-board frequency generator with a 12-bit and it has a 1 MHz sampling rate. Its block diagram is seen in Figure 2.5 (b). Using a USB connection and provided software, the impedance data including phase between the device and the monitored structure is measured. Compared to conventional impedance analyzer, AD5933 evaluation board has some advantages: (1) it is not bulky and not expensive ($150 per each), (2) it is portable to be adopted for real-world applications. From these attractive merits, the demand for this portable impedance device now increases. The electrical impedance of the plate was measured at the frequency range of 30 ~35 kHz. This frequency range was selected since the most visible resonant peaks of the specimen were found at this range. Temperature variation and loading conditions were applied to the plate as shown in Figure 2.6. Temperature was controlled from -24 to 40° C and the loading conditions were adjusted at 5 and 10 mm deflections at the middle of the plate.

(a) 
(b)

Figure 2.6 Test configuration for temperature and loading effects: (a) Test specimen in the temperature chamber for temperature variation test; (b) Test specimen under static loading condition using C-clamp
Table 2.1 shows the data sets for temperature test. Total nine cases were investigated based on the assumption that a real bridge structure would happen to face temperature range from -24°C to 40°C. In this temperature test, one bolt was loosed as a damage case. Table 2.2 shows the data sets for static loading test. Total eight cases were investigated in terms of the level of the loading, i.e. 5 mm and 10 mm deflections at the middle of the plate. In the loading test, the severity of the damage was produced as the number of loose bolts increase and maximum 4 bolts were loosed as the damage cases. Figure 2.7 shows the impedance profiles and the results of the data normalization corresponding to varying temperature cases in intact and bolt-loosen cases. In Figure 2.7 (a), it is noticeable that the temperature change affects the measured real impedance much than the effect of bolt-loosen.

Table 2.1 Data sets for temperature variation test

<table>
<thead>
<tr>
<th>Data</th>
<th>State</th>
<th>Temp.(°C)</th>
<th>Data</th>
<th>State</th>
<th>Temp.(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Baseline</td>
<td>24</td>
<td>6</td>
<td>Loose(1)</td>
<td>-24</td>
</tr>
<tr>
<td>2</td>
<td>Intact</td>
<td>-24</td>
<td>7</td>
<td>Loose(1)</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Intact</td>
<td>5</td>
<td>8</td>
<td>Loose(1)</td>
<td>24</td>
</tr>
<tr>
<td>4</td>
<td>Intact</td>
<td>24</td>
<td>9</td>
<td>Loose(1)</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>Intact</td>
<td>40</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2 Data sets for static loading test

<table>
<thead>
<tr>
<th>Data</th>
<th>State</th>
<th>Deflection (mm)</th>
<th>Data</th>
<th>State</th>
<th>Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Baseline</td>
<td>-</td>
<td>5</td>
<td>Loose(1)</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>Intact</td>
<td>-</td>
<td>6</td>
<td>Loose(1)</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>Intact</td>
<td>5</td>
<td>7</td>
<td>Loose(4)</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>Intact</td>
<td>10</td>
<td>8</td>
<td>Loose(4)</td>
<td>10</td>
</tr>
</tbody>
</table>
Figure 2.7 Results of data normalization for temperature variation: (a) Impedance profile with temperature and bolt loose; (b) Difference between 1st and 2nd eigenvalues; (c) Calculated eigenvalues; (d) Damage classification
Figure 2.8 Results of data normalization for static loading: (a) Impedance profile with loading condition; (b) Difference between 1\textsuperscript{st} and 2\textsuperscript{nd} eigenvalues; (c) Calculated eigenvalues; (d) Damage classification
From the generalized extreme value distribution, the parameters of location \( u \), scale \( \sigma \) and shape \( \gamma \) were determined to \( 7.706 \times 10^{-5}, 0.000168 \) and 2.318, respectively. From the calculation process of novelty index for the training data, the threshold value was computed to 0.070 from 95% confidence level of the cumulative density function of the estimated distribution. From the damage classification as shown in Figure 2.7 (d), the novelty index for test data was obtained and 80% values of the data were over the estimated threshold value. It indicates that the used data normalization technique separates the temperature effect from the measured impedance data appropriately.

Figure 2.8 shows the results of the data normalization corresponding to static loading conditions in intact and bolt-loosen cases. From the generalized extreme value distribution, the parameters of location \( u \), scale \( \sigma \) and shape \( \gamma \) were determined to \( 6.172 \times 10^{-5}, 0.000206 \) and 3.322, respectively. The threshold value was computed to 1.193 from 95% confidence level of the cumulative density function of the estimated distribution. From the damage classification as shown in Figure 2.8 (d), the novelty index for test data was obtained and all the test data obtained from the bolt-loosen cases were over the estimated threshold value. It indicates that the used data normalization technique isolates the effects of static loading from the measured impedance data accurately.
2.3.2 Example II: Loose bolt detection on a complex composite structure

(a) (b) (c)

Figure 2.9 Test configuration for temperature and loading effects: (a) Test specimen in the temperature chamber; (b) Static loading test set-up with an UTM; and (c) Test configuration of dynamic loading with a shaker.

The second experimental study was carried out to detect bolts loose under temperature variation and loading conditions on a complex composite aircraft wing. Figure 2.9 shows the overall experimental configurations for temperature and loading effects. In order to simulate the environmental and operational variations, several equipments including temperature chamber, UTM and dynamic shakers are utilized. In this study, a circular dual PZT (diameter: 30 mm, thickness: 2 mm) was used to detect the presence and growth of artificial bolts loose. The frequency range was selected as 60~70 kHz. In this study, temperature was controlled from -30°C to 50°C and the static loading conditions were adjusted from 10000 kN to 40000 kN. In addition, in the external dynamic loading test, an arbitrary waveform input signal with amplitude of 5, 7 and 10 voltages was generated by an shaker as shown in Figure 2.9 (c). For each test, total 10 data sets were used for training and test data.
Table 2.3 shows the investigated data set for data normalization with temperature variations. Total 12 data sets obtained from various different temperature conditions were used in this test. Figure 2.10 shows the results of the data normalization for varying temperature. The threshold was calculated as 0.027 from 97% confidence interval of the GEV. From Figure 2.10 (b), all test sets were classified to be damaged while the all training data sets were to be normal condition. It indicates that the utilized data normalization technique worked well and it demonstrates the applicability of this technique to real-structure applications.

Table 2.4 shows the data sets for the static loading test. Total 11 data sets with various static loading from 10000kN to 40000kN were used. First 6 data sets were trained for data normalization and other 5 data sets were used as the test data. Figure 2.11 shows the results of data normalization for static loading condition. All test data sets were classified to be bolt-loosen cases after data normalization. The threshold value was set at 0.131 from 97% confidence interval of the GEV. This result indicates that the used data normalization technique for various static loading conditions was accurately performed and it can be applied to real-structure applications.

