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Development of New Structural Health Monitoring Techniques

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DEVELOPMENT OF NEW STRUCTURAL HEALTH MONITORING

TECHNIQUES

A dissertation submitted in partial fulfillment of
the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

MECHANICAL ENGINEERING

by

Hadi Fekrmandi

2015
To: Dean Amir Mirmiran  
College of Engineering and Computing

This dissertation, written by Hadi Fekrmandi, and entitled Development of New Structural Health Monitoring Techniques, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this dissertation and recommend that it be approved.

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DEDICATION

To my wife Arlen and my parents, Ali and Zahra.
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ABSTRACT OF THE DISSERTATION

DEVELOPMENT OF NEW STRUCTURAL HEALTH MONITORING TECHNIQUES

by

Hadi Fekrmandi

Florida International University, 2015

Miami, Florida

Professor Ibrahim Nur Tansel, Major Professor

During the past two decades, many researchers have developed methods for the detection of structural defects at the early stages to operate the aerospace vehicles safely and to reduce the operating costs. The Surface Response to Excitation (SuRE) method is one of these approaches developed at FIU to reduce the cost and size of the equipment. The SuRE method excites the surface at a series of frequencies and monitors the propagation characteristics of the generated waves. The amplitude of the waves reaching to any point on the surface varies with frequency; however, it remains consistent as long as the integrity and strain distribution on the part is consistent. These spectral characteristics change when cracks develop or the strain distribution changes. The SHM methods may be used for many applications, from the detection of loose screws to the monitoring of manufacturing operations.

A scanning laser vibrometer was used in this study to investigate the characteristics of the spectral changes at different points on the parts. The study started with detecting a load on a plate and estimating its location. The modifications on the part with manufacturing operations were detected and the Part-Based Manufacturing Process
Performance Monitoring (PbPPM) method was developed. Hardware was prepared to demonstrate the feasibility of the proposed methods in real time.

Using low-cost piezoelectric elements and the non-contact scanning laser vibrometer successfully, the data was collected for the SuRE and PbPPM methods. Locational force, loose bolts and material loss could be easily detected by comparing the spectral characteristics of the arriving waves. On-line methods used fast computational methods for estimating the spectrum and detecting the changing operational conditions from sum of the squares of the variations. Neural networks classified the spectrums when the desktop – DSP combination was used. The results demonstrated the feasibility of the SuRE and PbPPM methods.
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1. INTRODUCTION

1.1. Structural Health Monitoring

Structural health monitoring (SHM) is a growing field that attracts a considerable research effort from scientists all over the world. Only in the United States are the maintenance and scheduled inspection of aging civil structures, industrial equipment and machinery costs more than $200 billion every year [1]. Structural health monitoring has multiple aspects and applications.

In condition-based monitoring (CBM), the goal is to replace the schedule-based maintenance with condition-based maintenance. This way, unnecessary maintenance sessions and consequent costs involved with the shutdown of the system would be eliminated. A new trend is to include the sensors and embedded monitoring systems within the structure from design and manufacturing stages. Such approach for health monitoring not only could reduce the installation costs of the SHM system and increase the reliability and safety, but also optimize the final weight, size and cost of systems. In prognostics and health management (PHM), the purpose is to diagnose the pattern of creation and development of defect in structure through proper data analysis and interpretation. This knowledge is used to predict the remaining life of the engineering structures. Such approach is especially important for aging structures and allows many civil and aerospace structures to stay in service beyond their original design life cycle.

SHM methods may be divided in two main groups: passive and active methods [3]. Passive-methods use one or multiple sensors to monitor temperature, acceleration, stress or other physical characteristics to identify the problems. The Impedance [4,5] and Lamb-wave [1,6] methods are very widely studied active SHM methods. Active-methods
excite the system with vibrations, heat, forces or other physical inputs. Problems are detected by evaluating the monitored signals of the sensors attached to the structure. Active SHM systems are similar to non-destructive evaluation (NDE) methods. Both categories of techniques are trying to detect the presence and extent of damage in the structure. The only difference is that the advances in sensors and embedded electronic systems have made it possible to have them be permanently installed on the structure and provide online information about its status. However, the size and cost of conventional NDE transducers impedes them being used directly installed on structure for SHM purposes. Piezoelectric elements and recently developed miniature actuators/sensors allowed the implementation of SHM methods in many applications. Structural health monitoring using piezoelectric elements is performed via multiple approaches [2]: (a) wave propagation (b) frequency response function (c) electromechanical impedance.

1.2. Rayleigh-Lamb Surface Guided Waves

Guided waves are elastic waves that propagate in solid structures. Lamb waves are a type of guided wave that propagates in plate and shell-like structures with free surfaces. The mathematical analysis of Lamb waves was developed and published by H. Lamb in 1917 [7]. Based on the pattern of motions, Lamb waves could be divided into two categories of symmetric and anti-symmetric waves (Figure 1-1).
Rayleigh waves are another type of guided wave that travels close to the surface of solid structures [8]. They include both longitudinal and transverse motions and could be generated by piezoelectric-based transducers. Guided waves particle motion happens on a single surface. Worlton produced guided waves for the first time experimentally in 1961 [9] and realized their potential application in non-destructive tests. Mindlin, in 1951 [10], completed a comprehensive theory for elastic waves and the governing equation of motion was presented in the form of:

Equation 1-1: \[
(\lambda + \mu)\nabla \cdot \mathbf{u} + \mu \nabla^2 \mathbf{u} = \rho \ddot{\mathbf{u}}
\]

Where \(\mathbf{u}\) is the displacement vector along the 3-axis coordinate system. \(\lambda\) and \(\mu\) are Lame’s constants for the isotropic material while \(\rho\) is the density. Mindlin used the Helmholtz decomposition method to split the equation into scalar and vector components. Then, considering the directional propagation of the waves, he found the harmonic solution for the set of differential equations. Applying the traction-free boundary
conditions, and the zero determinate condition for the non-trivial solution of matrix equations led to the Rayleigh-Lamb equations:

Equation 1-2: $$\frac{\tan \beta b}{\tan \alpha b} = \left[ \frac{-4\alpha \beta \xi^2}{(\xi^2-\beta^2)} \right]^{\pm 1}$$

Here, b is the thickness of the plate, and α and β are constants based on the bulk longitudinal and shear wave speeds, respectively.

