Damage Detection in beam like structures using Frequency Response Function& Iterative Modal Strain Energy Method

Author

Muhammad Wasif Khan

Reg. Number

2016-NUST-Ms-Mech-00000171958

Supervisor

Dr. Naveed Akmal Din

DEPARTMENT OF MECHANICAL ENGINEERING
COLLEGE OF ELECTRICAL & MECHANICAL ENGINEERING
NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY
ISLAMABAD

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Thesis Supervisor
Dr. Naveed Akmal Din

Thesis Supervisor's Signature: ____

DEPARTMENT OF COMPUTER ENGINEERING
COLLEGE OF ELECTRICAL & MECHANICAL ENGINEERING
NATIONAL UNIVERSITY OF SCIENCES AND TECHNOLOGY,
ISLAMABAD

DECLARATION

I certify that this research work titled “**Damage Detection in beam like structures using FRF & Iterative Modal Strain Energy Method”** is my own work. The work has not been submitted elsewhere for assessment. The material used from other sources, has been properly acknowledged / referred.

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2016-NUST-Ms-Mech-00000171958

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00000171958

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ABSTRACT

Structural Health monitoring is an important area of search which finds its application in all load carrying structures like bridges, buildings, aircrafts, submarines, and automobiles. In order to avoid any failure in such structures many Non Destructive Testing Techniques (NDT) are developed and a lot of research is carried in the modern era. Damage Detection using Vibration testing parameters e.g. natural Frequency & mode shapes is one of the most popular reliable approach for damage identification in structures. In this study, a damage detection Techniques is proposed which uses change in Frequency Response Function (FRF) and modal strain energy (MSE) for damage localization and severity estimation in beam and truss like structures.This method provides a robust approach for Structural Health Monitoring (SHM) problems as it requires only few natural Frequencies of damaged structure to detect the damage. In the current approach, a damage detection algorithm is developed and validated by conducting numerical studies of a Cantilever &Fixed-Fixed beam, both noise-free and noise-effected cases are simulated. The numerical studies reveal that proposed method is capable of Localizing and Quantifying the Damage Accurately at reduce computational cost.

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Chapter 1

Introduction

INTRODUCTION

Structural Health monitoring (SHM) finds its application in Mechanical , Civil and Aerospace structures. Damage in any structure is result of deterioration, degradation or any natural Disaster. Structural Damage Assessment is necessary to predict the structure present condition and service life. Visual Inspection methods for damage assessment are dependent on instrumentation and have limited capability to determine the damage extent and severity. Considering the importance of damage assessment to inaccessible regions in any component, modal parameter based damage identification, localization and quantification technique is developed and validated by experimentally measured modal characteristics e.g. natural Frequency and modes shapes.

1.1 Problem Statement

Development of a damage detection technique using natural frequency of damaged structure was purpose of this thesis. Reduced computational and time cost with minimum modal input from damage structure provides the basis for a robust damage assessment for any structure

1.2 Motivation

The first and foremost motivation to conduct this study is to reduced time & computational cost for Damage detection.In any modal testing setup frequency measurement is easy and provides accurate value. Generally mode shapes are incomplete due to sensor limitation and contaminated due to noise, so in order to overcome these limitations a frequency based damage detection algorithm is proposed which requires only measured natural frequencies of damaged structure to locate and estimate the damage severity accurately and effectively.

1.2 Challenges

Modal testing setup limitations and inaccuracy of measured modal parameters provides the basis for recent advances in the field of structural health monitoring. There is a set of certain limitation in any modal testing based parameters which provides the motivation to propose this algorithm. (1) Mode Shapes are contaminated due to noise . (2)In complete measured mode shapes are another reason to rely on natural frequency for structural damage assessment. (3) Sensors are limited in experimental setup. (4) Mode shapes based damage detection algorithms require higher time and computational cost.(5) Impact hammer based vibration testing does not provide higher modes for structure. Damage detection is vital for structure life assessment and failure prediction as human life is at risk in many cases as show in Figure 1.1.

Figure 1.1– Structural Damage in a bridge

1.3 Structure of thesis

The structure of thesis is as follows. Chapter-2 presents literature review regarding previous work conducted in domain of vibration based damage detection (VIBDD) methods. Chapter-3 explains the proposed methodology. Chapter-4describes the

Structures considered for damage detection.Chapter-5 is related to experimental data, system results supported by various analytical codes and then discussion. Finally, Chapter-6 concludes the thesis and mentions future work. The outcomes of this study proved to be highly satisfying and successful. Based on this study publication [1] was possible.