Table 2.5 shows the data sets of external dynamic loading test. Total 12 data sets with various external dynamic loading were used. First 7 data sets were trained as the training data and other 5 data sets were used as the test data. Figure 2.12 shows the results of data normalization for external loading conditions. All test data sets were classified to be bolt-loosen cases after data normalization even through the impedance signals varied with external loading conditions. The threshold value was set at 0.444 from 97% confidence interval of the GEV using the novelty index values. This result indicates that the used data normalization technique for external dynamic loading conditions was accurately performed and it will be applicable to real-structures for detecting bolt-loosen.
Chapter 2 Data normalization for impedance-based SHM

Table 2.3 Data sets for temperature variation test

<table>
<thead>
<tr>
<th>Data</th>
<th>State</th>
<th>Temp. (°C)</th>
<th>Data</th>
<th>State</th>
<th>Temp. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Intact</td>
<td>Baseline</td>
<td>7</td>
<td>Loose (1)</td>
<td>17</td>
</tr>
<tr>
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<td>Intact</td>
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<td>9</td>
<td>Loose (1)</td>
<td>-10</td>
</tr>
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<td>Intact</td>
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<td>10</td>
<td>Loose (1)</td>
<td>10</td>
</tr>
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<td>Intact</td>
<td>10</td>
<td>11</td>
<td>Loose (1)</td>
<td>30</td>
</tr>
<tr>
<td>6</td>
<td>Intact</td>
<td>30</td>
<td>12</td>
<td>Loose (1)</td>
<td>50</td>
</tr>
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</table>

(a)

Figure 2.10 Results of data normalization for varying temperature: (a) Impedance profile with temperature and bolts-loosen cases; (b) Damage classification
Table 2.4 Data sets for static loading test

<table>
<thead>
<tr>
<th>Data</th>
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<th>Loading (kN)</th>
<th>Data</th>
<th>State</th>
<th>Loading (kN)</th>
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<td>Loose (1)</td>
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</tr>
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<td>40000</td>
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<td></td>
<td></td>
</tr>
</tbody>
</table>

(a)

(b)

Figure 2.11 Results of data normalization for static loading: (a) Impedance profile with static loading and bolts-loosen cases; (b) Damage classification
Table 2.5 Data sets for external dynamic loading test

<table>
<thead>
<tr>
<th>Data</th>
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<th>Amplitude (Vpp)</th>
<th>Frequency (Hz)</th>
<th>Data</th>
<th>State</th>
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</tr>
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<td>-</td>
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<td>10</td>
<td>25 ~ 35</td>
</tr>
<tr>
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<td>Intact</td>
<td>Intact(-)</td>
<td>-</td>
<td>8</td>
<td>Loose(1)</td>
<td>5</td>
<td>5 ~ 15</td>
</tr>
<tr>
<td>3</td>
<td>Intact</td>
<td>5</td>
<td>5 ~ 15</td>
<td>9</td>
<td>Loose (1)</td>
<td>5</td>
<td>15 ~ 25</td>
</tr>
<tr>
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<td>5</td>
<td>15 ~ 25</td>
<td>10</td>
<td>Loose (1)</td>
<td>10</td>
<td>5 ~ 15</td>
</tr>
<tr>
<td>5</td>
<td>Intact</td>
<td>10</td>
<td>5 ~ 15</td>
<td>11</td>
<td>Loose (1)</td>
<td>10</td>
<td>15 ~ 25</td>
</tr>
<tr>
<td>6</td>
<td>Intact</td>
<td>10</td>
<td>15 ~ 25</td>
<td>12</td>
<td>Loose (1)</td>
<td>10</td>
<td>25 ~ 35</td>
</tr>
</tbody>
</table>

Figure 2.12 Results of data normalization for external dynamic loading: (a) Impedance profile with external loading and bolts-loosen cases; (b) Damage classification
2.4 Limitations

Data normalization technique on impedance signature has been investigated throughout Ch.2 By adopting the pattern recognition technique, this method is robust to environmental effects such as temperature variation and loading conditions. This will allow affirmative progresses in in-service monitoring of aerospace, automotive, civil and mechanical systems, which are subject to various operational and environmental conditions. However, this method has some limitations. First, this technique requires lots of data for training. In theory, the more number of data the more accurate damage classification is possible. In case of real structure monitoring, it is essential that all kinds of variations such as temperature, loading, humidity and boundary conditions should be concerned for reliable health monitoring. In aspect of data memory, it needs high-capacity device to store the train data. Secondly, it has possibility of a misclassification due to the property of the measured data. If an unknown data which is the untrained comes into the test data, the system would produce false-positive indication of damage. In other words, it is vulnerable to unexpected changes which can exist to the monitored system. These limitations bring about the barrier of reliable and robust health monitoring. To tackle these limitations, reference-free damage diagnosis which does not require any baseline or train data will be newly developed in Ch.3.
CHAPTER 3
REFERENCES-FREE IMPEDANCE-BASED DAMAGE DIAGNOSIS

3.1 Theoretical Development

3.1.1 Principle of conventional impedance method for SHM

Piezoelectric materials have been widely used in structural dynamics applications because they are lightweight, robust, and inexpensive. In general, piezoelectric materials produce mechanical strains when an electrical field is applied to the piezoelectric materials; conversely, when mechanical pressure is applied, it generates an electrical charge. Because of this unique nature, piezoelectric materials are commonly utilized in various applications.

Impedance-based SHM technique commonly uses small piezoelectric ceramic like PZT attached to a host structure to excite the structure and measure changes in the electrical impedance. A key aspect of impedance-based structural health monitoring is the use of piezoelectric materials as a collocated sensors and actuators. The self-sensing properties of the PZT allow one piece of material to sense the input and measure the output current. Since the PZT is bonded directly to the structure, the mechanical impedance of the structure is directly correlated with the electrical impedance. Therefore, assessments of any changes in the mechanical system can be made by observing changes of the electrical impedance which is defined as the ratio of the input voltage to the output current. Liang et al. 1996 [30] performed the coupled electro-mechanical analysis to determine the relationship between the PZT sensor bonded to the system and the host structure as shown in Figure 3-1.
Chapter 3 Reference-free impedance based damage diagnosis

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 shows that the electrical impedance \( Z_{total}(\omega) \) of the PZT actuator is a combined function of the mechanical impedance of the PZT actuator and that of the host structure:

\[
Z_{total}(\omega) = \left[ i\omega C \left( 1 - k_{31}^2 \frac{Z_a(\omega)}{Z_a + Z_s(\omega)} \right) \right]^{-1}
\]  