These equations yield the relation between the excitation angular frequency $\omega$ and the phase velocity $c_p = \omega / \xi$ which is called dispersion property. This means that the wave velocity is dependent on the frequency of the wave. This phenomenon could be presented by dispersion curves [Figure 1-2].

![Dispersion curves for symmetric and anti-symmetric lamb waves](image)

Figure 1-2 Dispersion curves for symmetric and anti-symmetric lamb waves [1]. Surface-guided waves are employed in structural health monitoring due to their unique property of being able to travel long distances with minimal dissipation. This allows for monitoring a large area on the target structure from a single sensor point while
limiting the number for sensors required to establish the SHM sensor network. In the lamb-wave-based damage detection techniques, knowing the propagation velocity of the certain frequency of guided wave, it is possible to detect the surface damages by monitoring the delay from a returning pulse [6].

1.3. Electromechanical Impedance Method

The Electromechanical Impedance (EMI) method is a new emerging structural health monitoring method. It has been proven that the presence of damages and structural defects causes the mechanical impedance of structure to change. However, it is very difficult to directly measure the mechanical impedance of structures with different shapes and configurations. On the other hand, piezoelectric transducers are used to indirectly measure this quantity [5, 62, 108]. Once a piezoelectric transducer is bonded to the mechanical structure, an electromechanical coupling exists between the electrical impedance of the piezoelectric transducer and the mechanical impedance of the structure. The electromechanical admittance $Y$ depends on mechanical impedances of monitored structure $Z_M$ and the piezoelectric transducer $Z_a$ according to work by Sun et al. [108]:

\[
Y = j\omega \left[ \varepsilon^T_{33} - \frac{Z_M}{Z_M + Z_a} d_{31}^2 Y^E_{111} \right]
\]

The superscripts E and T stand for mechanical stress and electric field. $Y^E_{111}$ is Young’s modulus, $\varepsilon$ is electric permittivity and $a$ is geometric constant of the piezoelectric transducer.

Park and Inman [112] determined the electromechanical impedance by directly measuring the voltage and current from the PZT element (Figure 1-3).
In SHM of aerospace structures, promising results have been obtained in detecting damages by the EMI method in the vicinity of piezoelectric transducers. However, for failures distant from the piezoelectric transducer, the method showed to be insensitive. In fact, the effective range is in millimeters and centimeters rather than meters [109]. The introducing damage to structures causes the impedance diagram to change, which is manifested by frequency shifts in some peaks, emerging of new peaks and increase of some peaks’ amplitudes [1].

A key issue in the correct estimating the size of failure in the EMI method is the proper selection of frequency range [110]. Various types of flaws including fatigue cracks and corrosion in aluminum riveted panels [111], delamination in composite patches [110] and loosenings in piping bolt joints [112] can be identified using this method. The majority of literature results have been obtained using laboratory the impedance analyzer, which is considerably expensive and bulky, and the practical implementing the method is pending on further hardware and software developments [27]. For measuring the impedance of the host structure using the EMI method, both direct piezoelectric effect (Figure 1-4) and inverse piezoelectric effect are used.
First, the structure is excited based on the inverse piezoelectric effect, where the strain is produced in the transducer due to electrical charge and the strain is transferred to the structure due to the bonding. Then, the electrical impedance is quantified based on the direct piezoelectric effect, where electrical charge is induced in piezoelectric elements due to the presence of strain. The electromechanical impedance is determined by directly evaluating the voltage and current from PZT [112].

Analytical models for simulating the electromechanical impedance method are limited to simple structures like plate, beam and rod [37, 38]. Numerical modeling of the EMI method has been subjected to previous studies in order to predict the crack growth or find the location of PZT transducers on the surface of the structure. Coupled field analysis, which takes both mechanical motions and electrical characteristics into account, was found to be the most efficient method for modeling complex structures [39, 40].

The surface response to the excitation method (SuRE) [29] monitors the health of the structure using characteristics similar to the EMI method. A piezoelectric element excites the surface waves and another piezoelectric element monitors the surface waves in another point on the structure. Piezoelectric elements are inexpensive and their

Figure 1-4 The contraction and expansion of PZT material due to direct piezoelectric effect
sensitivities are very high. However, it is not practical to attach tens of piezoelectric elements to the surface to evaluate the surface response characteristics of many points. In this study, the scanning laser vibrometer (SLV) was used to evaluate the surface response characteristics at a grid of scan points. The SLV uses the Doppler effect to measure the surface oscillations and its sensing mechanism is illustrated in Figure 1-5.

![Figure 1-5 scanning laser vibrometer structure and sensing mechanism](image)

The method has proved to be effective in detecting a variety of structural defects, including tool wear [31], loose bolts [32] and compressive loads in beam [33] and plate [34] structures. The SuRE method requires a separate sensor in addition to the piezoelectric actuator. This technique, which has been used for the experimentations of this study, will be further discussed in chapter 3.
1.4. Manufacturing Process Monitoring

For many years, monitoring technology was limited to expensive aerospace industries. Recently, due to advances in computer systems, sensor technology and data processing, it is possible to develop specialized monitoring systems for other fields, including automated manufacturing. In classical tool condition monitoring (TCM) [35], several parameters like cutting force, vibration and temperature have been used to monitor the tool life (Figure 1-6).