Chapter 2

Literature Review

LITERATURE REVIEW

All load carrying structures such as building, bridges, aircraft structures and automobiles accumulate damage during their service life. Early stage damage detection Is necessary to predict the failure in structure. Vibration bases damage identification techniques (VBDIT) have an increasing importance in recent decades due to their better sensitivity to damage. Any change in vibrational characteristics indicate the presence of damage. In the next step damage is localized in the structure for further quantification to estimate the damage severity in that specific region of structure. This whole practice helps to predict the present condition and subsequent failure in the future. A lot of work has been carried out in this domain as modal strain energy (MSE) is used in most of the work for damage localization and quantification. Vibration based damage identification methods are characterized into three major categories which will be discussed and elaborated in this literature review.

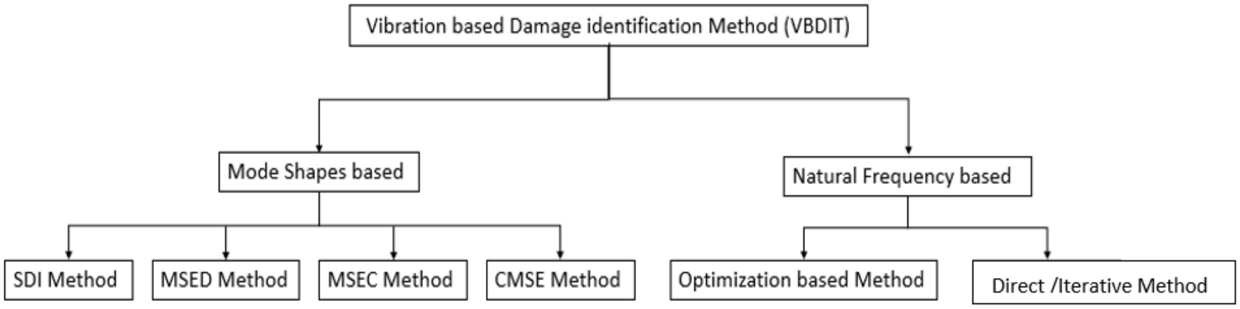


Figure 2.1 –Categorization of VBDIT methods based on Modal Characteristics

Change in modal characteristics such as mode shapes, natural frequency are one of the basis for damage identification in structures.MSE based methods use natural frequency and mode shapes for damage detection in different problems. Mode shapes based MSE Damage identification techniques utilizes the measured mode shapes of Damaged structure along with stiffness of structure. Damage in any structure reduces its stiffness and ultimately Modal strain energy also changes..Applications, benefits and limitations of these techniques are discussed in [2-8]. Generally modal strain energy base methods are sensitive to noise [9]. Mode shapes based methods are considered as promising approach for damage detection [1]. In any experimental setup, modes shapes are subjected to contamination and mostly measured mode shapes are incomplete due to sensor limitation [10]. Frequency based damage identification requires less modal input as natural frequency is easy to measure and require even only one sensor for damage identification [11] . Optimization based damage detection methods couple mostly Frequency with optimization algorithms for structural damage assessment[12].Damage identification process is divided in four steps 1.Damage identification 2.Damage localization 3. Damage severity estimation 4. Prediction of failure. A detailed discussion on proposed methodologies in the domain of mode shape based and frequency based damage identification techniques will be provided and discussed.

2.1 Mode shape based Methods

Mode shapes based damage detection method use the change in mode shapes of the damaged structure to identify the damage in structure. Modal Strain energy obtained from mode shapes of damaged structure identifies the damage. Higher value of Damage Index for an element indicates the presence of Damage at that specific location . In the next this damage localized is quantified using Modal Strain Energy (MSE) and stiffness of structure . These methods are characterized into Five types as

- Stub’s Damage Index (SDI) Method
- Modal Strain Energy Decomposition (MSED) Method
- Modal Strain Energy Change (MSEC) Method
- Cross Modal Strain Energy (CMSE) Method
- Optimization based Methods