(3-1)

where \( C \) is the zero-load capacitance of the PZT, \( k_{31} \) is the electro-mechanical coupling coefficient of the PZT, \( Z_s \) and \( Z_a \) are the impedance of the host structure and the PZT, respectively. Equation (3-1) 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 can be considered an indication of changes in the structural integrity.
3.1.2 Understanding of the relationship between Lamb wave and impedance

Although the basic principle of this method is well known, the understanding of physical meaning of impedance method is quite important. In this study, the meaning of impedance is analyzed in terms of the relationship between Lamb wave propagation and impedance. Let’s assume that when PZT wafers are adopted for damage detection in a plate-like structure, both transient and steady-state dynamic responses can be generated and measured through the electro-mechanical interaction between the PZT wafers and the structure. Shortly, Lamb wave method, which is called ‘pitch-catch’, is the transient dynamic response and impedance method that is called ‘pulse-echo’ is the steady-state dynamic response. Let’s assume that initial voltage input signals are applied on the PZT wafers as shown in Figure 3.2, Lamb waves begin to propagate from the actuating PZT wafers. If there is no additional excitation input signal on the PZT wafers, the state of Lamb wave is the transient. It means that there is one propagating wave that has dispersive and mostly shear horizontal properties. Otherwise, if a periodic additional excitation signal is applied to the PZT wafers, the traveling Lamb waves become resonant standing waves when the superposition of newly incoming and reflected waves is made after a certain time period. This resonant standing wave produces the natural mode shape of the structure (French, A. P. 1971 [31]; Kim, et al. 2010 [32]). It is well known that the modal dynamic responses of a structure are reflected on the impedance signature. Therefore, changes of dynamic responses of a structure can be detected by measuring the impedance of the structure.
Figure 3.2 Understanding of how the propagating Lamb waves become the resonant standing wave: (a) A schematic of a cantilever beam with collocated PZTs; (b) The 15th natural mode shape of the beam; (c) Initial wave propagation with a driving frequency; (d) Transient states: Superposition of newly incoming and reflected Lamb waves; (e) Resonant states: formation of resonant standing wave. (Note that the waveforms of (e) are identical to the natural mode shape in (b)) (Kim, et al. 2010 [32])

3.1.3 PZT polarization characteristic and mode conversion

Extension the reference-free technique to impedance method is made by utilizing the PZT poling directionality. The polarization characteristics of piezoelectric materials and its use in Lamb wave mode extraction are described (Kim, et al. 2007 [1]). In this study, the same line of polarization characteristics is followed here. A schematic of the target structure is shown in Figure 3.3 (a). It is assumed that the two identical PZTs labeled each “A” and “B” are located exactly at the same point but on the opposite sides of the plate. Two collocated PZTs are used to excite as well as sense the guided waves in pulse-echo
configuration. The guided waves are generated by either one of PZTs A and B or both PZTs simultaneously. The generated waves are then reflected from the boundaries of the structure and subsequently sensed by the same PZTs. In the figure 3.3 (b), the arrows indicate the positive poling directions of the PZTs. The symmetric Lamb mode corresponds to equal bending directions on both sides of the plate. The anti-symmetric mode corresponds to opposite bending directions on both sides of the plate. If an input voltage is applied on PZT A, a set of $S_0$ and $A_0$ modes is produced. The input to PZT B will generate an identical $S_0$ mode but an equal and opposite $A_0$ mode in the structure.

![Figure 3.3](image)

Figure 3.3 The effect of the PZT poling directions on the phases of the $S_0$ and $A_0$: (a) Test configuration with a single pair of collocated PZTs; (b) The $S_0$ mode produces the same bending for PZTs A and B while the $A_0$ mode results in the opposite bending

![Figure 3.4](image)

Figure 3.4 Selective mode generation scheme using PZT polarization directionality: (a) $S_0$ mode generation (PZT polarization in opposite direction); (b) $A_0$ mode generation (PZT polarization in same direction)
Su et al., 2004 [33] have reported the selective mode generation using the polarization characteristics of PZTs. In this study, the concept of selective mode generation of either \( S_0 \) or \( A_0 \) mode can be done by simultaneous excitation of the two PZTs, thereby reinforcing the desired mode and canceling out the other. Figure 3.4 describes the schematic of selective mode generation. Figure 3.4 (a) describes PZT polarizations in opposite direction and \( S_0 \) (symmetric) mode is generated only when the two PZTs are excited simultaneously. On the other hand, Fig. 3.4 (b) refers that PZT polarizations are same directions and only \( A_0 \) (anti-symmetric) mode is generated when the two PZTs are excited simultaneously.

Cho, 2000 [34] has reported that defects of a structure cause mode conversion in the context of Lamb wave propagation. Mode conversion of Lamb waves (e.g. from the \( S_0 \) mode to the \( A_0 \) mode or vice versa) takes place when waves propagating along a thin plate of uniform thickness encounter a discontinuity such as a sudden thickness variation due to damage as shown in Figure 3.5. When a \( S_0 \) mode arrives at the discontinuity point, the transmitted wave is separated into \( S_0 \) and \( A_0 \) modes (denoted as \( S_0/S_0 \) and \( A_0/S_0 \), respectively). In a similar manner, an \( A_0 \) mode is also divided into \( S_0 \) and \( A_0 \) modes (denoted as \( S_0/A_0 \) and \( A_0/A_0 \), respectively).

![Figure 3.5 Schematic of mode conversion that happens when propagating Lamb waves encounter a sudden thickness change in a plate](image-url)
The $S_0$ and the $A_0$ modes originally are produced by the PZTs encounter the defect and boundaries multiple times as they propagate back and forth. Thereby the waves undergo scattering and mode conversions before the signals is measured by the PZTs. The measured signal $L(t)$ will therefore be a linear superposition of four signal components: $L_{S_0/S_0}(t)$, $L_{A_0/S_0}(t)$, $L_{S_0/A_0}(t)$, $L_{A_0/A_0}(t)$, where $L$ and $t$ stand for measured Lamb wave signature and time, respectively as shown in Figure 3.6. $L_{A_0/S_0}(t)$, for example, is the mode converted component of the signal $L(t)$ which corresponds to an $S_0$ when generated but an $A_0$ mode when measured. The two first arrivals of the mode converted modes, $L_{A_0/S_0}(t)$ and $L_{S_0/A_0}(t)$, due to mode conversion occur between the $S_0$ and $A_0$ modes and the arrival times and waveforms of those signals are exactly same in the pulse-echo method. Therefore, in this study, the two mode converted modes are integrated into one. Theoretically, there would be no mode conversion for an undamaged plate without any discontinuity. So, the measured signals from undamaged plates would contain only two components. However, this is based on the assumption that the two transducers are identical and those are perfectly collocated. In practice, these assumptions cannot be fully satisfied because of variations in PZT size, alignment and bonding conditions.