![Diagram of tool condition monitoring process]

Figure 1-6 The framework of tool condition monitoring [114]

The new trend in manufacturing monitoring is the machining process monitoring (MPM), where the goal is to monitor the entire machining process to increase the quality and accuracy of the final product while reducing costs originating from tool failure and machine shut-down time [114]. MPM is needed not only to increase the productivity and product quality, but also to identify the risks to damage of the work-piece and machine components.

Manufacturing society has been using methods similar to SHM techniques for process monitoring. Recently, part-based manufacturing process performance monitoring (PbPPM) was introduced to monitor the manufacturing process based on the data collected directly from work pieces [36]. The purpose of this method is to detect various
manufacturing malfunctions, including tool breakage, chatter, manipulator out of calibration, and surface roughness by only monitoring the work-piece.

Part based Process Performance Monitoring (PbPPM)

![Diagram of process steps: Block -> Machining -> Welding -> Drilling -> Coating -> Final Product]

Figure 1-7 part-based process performance monitoring (PbPPM)[36]

1.5. Organization of the thesis

This dissertation consists of eight chapters. At the beginning, we will illustrate the potential of the surface response to the excitation method for SHM and MPM by using the finite element method. Then, the SuRE method, will be implemented using the scanning laser vibrometer to improve its capabilities. Later, this method will be used to monitor the machining applications. The performance of a digital signal processing-based device developed for implementing the SuRE was compared to laboratory equipment results.

- In chapter 1, an introduction to the structural health monitoring and the contribution of techniques of this study is presented.
- In chapter 2, the state of art in structural health monitoring (SHM) and manufacturing process monitoring (MPM) is presented.
• In chapter 3, the surface response to the excitation method is introduced and signals, computational methods, signal processing, experimental set-up and implementation techniques are discussed.

• In chapter 4, COMSOL is used to simulate the surface response to excitation method in a frequency domain study and evaluate its potential application for manufacturing process monitoring.

• In chapter 5, the loading condition detection capability of the SuRE method is assessed using the scanning laser vibrometer and then applied to examine the integrity of loose bolts.

• In chapter 6, the SuRE method is evaluated for remote performance monitoring of manufacturing machining operations, including drilling, cutting and milling.

• In chapter 7, the performance of the SuRE method, the reliability of each implementation technique and the computational accuracy of its algorithms are compared to each other.

• In chapter 8, the pros and cons of the SuRE method for SHM and Part-Based MPM are presented and the potential for future work is discussed.
2. REVIEW OF PREVIOUS WORKS

In this chapter, a literature survey over the state of the art of structural health monitoring using high-frequency surface guided waves is presented. An overview of the most impactful and recent studies for numerical simulations, measurement techniques, damage detection algorithms, signal processing methods, decision making strategies and machining monitoring systems is covered.

2.1. Major SHM methods for aerospace applications

The propagation of elastic surface guided waves on the structures has been studied extensively and structural health monitoring (SHM) systems have been developed [41]. Guided Lamb-wave-based methods [42,41] and electromechanical impedance (EMI)-based methods [58,59] are the most commonly used active SHM methods.

The surface guided waves (Lamb waves) are introduced to the structure through a piezoelectric actuator in the Lamb wave approach and the propagation of them is monitored at the same and/or additional point(s) via sensor(s). Structural problems are detected from the change of the characteristics of the monitored signals. Generally, development of additional wave patterns and their delays indicated the presence of defects and their locations. A comprehensive state of art for these methods is presented at reference [42]. This approach can be used for many large structures, since the generated Lamb waves are capable of traveling along the plates of many materials with very little attenuation [43, 44, 45]. However, the difficulty of sampling such a high speed wave, following multiple wave modes, complexity of wave propagation and reflections from boundaries creates significant challenges for the researchers [46].
The second major SHM approach is the impedance method [5]. This approach evaluates the impedance of a piezoelectric element attached to the surface of the structure. Experimental studies have shown that the impedance characteristics within a carefully selected frequency range change, when various defects are created at the structure or loading changes. Most of the researchers used the impedance analyzer, which automatically generates the signal and analyzes the collected data.

Tansel et al. [47] developed the surface response to excitation method (SuRE) to evaluate the same characteristics by using a simpler experimental setup. The SuRE method evaluated the surface-response characteristics similar to the EMI, but required simpler instrumentation. A piezoelectric element excites the surface and the surface response is evaluated with a similar piezoelectric sensor. The EMI and SuRE methods calculate the sum of the squares of the differences of the real part of the impedance and magnitude of the transfer function, respectively. The impedance method is more sensitive to the loading conditions compared to the Lamb wave method. In the impedance method, only a single piezoelectric element is used both for exciting and sensing. Detecting a point load on the structure could be used for detecting the loose bolts in the joints. This way, the integrity of structural bolt joints could be examined using this method and any possible loose components could be identified.

Most of the researchers have used the laser vibrometers for health monitoring by evaluating the modal parameters like mode shapes, natural frequencies and damping ratios [1-48]. Sharma [49] used the scanning laser vibrometer to get information to calculate the strain energy distribution for defect detection. Staszewski et al [50-51-52] have used the laser vibrometer to capture the Lamb waves to evaluate the integrity of an
aluminum plate. Marterelli [53] also made important contribution to laser-based scanning. Leong et al. 52] used SLV in an effort to detect fatigue cracks using high-frequency guided waves. In their study, the Lamb wave method was used.

Since the impedance method uses only a single piezoelectric element, it is not possible to implement this technique using non-contact SLV sensors. However, separating the sensor and exciter in the SuRE allows the SLV to collect data from a virtually infinite number of points. This way, the SuRE will have both advantages of the Lamb and the impedance method. Like the Lamb wave method, The SuRE method will cover large areas since it uses surface guided waves and at the same time it will be able to detect the loads since it has similar characteristics to the impedance method. This will be discussed further in chapter 5.