![Figure 3.6](image)

Figure 3.6 Comparison of Lamb wave signals obtained from the undamaged (without a notch) and damaged (with a notch) conditions: (a) With and (b) Without a notch
3.1.4 Excitation and sensing configuration

From the aforementioned selective mode generation and mode conversion schemes, an impedance-based reference-free technique is developed using a single pair of collocated PZTs.

Based on the discussion earlier in this section, the relative signs of the signal components \( L_{(S0/S0)}(t) \) etc.) would be different depending on which PZT actuates and senses. For instance, the signal actuated by PZT A and sensed by PZT A is called \( L_{(AA)} \).

For the sake of convenience, the parentheses \( (t) \) are dropped from all the signal notations in the remainder of the paper. Figure 3.6 in the previous section shows an example case, in which the relative phases of the constituent Lamb wave modes in the measured signals \( L_{(AA)} \) and \( L_{(BB)} \). The only difference between \( L_{(AA)} \) and \( L_{(BB)} \) is the phase in the mode converted mode which is the combination of \( L_{(A0/S0)} \) and \( L_{(S0/A0)} \). In this study, total 6 cases of excitation and sensing schemes are utilized to extract the mode conversion component by using the PZT polarization characteristics. Table 3.1 categorizes the notations depending on the PZT locations of excitation and measurement.

<table>
<thead>
<tr>
<th>Notations</th>
<th>Actuation</th>
<th>Sensing</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_{AA} )</td>
<td>PZT A</td>
<td>PZT A</td>
<td>Self-sensing</td>
</tr>
<tr>
<td>( L_{BB} )</td>
<td>PZT B</td>
<td>PZT B</td>
<td>Self-sensing</td>
</tr>
<tr>
<td>( L_{S0A} )</td>
<td>PZT A&amp;B</td>
<td>PZT A</td>
<td>S mode selection</td>
</tr>
<tr>
<td>( L_{S0B} )</td>
<td>PZT A&amp;B</td>
<td>PZT B</td>
<td>S mode selection</td>
</tr>
<tr>
<td>( L_{A0A} )</td>
<td>PZT A&amp;B</td>
<td>PZT A</td>
<td>A mode selection</td>
</tr>
<tr>
<td>( L_{A0B} )</td>
<td>PZT A&amp;B</td>
<td>PZT B</td>
<td>A mode selection</td>
</tr>
</tbody>
</table>
In Table 3.1, first and second subscripts indicate the ‘excitation’ and ‘sensing’ PZTs, respectively. Also, subscript ‘$S_0$’ and ‘$A_0$’ denote only $S_0$ mode generation and only $A_0$ mode generation when simultaneous excitation of PZTs A & B, respectively.

Figure 3.7 Comparison of relative mode combination between intact (without a notch) and damaged (with a notch) conditions: (a) Relative mode combination without a notch; (b) Relative mode combination with a notch
Figure 3.7 describes the schematic diagram of the relative mode combination. The magnitude of triangles indicates amplitude of the individual modes, triangle presents in-phase of individual modes and the inverted triangle denotes out-of-phase of individual modes. In this study, this term of “in-phase” is used when the positively polarized side of the PZT is subjected to tensile strain. On the other hand, this term of “out-of-phase” is used when the negatively polarized side of the PZT is subjected to tensile strain. Equation 3-2 is the compact mathematical representation of the measured signals.

\[
L = ML_{IM}, \quad \text{where} \quad L = \begin{pmatrix} L_{AA} \\ L_{BB} \\ L_{SA} \\ L_{SB} \\ L_{ApA} \\ L_{ApB} \end{pmatrix}, \quad M = \begin{pmatrix} 1 & 1 & 1 \\ 1 & -1 & 1 \\ 2 & 1 & 0 \\ 2 & -1 & 0 \\ 0 & 1 & 2 \\ 0 & 1 & -2 \end{pmatrix} \quad \text{and} \quad L_{IM} = \begin{pmatrix} L_{S0} \\ L_{MC} \\ L_{A0} \end{pmatrix} \quad (3-2)
\]

where M is the relative mode combination of measured Lamb wave signals and \( L_{IM} \) represents the individual modes, \( S_0 \), MC and \( A_0 \). The notation \( L_{S0} \) stands for the measured signals actuating only the \( S_0 \) mode and the corresponding signal measured by PZT A when the two PZTs in opposite positive poling directions are excited simultaneously. In a similar manner, the notation \( L_{A0} \) can be defined that actuating only the \( A_0 \) mode and the corresponding signal measured by PZT A when the two PZTs in same positive poling directions are excited simultaneously (Su, Z. and Ye, L. 2004 [33]).

Based on the findings, the extension of Lamb wave signals to electromechanical impedance signature is made in the following section.
3.1.5 Extraction of mode conversion impedance signal

In this section, modal dynamic response of a structure reflected on the electro-mechanical impedance of the PZTs is presented. When traveling Lamb wave becomes resonant standing wave which is the same as the natural mode shape of a structure. Electro-mechanical impedance signal reflects on dynamic characteristic because the mechanical impedance of a structure is a function of modal parameters such as resonant frequencies, modal damping and mode shapes (Park, G. et al. 2003[5]). Once the modal dynamic responses of the plate-like structure is analyzed in the context of Lamb wave propagation, extension of the relative mode combination for the Lamb wave signals to the electromechanical impedance signals is obvious. The Equation (3-3) shows the relative mode combination of the measured impedance signals.

\[
E = ME_{IM}, \quad \text{where} \quad E = \begin{pmatrix} E_{(AA)} \\ E_{(BB)} \\ E_{(S_0A)} \\ E_{(S_0B)} \\ E_{(A_0A)} \\ E_{(A_0B)} \end{pmatrix}, \quad M = \begin{pmatrix} 1 & 1 & 1 \\ 1 & -1 & 1 \\ 2 & 1 & 0 \\ 2 & -1 & 0 \\ 0 & 1 & 2 \\ 0 & 1 & -2 \end{pmatrix} \quad \text{and} \quad E_{IM} = \begin{pmatrix} E_{(S_0)} \\ E_{(MC)} \\ E_{(A_0)} \end{pmatrix} \quad (3-3)
\]

where E stands for the measured electromechanical impedance signals and E_{IM} indicates the combination of the individual impedance modes, S_0, MC and A_0. The meaning of the all notations is the same as before. From the Equation 3-3, a least-square estimate of the individual modes, which are \( E_{(S_0)} \), \( E_{(MC)} \), \( E_{(A_0)} \), can be obtained from the measured impedance signals by using Moore-Penrose (pseudo) inverse (Penrose, R. 1955 [35]):
where \( \dagger \) denotes the pseudo inverse of a matrix. Ideally, \( E_{(MC)} \) would be zero for undamaged structures but non-zero for damaged ones. However, in practical situations, even undamaged structures are expected to be non-zero \( E_{(MC)} \) due to PZT imperfection and different bonding conditions between the PZTs A and B.

3.1.6 Instantaneous damage diagnosis

Based on the findings above, a damage classifier that operates on the energy of extracted mode conversion is developed. The objective here is to determine the existence of a crack solely based on the impedance signals measured from the current state of the structure. As mentioned earlier, Moor-Penrose inverse gives the least-square estimate which contains the non-idealities in the measurement system. This least-square error is computed through the reconstruction of the measured signals. The reconstruction impedance signal of the measured impedance signals can be reformulated as follows:

\[
\tilde{E} = M\tilde{E}_{IM} = MM^\dagger E
\]  

(3-5)

The reconstructed signal \( E \) would not be exactly same as the originally measured signals. It indicates that the process of the reconstruction causes non-zero \( E_{(MC)} \) in an undamaged structure. So, reconstruction errors (\( e \)) can be obtained by subtracting the reconstruction signals from the measured signals as follow:
If the damage index is defined as the energy level of the decomposed mode conversion (\(E_{MC}\)), a reasonable damage threshold would be set based on the energy level of the reconstruction errors (\(e\)). This non-zero damage threshold contains the effects of measurement noise and non-idealities of the structure as well as bonding conditions between PZTs and the structure. The estimation of energy level of mode conversion and errors is obtained by RMS (Root Mean Square) approach and is calculated as follows:

\[
R_{MC} = \sqrt{\frac{1}{F_e - F_s} \int_{F_s}^{F_e} (\tilde{E}_{MC}(f))^2 df}
\]  

(3-7)

\[
R_{Error} = \frac{1}{6} \sum_{i=1}^{6} \sqrt{\frac{1}{F_e - F_s} \int_{F_s}^{F_e} (e_i(f))^2 df}
\]  

(3-8)

where \(F_s\) and \(F_e\) denote the start frequency and end frequency, respectively. \(e_i\) is the \(i^{th}\) reconstruction error so that \(e_1\) is the error in reconstructing signal \(E_{AA}\) (i.e. \(e_1 = E_{AA} - E_{AA}\)), etc. The energy level of reconstruction errors is averaged over these six reconstruction error values. Finally, the damage criterion for classifying a given structure into undamaged or damaged category is established by comparing the energy levels between mode conversion and errors.

If \(R_{MC} > R_{Error}\) then damage exists,
Otherwise no damage.

(3-9)

This damage classifier identifies crack formation when the energy level of crack-induced mode conversion impedance signal is larger than those of errors.
3.2 Numerical Simulation

3.2.1 Numerical simulation setup

The concept of using a single pair of collocated PZTs for impedance-based crack detection was first validated through numerical simulation. Using ABAQUS 6.7-1 software (ABAQUS 6.7-1 User’s manual, 2007 [36]), electromechanical impedance signal in a two-dimensional aluminum was simulated using combination of plain strain, piezoelectric plain strain, and dielectric modules in ABAQUS software. The length of the plate was 200 mm, and its thickness was 0.6 mm. Two identical PZTs with 12 mm length and 0.507 mm thickness were attached to the plate model as shown in Figure 3.8. In the damaged case, the formation of a notch was 3 mm depth and 1 mm width and the location of that was introduced 50 mm away from PZT A. Due to the plain strain assumption of the model, 2-D PZTs were also modeled with infinite width. A narrowband chirp signal from 15 kHz to 25 kHz was used as an input signal and the increment of the signal was 1Hz. In the simulation, relative tolerance for the solution was chosen as $10^{-6}$ to control the error in each integration step.

![Figure 3.8 Configuration and dimensions of the investigated aluminum plate used in numerical simulation](image-url)
3.2.2 Numerical simulation results

Figure 3.9 Comparison of raw admittance signals between intact and notched cases: (a) Intact case without a notch; (b) Damage case with a notch

In this section, simulation results are illustrated to validate the theoretical background. Figure 3.9(a) illustrates that admittance signals $E_{AA}$ and $E_{BB}$ were almost identical and this matches well with theory. In a similar manner of admittance signals $E_{AA}$ and $E_{BB}$, signals $E_{S0A}$ and $E_{S0B}$, $E_{A0A}$ and $E_{A0B}$ are also identical without damage. On the other hand, once a notch of 3 mm depth and 1 mm width was introduced 50 mm away from
PZT A and PZT B, signal $E_{AA} (E_{S0A}, E_{A0A})$ became different from signal $E_{BB} (E_{S0B}, E_{A0B})$ as a result of the mode conversion induced by the crack, as illustrated in figure 3.9(b). After raw admittance signals are obtained, the decomposition process described in equation 3-4 was conducted and shown in figure 3.10. Because the effect of PZT imperfection was neglected in modeling, individual admittance modes ($E_{S0}, E_{A0}$ and $E_{MC}$) were clearly extracted.

![Graphs showing decomposed admittance signals](image)

Figure 3.10 Comparison of decomposed individual admittance signals between intact and notched cases: (a) Intact without a notch; (b) Damage case with a notch
In figure 3.10 (a), $E_{S0}$ and $E_{A0}$ modes were clearly decomposed without the $E_{MC}$ mode and the effect of mode conversion did not appear. On the other hand, figure 3.10 (b) shows that the additional modes due to mode conversion show showed up in the decomposed $E_{MC}$ mode. In the following experimental results, the outcome of this numerical simulation is further substantiated and the effect of initial error including PZT imperfection is investigated.
3.3 Experimental Verification

3.3.1 Experimental setup

To further examine the proposed impedance-based reference-free NDT technique, experimental tests have been conducted on an aluminum plate. The overall test configuration and test specimen are shown in Figure 3.11. The data acquisition system was composed of an arbitrary waveform generator (AWG), a high-speed signal digitizer (DIG) and three multiplexers. The dimension of the plate was 610 mm × 400 mm × 6 mm and two PSI-5A4E type circular PZT wafer transducers (12 mm × 12 mm × 0.507 mm) connected to SMA connector were mounted in the middle of the plate. Note that insulated PZTs were used to prevent any electromagnetic interference. PZTs A and B were collocated and attached on the other side of the plate. In this experiment, a commercial cyanoacrylate adhesive is used to attach the PZTs on the plate. Using the 16-bits AWG, chirp input signals range from 15kHz to 25kHz with a ±10 peak to peak voltage are generated to excite the PZT wafers. In order to improve the signal-to-ratio, 10 times average was performed in the frequency domain. Using three multiplexers, integration of self-sensing circuit was carried out and the switching of the actuation and sensing PZTs was accomplished. More details about the self-sensing circuit is presented in the following section. In addition, all operations for actuation and sensing are controlled by the LabVIEW software installed in the NI (National Instrument) controller.