2.2. Inspecting bolts by using SHM methods

Many structural health-monitoring (SHM) techniques are developed to improve the reliability and safety of the systems, while the maintenance costs and service time are reduced. Some of these methods are developed for detecting loose bolts. Bolt joints have been widely used in many civil, mechanical and aerospace structures. In some critical operations, any failure could have catastrophic consequences and manual inspection of the bolts is not feasible. The development of remote monitoring techniques is necessary to address these applications.

Todd et al. [57] evaluated the condition of bolt joints by using the modal parameters. He experimentally found that the modal properties were relatively insensitive to the clamping force as long as they were above a critical level. Todd suggested
evaluating the modal parameters might not be a reliable approach for assessing the condition of the bolt joints. He recommended alternative methods should be considered for developing more sensitive monitoring techniques.

Peairs et al. [13] employed the impedance-based structural health monitoring technique by applying high-frequency excitations through a PZT transducer. He found that the impedance characteristics were sensitive to loosening bolts. Peairs also tried to replace the impedance analyzer with a smaller and more effective device, since it was heavy and bulky. Ritdumrongkul et al. [60] studied the structural integrity of two aluminum beams connected through a bolted joint. They found the EMI method promising; however, it was mentioned that the application of the method to real structures required further study of the characteristics of more complex structures and environmental effects. Chakraborty et al. [61] introduced an advanced time-frequency signal processing technique for detecting loose bolts in complex structures. The method required a significant amount of experimental data for the training of the damage classification algorithm. Chakraborty suggested the use of numerical simulation for preparing training data.

Previous studies have proven that the impedance method performed considerably better for health monitoring of bolted joints like gas pipelines and composite structures [29,62]. The location of the loose bolts could be estimated if multiple elements were installed carefully. In critical applications like the integrity of bolt joints in satellites [63], it was hard to access and impractical to create a large network of PZT sensors.

Liang et al. [63] first developed a one-degree of freedom model for a coupled electromechanical PZT actuator system. The study showed that the change of the
structural impedance would dominate the electrical impedance of the piezoelectric element. Monitoring the impedance of the PZT with an impedance analyzer was enough to determine the condition of the structure. To evaluate the condition of the structure, the real part of the impedance was analyzed, since it was more sensitive to structural damages [64].

In section 5.2 of chapter 5, the integrity of a bolted-joint section of a robot will be inspected by non-contact implementing the surface response to the excitation (SuRE) method using the SLV. The motivation behind this study is to introduce SLV as an alternative to sensor networks. In many critical applications, such as the inspection of the control surfaces of rockets at the launch pad, the use of SLV could be easily justified. The frequency domain methods have not been implemented through non-contact sensors for health assessment of multi-bolt joints in previous studies.

2.3. Detection of structural defects with SHM methods

All guided-wave-based structural health-monitoring methods use some sort of signal processing for sensory data. The objective is to extract some information about the presence and location of damage, type of damage and its severity for prognostics of remaining life. In the Lamb-wave-based methods, the damage is detected by calculating the time delay of the incoming pulse. An effective signal processing method isolates the time-frequency centers of the pulses from propagated waves, specifies their associated modes and addresses the issue of noise in the signal [41]. Although it is possible to borrow some of the techniques from non-destructive evaluation (NDE), the algorithms of SHM must be computationally efficient enough to run real-time.
Preprocessing and data cleansing is necessary, especially where the sensor is susceptible to noise or the feature extraction is not robust to noise. These groups of techniques include statistical averaging [117], wavelet transform and filtering [118], and outlier reduction [119]. A comprehensive review of low-pass filters for data cleansing is presented in the reference [120].

After data cleansing, the proper features and parameters for damage detection are selected and extracted from the signal. Features are the best parameters of signal to represent the health condition of the structure. The Lamb guided wave-based methods are generally categorized into time-frequency analysis and sensor array approaches. In fact, the features are inputs for any pattern recognition algorithm [121]

While Fourier analysis only reveals the frequency content of the signal, it does not provide any information about when each of the components arrived to the sensor. In the time-frequency representations (TFRs), the diagram involves a time axis that actually shows when each of the frequency components entered the signal. These techniques are well suited to Lamb wave methods that work based on sending-receiving pulses and figuring out the damage by calculating the time delay. This is important, especially considering the dispersive property of Lamb-waves where different frequency and mode shapes of guided waves travel with different speeds. Once the time-frequency image is generated, the locations of frequency centers are identified to find the exact time interval (Figure 2-1).
Various techniques [122] have been used to isolate multiple closely space guided wave modes in time and frequency. Recently, wavelet transform has emerged as a very important signal processing technique for feature extraction and the selection of signals [123]. There are two types of wavelet transforms; the continuous wavelet transform is more suitable for time-frequency graph generation while the discrete wavelet transform is mostly suitable for feature extraction and selection.

The second major trend in Lamb-guided wave-based techniques is using an array of sensors on the structure. This allows both time and spatial dimensions to be considered in calculations. The goal is to identify the individual guided wave modes and their corresponding amplitudes at certain propagation distances [124]. Since it has been proven that different modes of guided waves are sensitive to different types of defects, an array of sensors could target various types of structural damages [125]. Some algorithms use a
linear sensor array for directional detection [126]. The idea is to use an appropriate signal processing to find the direction of incoming waves and therefore virtually scan the structure without moving the sensors. Another advantage of this approach is that a radar type of scanning sensors allows keeping the number of sensors minimal [127]. Beamforming [128] is a signal processing technique that is developed based on the linear array of piezo sensors for damage detection and localization. Methods based on beamforming have been able to detect cracks that are not directly located in the field of sensor arrays. Methods based on this technique have been able to locate the damage with exceptional accuracy in isotropic plate structures [129].