All investigated test specimens which PZTs A and B were collocated and attached on the opposite sides of the plate are shown in Figure 3.12. In this test, the damage I, which is crack-induced along the horizontal direction of the specimen, is the simplest case and the damage III, which is crack-induced identically from the PZT case is the most severe damaged case.
Figure 3.11 Overall experimental set-up and test specimen: (a) Data acquisition system; (b) Test specimen: an aluminum plate with a single of collocated PZTs.

Figure 3.12 Investigated intact and three damage cases. All dimensions are in mm. Each notch is 3 mm deep, 30 mm long and 1 mm wide: (a) Intact case; (b) Damage case I; (c) Damage case II and (d) Damage case III.
3.3.2 Self-sensing circuit

The circuit scheme for acquiring impedance signals is shown in Figure 3.13. Here, a voltage divider circuit is used to allow measurement of the piezoelectric voltage across the PZTs. Such a circuit is called a self sensing circuit as it allows simultaneous actuation and sensing using a reference capacitor (Dosch, et al. 1992 [37]; Lee and Sohn, 2006 [38]). When a known input voltage (Vi) is applied to the PZT bonded on a plate, the output voltage (Vo) can be measured by using a reference capacitor (Cr) and the current flowing through the PZT is estimated from the Ohm’s law. Therefore, the electrical impedance of the PZT is calculated and the mechanical responses of the system are obtained from information of the electrical impedance of the PZT. The electrical impedance, which is related to the capacitance of the PZT (C_p) and the reference capacitance (C_r), can be calculated in Equation 3-10:

\[ Z(\omega) = \frac{1}{(C_p + C_r) V_o(\omega)} \frac{V_i(\omega)}{V_o(\omega)} \]  (3-10)

Here, Z stands for the electrical impedance of the PZT and the electrical impedance is a function of frequency \( \omega \).
Figure 3.14 illustrates four types of voltage divider-based self-sensing circuit depending on measured signals. Figure 3.14 (a) shows the circuit for excitation at PZT A and sensing at PZT B. Also, Figure 3.14 (b) shows the circuit for excitation at PZT B and sensing at PZT A. Figure 3.14 (c) and (d) represents the circuit for only $S_0$ mode and $A_0$ mode excitation, respectively. For the only $S_0$ mode generation, Figure 3.14 (c) illustrates the circuit for excitation at both PZTs A and B and sensing at PZT A or PZT B. On the other hand, for the only $A_0$ mode generation, Figure 3.14 (d) illustrates the circuit for excitation at both PZTs A and B and sensing at PZT A or PZT B. The difference between the two circuits is the excitation position of PZT B. From the self-sensing circuit using three multiplexers, automated switching system is successfully performed.
3.3.3 Experimental results

In this section, experimental results on the aluminum plates are described. In Figure 3.15, admittance signals from $E_{AA}$ to $E_{A0B}$ are instantaneous measured from intact and damage III cases. In the intact case, the signal $E_{AA}$ and $E_{BB}$ are supposed to be identical since two PZT sensors are situated at the same location. However, a little initial difference between signals $E_{AA}$ and $E_{BB}$ was observed even in the absence of a crack. In the damage case III, it can be shown that signal-shifts between those two signals were observed.

Figure 3.15 Comparison of raw admittance signals obtained from experiments: (a) Intact case without a notch; (b) Damage case III with a notch
Figure 3.16 Comparison of decomposed individual admittance signals: (a) Intact case without a notch; (b) Damage case III with a notch

Figure 3.16 shows the decomposed individual modes $E_{(So)}$, $E_{(Ao)}$, $E_{(MC)}$ in intact and damage III case. It is noticeable that the resonant peaks of the decomposed $E_{(So)}$ through the frequency range are few compared to those of the decomposed $E_{(Ao)}$. In the decomposed mode conversion signal $E_{(MC)}$, it is revealed that the amplitude in undamaged case did not change much because they were not related to mode conversion. On the other hand, the appearance of mode conversion is clearly observed in the damage case III.
3.3.4 Instantaneous damage classification

In this section, based on the decomposed mode conversion signals between the intact and damage cases, instantaneous damage diagnosis is implemented by comparing the energy level of the damaged case with the intact case. Figure 3.17 shows the reconstruction errors occurred due to initial errors in intact and damage case III. From comparison between both the reconstruction signals, the energy levels of the signals do not have a large difference.

![Graphs showing reconstruction errors](image)

Figure 3.17 Comparison of reconstruction errors between intact and damage cases: (a) Intact case without a notch; (b) Damage case III with a notch
Table 3.2 shows the energy levels obtained from RMS approach in all investigated cases. Even though the locations of the notch are different, RMS value of mode conversion is commonly larger than that of error in damage cases.

Figure 3.18 indicates the instantaneous damage classification results. The left bar indicates the energy level of error and the right bar represents the energy level of the mode conversion. In the undamaged plate, the energy of errors is larger than those of three damaged cases. Whereas, the energy levels of the mode conversion are larger than that of mode conversion in all damaged cases. In intact case, since ‘Error’, which indicates the energy level of reconstruction error, is larger ‘MC’, which is the energy level of decomposed mode conversion signal, it can be stated that the plate does not have a crack and the condition of the plate is instantaneously diagnosed as “Healthy condition”. On the other hand, the energy levels of the mode conversion in all damaged cases are much larger than that of error, theses are classified to be damaged.

<table>
<thead>
<tr>
<th>Cases</th>
<th>Root Mean Square (RMS) ($\times 10^{-7}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Error</td>
</tr>
<tr>
<td>Intact</td>
<td>1.27</td>
</tr>
<tr>
<td>Damage case I</td>
<td>1.07</td>
</tr>
<tr>
<td>Damage case II</td>
<td>0.86</td>
</tr>
<tr>
<td>Damage case III</td>
<td>0.89</td>
</tr>
</tbody>
</table>
Figure 3.18 Instantaneous damage classification: (a) Intact case; (b) Damage I case; (c) Damage II case; and (d) Damage III case (a structure is classified as damaged only when ‘MC’ becomes larger than ‘Error’)

3.4 Limitations

Although the reference-free impedance-based crack detection technique has lots of advantages, there are some limitations of this technique. First, it is vulnerable to initial errors due to imperfect PZT arrangement caused by the necessity of exactly same bonding locations on both sides of the structure. Second, this technique is limited to simple plates so that it has difficulties to apply to more complex structures.
CHAPTER 4
THE ENVIRONMENTAL EFFECTS ON REFERENCE-FREE DAMAGE DIAGNOSIS

In the previous chapter, the impedance-based reference-free damage detection technique using a single pair of collocated PZTs is developed. In this chapter, environmental and operational effects on the proposed reference-free damage detection technique are investigated. As mentioned earlier, in-service structures are subjected to changing environmental and operational conditions that affect measured signals, and these ambient variations of the system often make it hard to detect the structural damage. In this study, in order to investigate the effects of operational variability on the reference-free impedance-based damage detection technique, temperature variation and external dynamic loadings are investigated.