Integrated solutions are efficient designs of guided-wave-based SHM systems that include sensors and actuators, wirings and data processing within an embedded system. Among theses technologies are: “SMART Suitcase” [134], Integrated Vehicle Health Management “IVHM” [135] and the diagnostic network patch [136]. Some of the crucial issues involved in development of integrated systems are to include wireless communication capability to address the issues related to wires and local computational power to limit the volume of data required to be transferred. In the case of active SHM techniques, the power supply for actuators is another challenge in front of the embedded solution. (Figure 2-2)
2.4. Automated interpreting SHM signals with neural networks

Pattern is a certain behavior of selected features that could be used to indicate the state of health of structure. Neural networks are one of the most popular pattern recognition techniques used in guided wave-based damage detection techniques in plates. Spectrographic features in the time-frequency domain have been used to train neural networks. Practical application has been proved in composite laminates [130], aluminum T-joints [131] and metallic welds [132]. To overcome the problem of overtraining, the support vector machine (SVM) was used to classify defects in metal matrix composites [133].

Neural networks are systems composed of simple elements operating in parallel. These are inspired in biological nervous systems. The network function is determined by the connections between the elements (nodes). The training of the neural network consists of adjusting the values of the connections between elements (weights) [72]. For computing the weights of these elements several types of algorithms can be used. These
algorithms differ in the activation and training function used for connect nodes of the neural network

The Levenberg-Marquardt algorithm [73] was designed to approach second-order training speed without having to compute the Hessian matrix. When the performance function has the form of a sum of squares (as is typical in training feed forward networks), then the Hessian matrix can be approximated in terms of the Jacobean. For a more detailed discussion of the scaled conjugate gradient algorithm see Ref [74]

The scaled conjugate gradient algorithm is based on conjugate directions, but this algorithm does not perform a line search for each iteration. For a more detailed discussion of the scaled conjugate gradient algorithm see Ref

In order to compare which algorithm has a better performance, the following function to measure the error is used:

\[
\text{Equation 2-1} \quad f_{\text{error}}(Z, \tilde{Z}) = 100 \times \frac{\sum_{i=0}^{n} |z_i - \tilde{z}_i|}{(\max(Z) - \min(Z)) \times n}
\]

where, \(Z\) is target function vector, \(\tilde{Z}\) is neural network output vector and \(n\) is number of points of the matrix of reference.

2.5. Monitoring the performance of machining operations

Machining process monitoring is an essential part of the automated manufacturing processes [75,76]. The purpose is to improve tool maintenance and product quality. The need for manufacturing automation and demand for more sophisticated parts are major reasons for the development of intelligent machine tools. There are still major challenges for the practical application of current monitoring systems due to the reliability and costly
implementation procedure. Many methods have been developed to evaluate the manufacturing operations; however, the complexity and the cost of these systems limit their implementation in industry.

There are two fundamental approaches in the machining condition monitoring field, direct and indirect methods [77,78]. Direct methods such as vision-based or optical methods directly measure the dimensions of the tool or the work-piece to identify the product quality. Their application requires the tool and work-piece to be cleaned from the chips and fluids.

During the metal cutting operation, chips and cooling fluid could easily block the vision of the camera. Due to this reason, although being extremely accurate, the practical application of direct methods has been limited to the laboratory. On the other hand, the indirect methods have the advantage of not interrupting the operation. During the manufacturing operations, several parameters influenced and could be employed for monitoring the state of the tool or metal removal process [79]. Among those parameters measurement of cutting forces [80,81], acoustic emission signal [82,83], ultrasonic signal [84], currents of servo drivers [84] and the combination of them [86] have been used more frequently.

Various signal processing methods could be used to process the data. Wavelet Transform [87,88], Short Fourier Transform [6], Hilbert–Huang Transform [89] and singular value decomposition method [90] were used as processing techniques for the above-mentioned signal readings. Also, in multi-sensor methods, a combination of the sensor data has been used [91] and its sensitivity was compared [92]. The last step in developing a process monitoring technique is to find a decision-making approach. When
developing any machining process monitoring method, the amount of complexity of the system should be considered carefully. Otherwise, the complexity of the system would compromise any future industrial application.

Hsieh et al. [98] applied a neural network method for spindle vibration-based tool wear monitoring in micro-milling. However, their methodology was not able to distinguish if the change in energy level of the other frequency domain signals was due to the worn tool or they were affected by changes in parameters such as material and noise. Cus et al. [99] used the Adaptive Neuro-Fuzzy Interference System (ANFIS) to predict the flank wear of the tool in the end milling process. Neural network was used as a decision-making system to predict the condition of the tool and the cutting forces are used as an indicator of the tool flank wears variation. However, due to the high computational power required for training the neural network, their method required parallel processing for the monitoring of the cutting process with high reliability; they suggested different decision-making tools, such as fuzzy logic, to be applied to obtain a smaller error of detection.