4.1 The Effect of Varying Temperature

4.1.1 Experimental setup

The overall experimental setup for temperature variation and external dynamic loading using a single pair of collocated PZTs is shown in Figure 4.1. The specifications of the data acquisition system are the same as in the previous section. A thermocouple was used for precise temperature measurement of the specimen and temperature chamber was controlled from -30°C to 70°C. Humidity was kept at 30% for only investigating
temperature effects on impedance signals. Since high temperature can have affect electric cables and adhesive tapes, resistive cables and Teflon tapes of 3M 5451 type were used for preventing undesirable signal variations. 10 times frequency average was performed to improve the signal-to-noise ratio. The investigated specimens were the same as the previous test.

Figure 4.1 Experimental setup for temperature variation: (a) Overall test configuration; (b) Test specimen in the temperature chamber

### 4.1.2 Experimental results

In this section, test results with temperature variations are presented. Figure 4.2 shows the decomposed individual admittance signals in the intact and damage III cases with varying temperature. Note that the driving frequency range of the chirp excitation input signal was set from 15 kHz to 25 kHz. In order to clarify the figure clearly, each mode is plotted in the zoomed-in frequency range. It is noticeable that the admittance
signals of each individual mode change depending on temperature variation. The amplitude of the admittance signals in both the intact and damage III cases at higher temperature (70°C) was higher than those of the admittance signals at -30°C and 20°C. In addition, left-ward shift was identified as temperature increases. In the decomposed mode conversion signals, peaks caused by mode conversion were clearly identified although temperature variations affect the amplitude of the decomposed admittance signals.

Figure 4.2 Comparison of decomposed individual modes of admittance signals obtained from experiments with temperature variations: (a) Intact case without a notch; (b) Damage case III with a notch
Table 4.1 Energy level of error and mode conversion with temperature variations and instantaneous damage classification

<table>
<thead>
<tr>
<th>CASE</th>
<th>Temp. (°C)</th>
<th>Damage Index (×10^-7)</th>
<th>Damage Classifier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>MC</td>
<td>Error</td>
</tr>
<tr>
<td>INTACT</td>
<td>-30</td>
<td>0.38</td>
<td>0.57</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0.53</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>1.11</td>
<td>1.68</td>
</tr>
<tr>
<td>DAMAGE I</td>
<td>-30</td>
<td>0.61</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>1.25</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>1.91</td>
<td>1.53</td>
</tr>
<tr>
<td>DAMAGE II</td>
<td>-30</td>
<td>0.54</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>1.06</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>1.42</td>
<td>0.74</td>
</tr>
<tr>
<td>DAMAGE III</td>
<td>-30</td>
<td>0.57</td>
<td>0.37</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>1.85</td>
<td>0.62</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>2.56</td>
<td>1.04</td>
</tr>
</tbody>
</table>

Table 4.1 shows the results of instantaneous damage classification based on energy comparison. It shows that the overall RMS values, which indicate the energy levels of the decomposed mode conversion signals, increase as temperature goes up in both intact and damage case III. However, in all the cases with temperature variations, the damage classification provides correct results because all 6 admittance signals are obtained at the same time. Therefore, it proves that the proposed reference-free impedance based damage detection technique remains robust to temperature variation.
4.2 The Effect of External Dynamic Loading

4.2.1 Experimental setup

Most in-service structures can be affected by external dynamic loads and cause false alarms due to misclassification for damage detection. In this subsection, experimental verification of the proposed reference-free damage diagnosis technique under ambient vibration was carried out. Figure 4.3 shows the overall experimental configuration. In order to induce ambient vibration, arbitrary dynamic loads with 500 Hz of frequency were made by the function generator acted on the specimen by the shaker as shown in Figure 4.3 (b). 10 times average was performed in the frequency domain to improve the signal-to-noise ratio. In addition, 4 holders located at each corner shown in Figure 4.3 (b) were used to prevent movements of the aluminum specimen. The investigated specimens were the same as the previous tests.
4.2.2 Experimental results

In this subsection, test results with external dynamic loading are presented. Figure 4.4 shows the comparison of the decomposed individual signals between pristine condition and ambient vibration condition in the intact and the damage III case. Note that ‘Unstressed’ indicates the measured admittance signals in the pristine condition and ‘Stressed’ denotes the signals in the ambient vibration condition. The overall admittance signals in both cases are almost same except for the differences in the amplitude of the
decomposed admittance signals. In the decomposed mode conversion signals, a little of mode conversion due to initial errors was observed in intact case and peaks caused by the crack were clearly identified although external loadings affect the amplitude of the decomposed admittance signals in damage case III.

Table 4.2 shows the energy levels obtained from RMS approach in all investigated cases. Even though the locations of the notch are different, RMS value of mode conversion is commonly larger than that of error in damage cases.

Table 4.2 Energy level of error and mode conversion under external dynamic loading

<table>
<thead>
<tr>
<th>Cases</th>
<th>Error ($\times 10^7$)</th>
<th>MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact</td>
<td>1.03</td>
<td>0.82</td>
</tr>
<tr>
<td>Damage case I</td>
<td>0.84</td>
<td>1.37</td>
</tr>
<tr>
<td>Damage case II</td>
<td>0.63</td>
<td>0.94</td>
</tr>
<tr>
<td>Damage case III</td>
<td>0.80</td>
<td>2.16</td>
</tr>
</tbody>
</table>

Figure 4.5 shows the instantaneous damage classification results under external loading conditions. In the undamaged plate, the energy of the error is larger than that of the mode conversion. Whereas, the energy levels of the mode conversion are larger than that of mode conversion in all damaged cases. Therefore, it proves that the proposed reference-free technique can diagnose the existence of a crack regardless of being under external loading conditions.
Figure 4.5. Instantaneous damage classification under external loading conditions: (a) Intact case; (b) Damage I case; (c) Damage II case; and (d) Damage III case.
CHAPTER 5
CONCLUDING REMARKS

5.1 Executive Summary

The major objective of this thesis is development of robust impedance-based damage detection techniques considering temperature and loading effects. This thesis proposes two technical developments to overcome the limitations of the previous impedance-based methods. The main achievements of this study are summarized as follows:

1. Application of data normalization technique to impedance-based damage diagnosis method: data normalization technique, which isolates structural damages of the structure from environmental effects including temperature variation and loading conditions, is investigated on impedance signatures using unsupervised support vector machine. In addition, experimental studies are carried out to demonstrate the effectiveness of the novelty technique against temperature and loading conditions.