Brecher et al. [103] used NC kernel data for surface roughness monitoring in milling operations. He used experimentation in order to obtain the data to be modeled with artificial neural networks (ANNs) for surface roughness average parameter predictions. The major drawback of the method was that it required performing several prior cutting tests in the corresponding machine tool, cutting tool, tool holder, and material combination. Huang [104] developed an intelligent neural-fuzzy model for an in-process surface roughness monitoring system in end milling operations. The disadvantage of fuzzy-net was that when the number of fuzzy sets was increased, there was a need for
training data to be increased to fulfill all the possible IF-THEN rules. Marinescun. et al. [105] developed an on-line automated monitoring method based on acoustic emission (AE) measurement for surface anomalies during the milling of aerospace alloys. Their method reduced surface anomalies by a process monitoring solution that detects work piece anomalies associated with the cutting tooth of a milling cutter through signal analysis, which causes improvement of fault detection and the avoidance of surface anomalies or tool malfunctions. Although the method was efficient in controlling the tool to minimize process malfunctions in milling operations, it was reported that in higher feeds and speeds, the system was limited by the processing capability of the operating system and amount of data processing needed to detect the malfunctions. Quintana et al. [106] developed a process solution that controls the surface process based on artificial neural network models by capturing the vibrations that occur during metal removal operation with the help of piezoelectric accelerometers. The method calculates the current in-process roughness average, looks at the cutting parameters and applies the neural network developed using dynamic parameters measurement. Like similar methods, an extensive number of experiments is required to be carried out to increase the software performance by training the network on the basis of a large number of experiences. Bisu et al. [107] proposed a method based on the vibration analysis that refers to the spectral envelope based on Hilbert transform, and identifies mechanical defects to obtain a better response on the milling process quality. In chapter 6 of this study, the SuRE method is used to develop an efficient non-contact milling process monitoring.
3. SURFACE RESPONSE TO EXCITATION (SURE) METHOD

3.1. Introduction

The Electromechanical Impedance Method (EMI) monitors the impedance change of a piezoelectric element as it reacts to vibrations in the structure. The Lamb Wave Method monitors the propagations of the waves. It is used to estimate the location of the defects by measuring the delay of the arriving wave; however, it is not as sensitive to the variation of the compressive forces applied to the structure as the Impedance Method. In practice, most of the researchers use an impedance analyzer such as HP 4194A for characterization of the piezoelectric element when implementing the Impedance Method. These impedance analyzers are expensive, their excitation signal power is limited, and the user has limited control over determining the transfer function or excitation signal. They may also have problems when the piezoelectric elements are attached to long wires or there are additional components in the circuit. Analog Devices like 5933/5934 impedance-to-digital converter (IDC) offer another approach to measure impedance; however, IDCs are not as powerful as impedance analyzers. When the impedance analyzers and IDCs are used, the user selects the test frequencies. The device manages signal generation, data collection and analysis. There are two approaches alternative to impedance analyzers. The first approach directly replaces the impedance analyzer with a circuit [12,13,14,15]. A data acquisition system with a programmed real-time analyzer, Digital Signal Processor (DSP) or spectrum analyzer may be used to monitor the characteristics of the piezoelectric element with the help of a relatively simple circuit. The second approach excites a piezoelectric element attached to the structure. The dynamic characteristics of that piezoelectric element and the attached structure are
monitored using second piezoelectric element [16,17,18]. The spectrum analyzer or signal generator-voltmeter combination [17,18] have been used for this approach. Tansel and co-workers called this approach Surface Response to Excitation (SuRE) [30].

3.2. Excitation and sensing of the SuRE method

The Surface Response to Excitation (SuRE) method is an emerging structural health monitoring technique. With similar characteristics to the electromechanical impedance method, the state of health of the structure is determined based on changes in signature characteristic spectrums. The difference is that the signature spectrum is generated as the frequency transfer function between the excitation point and the sensing point. Therefore, in the SuRE method, the excitation and sensing are performed using separate sets of elements. This means that instead of only one piezoelectric transducer making measurement from a single point, the measurements could be captured from any point on the structure.

The SuRE method excites the high-frequency surface-guided waves over a range of high frequencies. The excitation is in fact in the form of sine wave covering from starting frequency to stopping frequency. Usually, the minimum start frequency is 20 kHz, slightly above the audible zone to avoid the hazardous sound in the lab environment. The maximum of the end frequency depends on the maximum speed of analogue to digital conversion available in the data acquisition card. Another parameter that limits the maximum end frequency is the exciter transducer’s specification. In the experimentations of this study, this parameter varies depending on the equipment or device being used. A schematic of the SuRE method is shown in Figure 3-1.
The SuRE method has advantages from both Lamb-wave-based and EMI-based approaches that were described in the previous sections. Similar to Lamb-wave-based techniques, the surface guided waves are being excited in the SuRE method and it is possible to monitor large areas on the structure, and the area of detection is not limited to the vicinity of the transducer. On the other side, using the signature spectrum for SHM allows the SuRE method to retain some of the unique characteristics of the EMI method. The fundamental assumption of the SuRE and the impedance method are similar. The impedance method assumes that the real part of the impedance of any point on the structure within a carefully selected frequency range is like a fingerprint. For the SuRE method, this is the magnitude of the transfer function or the spectrum of the monitored signal.

This representative curve should be the same as long as the structural integrity or loading is not changed. The spectrum of the monitored signal without any change at the
loading condition is presented in Figure 3-2 (a). The spectrums changed drastically when the load was applied in Figure 3-2 (b). [33]

Figure 3-2 (a) The spectrums of a point on the grid for two successive no load scans (b) Spectrums of a point on the grid before and after the load was applied

3.3. Excitation signal and analysis of the sensory data

There are two major excitation and signal analysis approaches for the SuRE method. The first method excites the surface with a sine wave and analyzes the sensory signal by using the Fast Fourier Transformation (FFT). The spectrum is captured by the peak hold of simultaneous FFT of the incoming signal from the sensor. Figure 3-3 shows capturing the peak of FFT of the measured signal during a complete sweeping cycle created the frequency spectrum. Since the excitation frequency at any time is a pure sine wave, in the frequency domain it has only a single peak. Since each
excited frequency transfers with different amplitudes, as the sweep happens, the amplitude of peak drops and increases. The peak-hold procedure draws the signature spectrum by capturing the footprint of the sweep at each frequency as it passes throughout the entire frequency range.

![Figure 3-3 FFT of sweep sine wave excitation and corresponding peak hold spectrum](image)

In the second approach, the time domain data is used directly to generate the frequency transfer function. For this purpose, the structure is excited at a series of frequencies one by one. In this study, the Teager-Kaiser (TKA) [19,20], Goertzel [21], RMS and the average of the positive readings algorithms will be discussed for estimating the characteristics of the piezo-structure combination.

The advantage of the second approach is that it allows embedded implementing of the SuRE method using digital signal processors (DSPs). While complicated signal transforms are hard to implement on embedded system, simpler amplitude estimation algorithms could be efficiently used to capture the system characteristics. An example of a typical time domain set of data is shown in Figure 3-4.
Figure 3-4 (a) Received signal in the time domain (b) Zoom of the received signal in the time domain [138]

The spectrogram of the excitation wave is shown in Figure 3-5. At any time, only one frequency step is excited and the amplitude of the response is measured in the sensor, which could be a second piezo or a non-contact laser scan point.
The surface is excited by using a piezoelectric element when the SuRE method is used. Rather than measuring the impedance changes of the ceramic disc, this method excites it with a sine wave voltage. This creates waves on the surface. The wave generation, propagation and amplitude of the received signal at the sensor are different at each frequency. The amplitude variation pattern (spectrum) at the monitored frequency range is the same as long as the surface stays at the same condition. This spectrum changes when the part experiences any changes including defects, cracks, loading, cuts, holes, welding and coating. These spectrum changes can be monitored to detect the listed conditions at the part. In order to compare the spectrums to each other, the sum of square of differences (SSD) method is used. Figure 3-6 shows the increased SSD once the spectrum is altered due to the change in the original condition of the structure.
3.4. Computational methods for calculation of the spectrum of the signal

The SuRE method gives flexibility to the user in terms of the excitation signal, actuator, sensor, data acquisition system and signal processing.

3.4.1. Fast Fourier Transform

The Discrete Fourier Transform (DFT) [139] is used for computer-based frequency domain analysis. Applications include spectral analysis, de-noising, compression and filtering. The signal requires being discrete in time and having a finite duration before its DFT could be calculated. The discrete Fourier transform of $x[n]$ signal with N number for samples is calculated from Equation 3-1:

$$\sum_{x=0}^{N-1} x[n]e^{-j\frac{2\pi}{N}kn}$$

Equation 3-1

Fast Fourier Transform (FFT) is a fast computational algorithm for DFT.

Figure 3-6 The change of squares of the differences (SSD’s) in drilling operation
3.4.2. The Teager-Kaiser Algorithm

The Teager-Kaiser Algorithm (TKA) [140] is an extremely convenient method for the analysis of pure harmonic signals. In theory, since the TKA estimates the frequency and the amplitude at the same time, the user does not need to keep track of the frequency of the signal separately. However, in practice, the noise, limited information, and difficulty of estimating of two variables from two inputs limited the performance of the method. In addition, calculating the frequency was not necessary with the DSP since the frequency was a known value, sent from the DSP to the Digital Data Synthesizer (DDS).

3.4.3. The Goertzel Algorithm

The Goertzel algorithm [21,24] may be used to estimate the amplitude of a pure sine wave signal once the coefficient, which corresponds to the frequency of the signal, is calculated. The estimate can then be updated for each sampling or performed at once after the signals at the same frequency are collected. The estimations are good and theoretically the contamination from the other frequencies is ignored. This is a well-known and widely used method for DSP applications.

3.4.4. Sine Wave RMS and Mean Value Methods

As stated earlier, the monitored output signal is a sine wave. Because of this, the properties of the shape of a sine wave could be exploited for quick and effective calculations. The magnitude of a sine wave is proportional to its RMS value and the average value of either the positive or negative sides [25].

The RMS values is calculated with Equation 3-2:
Equation 3-2  \[ RMS = \sqrt{\frac{\sum x(i)^2}{N}} \]

Where the “N” is the number of samples of the \( x(i) \) signal. The amplitude “a” is calculated by Equation 3-3:

Equation 3-3  \[ a = RMS \sqrt{2} \]

The relation between the amplitude and the mean of the positive values is calculated with Equation 3-4:

Equation 3-4  \[ a = \pi \left( \frac{\sum x(i)}{N} \right) \text{ where, } x(i) = \begin{cases} 0 & \text{if } x(i) < 0 \\ x(i) & \text{if } x(i) > 0 \end{cases} \]

This is the easiest and fastest way for calculating the amplitude of the output signal. It also turns out to be the most convenient way to achieve this, since DSP analog-to-digital converters normally operate by treating voltages less than 0 V as 0 V.

3.5. Signal Processing for comparing the response magnitudes

3.5.1. Sum of square of differences (SSDs)

Once the amplitudes are calculated, the similarity between the two signals may be represented by the sum of the squares of the difference (SSD) between both signals, shown in Equation 3-5:
Equation 3-5  
\[ SSD = \sum_{i=1}^{n} (a_{j,i} - a_{r,i})^2 \]

Where \(a_{j,i}\) are the amplitudes of the considered case and they are compared to the baseline \(a_{r,i}\).

3.5.2. Sum of square of differences for multiple sensing point

The FFT or an amplitude estimation method is then used to calculate the frequency transfer function. Studies have shown that the calculated spectrum for any measurement point on the structure is a signature characteristic and behaves consistently as long as no change occurs on the condition of structure. As soon as the condition changes due to applied load or structural damages, the frequency spectrum changes. To quantify the changes using the SuRE method, the Squared Difference (SD) of frequency spectrums with respect to a reference one is used from Equation 3-6:

Equation 3-6  
\[ D_{m\times n\times p} = \| A_{m\times n\times p} - R_{m\times n\times p} \|^2 \]

Here, R and A are the reference and altered data matrices, including the frequency spectrums of intact and damaged structures. The dimension of each data matrix is m rows by n columns by p layers. m includes the frequency samples of point n during the p measurement. In this case, the Sum of the Squared Differences (SSD) for each scan point is calculated from Equation 3-7:

Equation 3-7  
\[ S_{1\times n} = \sum_{m} D_{m\times n} \]

S is a matrix with the size of measurement points that contains a SSD value for each scanning point. This value quantitatively represents the amount of change in the
spectrum for each scanning point. Depending on the configuration, scan S could be a one-dimensional or two-dimensional array.