2. Development of reference-free impedance based crack detection technique: A new impedance-based reference-free damage detection technique using PZTs polarization characteristics is developed by utilizing a layout of a single pair of collocated PZTs on plates. The developed technique is theoretically investigated and it is also verified the effectiveness through numerical and experimental tests. By using an energy-based novelty damage classifier, damage classification is accurately performed.

3. Investigation of temperature and loading effects on the reference-free impedance-
Chapter 5 Concluding remarks

Based crack detection technique: The robustness of the proposed reference-free technique is identified and demonstrated through temperature and external dynamic loading tests. It turned out that the proposed reference-free technique is valid regardless of temperature and loading variations.

In summary, the robust impedance-based damage detection techniques against environmental and operational variations are developed and the verification of the proposed technique is implemented successfully. These developed techniques considering temperature and loading effects are expected to give a great contribution for overcoming the limitations of conventional impedance-based damage detection technique in fields of civil infrastructure, mechanical machine and aircraft health monitoring.
5.2 Future Study

Further studies are planned to apply the proposed techniques to real structures. The final destination of SHM / NDT is the prediction of unexpected accidents in advance using some novelty damage detection techniques. To satisfy the goals of SHM / NDT, some possible improvement studies are proposed and listed as follows:

(1) In data normalization technique, applications to real structures such as bridge, mechanical machine and aircraft will be performed to identify the applicability of this data normalization method. Also, other damage types like crack, debonding and corrosion will be investigated.

(2) In reference-free damage detection technique, the technique will be extended to real structures such as critical points of bridge and wing section of aircraft. Also, investigation of other damage types like bolts-loosen and corrosion cases will be studies for reliable on-line health monitoring.

(3) From the fundamental finding that impedance method is quite associated with Lamb wave based method, more robust damage detection techniques incorporating those two techniques will be developed and applied to lab and real structures.
SUMMARY (IN KOREAN)

요 약 문

온도 및 하중 영향을 고려한 임피던스 기반의
향상된 손상 감지 기법

본 논문에서는 압전센서(Piezoelectric sensors)를 활용한 임피던스 기반의 새로
운 구조물 손상 감지 기법을 다루고 있다. 과거 임피던스 기반 손상 감지 기법은 과
거 기저 자료와 현재 측정된 신호를 비교하여 구조물의 현재 상태를 진단할 수 있는
기법이었다. 하지만 손상 감지에 사용되는 구조물의 임피던스 신호는 측정 장소의 온
도 및 외부 하중 등의 환경 잡음에 의해 크게 변화하여 손상이 없는 경우라도 손상이
발생한 것으로 오보가 발생하는 경우가 많다. 또한, 기준 데이터로 사용하는 기저 자
료는 구조물의 생애 주기 동안 상시적으로 변하기 때문에 기존의 임피던스 기반 손상
기법은 신뢰성 측면에서 한계를 가진다.

본 논문에서는 이러한 임피던스 기반 손상 감지 기법의 한계점을 극복하기 위하여
다음과 같은 연구를 수행하였다.

(1) 임피던스 신호를 이용한 데이터 정규화 기법의 적용: 데이터 정규화 기법은
환경 잡음(온도 및 하중 변화)에 의한 영향을 실제 구조물의 손상 정보부터
분리 시킬 수 있는 방법으로서, 이 논문에서는 패턴 인식 기법의 한 종류인
Kernel 주성분 분석을 이용하여 온도 및 하중 영향에 관계없이 구조물의
손상을 감지하는 데이터 정규화 기법을 적용하였다. 온도 및 하중 영향 설
험을 통하여 본 데이터 정규화 기법의 효용성을 검증하였다.
(2) 임피던스 기반의 무 기저 손상 감지 기법 개발: 임피던스 신호에 기반하여 기저 자료와 현재 측정된 신호의 비교 없이 현재 측정된 신호만으로 구조물의 손상 여부를 진단할 수 있는 무 기저 임피던스 손상 감지 기법이 개발되었다. 이 기법은 압전 센서가 가지는 극성을 이용하여 한 쌍의 압전 센서를 구조물의 양면에 배치하여 구조물의 손상 여부를 판정하는 것으로 Guided wave와 임피던스의 개념적 상관 원리를 바탕으로 한 새로운 개념의 손상 감지 기법이다. ABAQUS를 이용한 수치해석과 다양한 균열 손상을 가진 시편을 이용한 실험 연구를 통하여 본 기법의 효용성을 검증하였다.

(3) 온도 및 외부 하중 실험을 통한 무 기저 기법의 외부 환경적 영향 검증: 무 기저 손상 감지 기법의 주요 목적은 외부 환경적 영향으로부터 독립적으로 구조물의 손상을 감지하는 것이다. 이를 검증하기 위해 온도 변화 및 외부 하중 실험이 수행하였다. 실험 결과를 통하여 본 무 기저 임피던스 기법은 운도 및 외부 하중 영향과 관계없이 손상 감지가 가능함을 검증하였다.

본 연구는 환경적 영향을 고려한 임피던스 기법을 개발하고 이 기법들의 실험적 검증에 관해 다루고 있다. 제시된 임피던스 기반의 손상 감지 기법은 향후 토목, 기계 및 항공 구조물의 손상 감지 분야에 크게 기여할 것이라 기대한다.
REFERENCES


References


[34] Cho, Y. “Estimation of Ultrasonic Guided wave Mode Conversion in a Plate with Thickness Variation,” IEEE transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 47, pp. 591-603, 2000


감사의 글

‘할 수 있다’는 믿음으로 시작한 대학원 생활이 어느덧 1 년 6 개월이란 시간이 지났습니다. 이 기간 동안 좌절과 시련도 있었지만 성과 과정을 무사하마침 수 있도록 협이 와어 준 이들이 있어 감사의 뜻을 전합니다.

우선 인생의 선배이자 학문적 스승으로서 저의 부족함에도 믿고 겪려 주신 지도교수님 손 혜 교수님께 깊은 감사의 뜻을 전합니다. 교수님께의 배려와 충고가 있었기에 지금의 제가 있을 수 있었습니다. 또한 연구를 수행할 수 있도록 지원해 주신 한국과학재단 (NRL), 국방과학연구소 (ADD), 그리고 KAIST의 스마트 사회기반시설 연구센터 (SISTeC)에 감사드립니다.

불철주야 연구에 매진하는 연구실 동료들에게 감사합니다. 연구실 랩장으로서 부족한 저를 지켜봐 주신 준 윤규형, 항상 든든한 맛형으로 우리에게 웃음을 주신 이재형, 학문적으로 조언을 주신 미국에 계신 상준이 형, 그리고 카이스트에서 6 개월 동안 동고동락한 Debaditya, 램의 흥일점으로 램 살림을 맡아 준 선혜에게 감사의 말을 전합니다.

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