3.5.3. Normalized sum of square of differences (NSSDs)

In this study, the structure was excited using a piezoelectric element and the surface vibrations were monitored by the scanning laser vibrometer. The reference scan was performed when all the bolts were tight.

The altered scans were performed after one or more bolts were loosened. The change of the compressive forces on the structure surfaces changed the surface response to excitation. To quantify the change, the Squared Difference (SD) of two matrices is calculated with Equation 3-8:

\[ D^2_{i,j} = (A_{i,j} - R_{i,j})^2 \]

R and A are the reference and altered data matrices obtained by the spectrum analyzer. Data matrices have m rows by n columns, where each column includes the frequency spectrums of a scan point. The frequency range was distributed over the matrix row. The average of the squared differences was calculated with Equation 3-9:

\[ \text{Average} = \frac{1}{mn} \sum_{i=1}^{m} \sum_{j=1}^{n} D^2_{i,j} \]

where m and n are the number of frequencies and the number of scan points, respectively. The Normalized Squared Differences (NSD) was obtained from dividing the squared differences by the average in Equation 3-10:
The normalized differences for each scan point could be averaged versus the frequency range to obtain the Normalized Sum of Squared Differences (NSSD), and in fact this criterion was an array with the size of scan points:

\[
\bar{D}_{i,j} = \frac{D_{i,j}^2}{\text{Average}}
\]

The normalized values for each scanning point could be averaged versus the frequency range to obtain the Normalized Sum of Squared Differences (NSSD), and in fact this criterion was an array with the size of scan points:

\[
\bar{S}_i = \frac{1}{n} \sum_{j=1}^{n} \bar{D}_{i,j}
\]

\(\bar{S}\) is a matrix with the size of the scanning grid that contains a normalized value for each scanning point. This normalized value quantitatively represents the amount of change in the spectrum for each scanning point. Depending on the dimension of the scan grid, \(\bar{S}\) could be a one-dimensional or two-dimensional array and could be represented in different graphical ways.

3.6. Experimentation setup

In this study, three different approaches were used for implementing the SuRE method. In order to excite surface waves on the beam, an APC piezoelectric model D-.750”-2MHz-850 WFB was attached to the middle of the plate. All the approaches excited the surface with a piezoelectric element (Figure 3-8). To remove oil and any other possible contaminants, the surface of aluminum plate was cleaned with acetylene, ethanol and water. The bonding agent was LOCTITE Hysol Product E-30CL epoxy adhesive, with a curing time of 24 hours. An applicator gun simultaneously mixed and dispensed the bonding agents from a dual-cylinder cartridge by passing the ingredients
through a mixing nozzle. Normally, a frame is used to position the specimen in front of the laser head (Figure 3-7). The scan points are marked on the clamp to make sure that at every step of experimentation the same points would be scanned. A RIGOL DG1022 function/arbitrary waveform generator with a maximum peak-to-peak amplitude of 20 volts generates the waves. In order to have a higher signal-to-noise ratio in measurement points, the waveform is amplified by 5 times through passing a TEGAM power amplifier model 2348. The laser scanning Doppler vibrometer (LSDV) model Polytech PSV-400 remotely measures the surface vibrations from a grid of scan points on the aluminum plate. Due to the limitation of sampling frequency of the A/D converter of laser junction box, an external data acquisition system was used. Data Translation simultaneous A/D convertor model DT9832-A was employed to capture the peak holds of the transfer function for the frequency input sweep sine wave. The maximum sampling rate of the device was set to 1 million samples per second. This allowed a maximum frequency of 400 kHz to be sampled. Since the SuRE algorithm requires the frequency domain data, the FFT of the input data was used. The DT9832-A has a built-in FFT package.
The first two approaches monitored the surface vibrations with a second piezoelectric element but used different approaches for the analysis of the monitored signal. The third approach used the scanning laser vibrometer to monitor the surface waves at a grid on the surface. They will be briefly discussed in this section.

Figure 3-7 An example of the frame used to hold the plate for laser scan

Figure 3-8 ¼” diameter APC PZT model D-.750"-2MHz-850 WFB
3.6.1. Implementing the SuRE method with Digital Signal Processors (DSP):

Figure 3-9 shows the schematic of implementing SuRE method. It uses the Signal Analyzer or Microchip dsPIC33FJ64MC802 DSP mounted on a Microstick development board. One limitation of the DSP was that it could not generate good quality sine waves through Pulse Width Modulation (PWM) at the frequencies desired. A Midnight Design Solutions Direct Digital Synthesizer (DDS) board, the LLC DDS-60 Daughterboard, was used to generate the sine waves. The generated sine waves were passed through AD826AN operational amplifier to boost signal power and applied to the piezoelectric element attached to the structure. The signal of the other piezoelectric element on the structure was sampled through the DSP after it was conditioned with another operational amplifier (AD826AN). Sampling was performed at the 1.1 million samples per second. The DSP selected the test frequencies, collected data, calculated the amplitudes, compared them with the reference signal and estimated if the structure is under a compressive force or not.

![Figure 3-9](image-url)

Figure 3-9 The experimental setup for the SuRE method using a signal analyzer and a DSP circuit

The embedded device that has been developed based on PIC’s 16-bit Digital Signal Controller is shown in Figure 3-10. A Digital Signal Controller (DSC) is a single-