2.1.1 SDI Method

All damage detection method ascertains the structural Health Monitoringas Stub was thefirst one who used modal strain energy for structural damage assessment. Stub s index (SDI)method[12] uses modal strain energy to detect damage in all kind of structures. Soon after the development of this method to predict structure health this method was named as DI Method [7,13,14].There are many improved forms of Stub s Di method but in this research thesis only the Simple form of Stub s DI method is discussed [15]. DI method requires mode shapes from damage and intact structure to localize the damage and as normalization of mode shapes is not considered as a prerequisite for implementation of this method. This method is numerically applied and experimentally verified on many real life applications such as at earlier stages it was applied on a numerically simulated offshore platform. Numerically calculated modal parameters for intact structure and experimentally measured modal parameters which were subjected to contamination and incomplete measurement were used to validate this method.[16]. Latterly SDI method was applied on I40 Bridge data and damage was localized base on the experimental data obtained from real structure. [17,18,19] . Visual Inspection supported the results of SDI method. Earlier it was believed that this method is limited to beam like structures but later on this method successfully proved its application to metal & composite Plates[20-23] and hollow Cylinder [24]. SDI performed better than other damage detection algorithm in its earlier days as this performance was analyzed on an experimental data of I-40 bridge.[13,25]. SDI method is more stable under noisy conditions and results obtained from damage detection are more reliable.[7,26,27] .SDI method is a better option structural damage localization but for damage quantification an improved form of SDI method was introduced to localize and quantify the damage [28,29] . Improved SDI method is a better approach for damage a regular damage localization and quantification.[30]. As Improved SDI promises improved damage quantification but this method is not much successful for small damage under noisy condition.

2.1.2 MSED Method

Considering the limitations of SDI method , another improved form of SDI method is developed which decomposes the stiffness of structure into its axial and transverse components[31,32] This method corresponds to axial and transverse stiffness of each nodal coordinate. Two damage indices are introduced for each element which indicates the damage in both DOF. This approach proves to be more elaborative for localizing the damage more accurately. MSED method is applied to off shore jacketed plate form and five story frame structure. Experimental validation with numerical studies proved the credibility of this approach for robust, and accurate damage detection in structures. [32-34]. Effective Damage detection under Temperature variation is another success of this technique [35]. Comparative studies of MSED method with SDI method make this method more preferable over SDI for structural damage assessment.[36]

2.1.3 MSEC Method

Modal strain Energy change Method (MSEC) is based on change in modal strain energy of a damaged structure as damage changes the modal characteristics of structure, MSEC method uses this change for damage identification. This approach develops the formulation which localizes the damage effectively and efficiently. Modal Strain energy change ratio (MSECR) is developed and used for damage detection in a real life 2D structure[37].MSEC uses its sensitivity for damage size determination after its localization [38]. MSECR method is further improved by reducing the effect of truncation and modeling for higher modes for damage quantification[39]. MSEC method is an impressive method for damage detection as few issues regarding the use of absolute value of MSE , convergence issues and sensitivity related problems are elaborated and disused [40,41]. Modified Modal Strain Energy[42] based on iterative process to detect damage was proposed to overcome the limitations as explained by [40]. Further this method is applied on composite sandwich beam and bridge structure [43-45]. One of the limitation MSECR method is its sensitivity to noise and incomplete measurement of mode shapes which reduces the accuracy of damage quantification method[37,41]. MSECR is used in formation of many damage detection methods which are currently in use for damage detection in different applications. MSEC based methods are categorized into three categories. Element based modal strain energy method is one of these methods. First order sensitivity formulae were derived and applied on damage detection problem to localize and quantify the damage [46,47] statistical closed form of modal strain Energy (MSE) was proposed to overcome the uncertainty between analytical and experimentally measured modal characteristics.[48] Elemental modal strain energy sensitivity based methods have become an interest for researchers in a recent past[49-51], as it is also revealed that that this method also provides evidence to examine the damage location identification. Elemental MSE for elements with larger modal Displacements are more sensitive to Structural stiffness than those with smaller displacements[46]. MSE methods are also beneficial to investigate the damage at specific location with selected modes.

2.1.4 CMSE Method

Cross modal strain energy (CMSE) method is developed to overcome the limitations of DI and MSEC method as these methods are unable to accurately identify the damage under certain practical limitations. CMSE method uses cross over Analytical and measured modal strain energy terms for damage quantification.[30] Damage detection techniques using MSEC for damage localization and CMSE for damage severity estimation are developed.[57] Similar work based on combination of niche genetic algorithm and CMSE was proposed for structural damage assessment[58]. CMSE methods have certain advantages over other methods . as it’s a direct approach for damage quantification requires only few measured modes of damaged structure and no such normalization of modes is considered as prerequisite for damage detection. At early stages , this method was limited to only damage severity estimation practices but at latterly few improved forms of these methods were formulated for damage localization as well[59,60]. This method was further explored by other researchers extending it for model updating Cross-model cross mode (CMCM) method was proposed for structural model updating [61-63].damage detection and other domains [64-68]

2.1.5 Optimization based Methods

Another improved form of MSEC method is coupling MSEC with optimization algorithms, Damage is located by MSEC methods and further quantified by optimization algorithm based on a n objective function. This approach helps to identify, locate and quantify damage in complex and large structures with reduce computational resources. Frequency and mode-shape criterion were developed for damage detection in a Fixed-Fixed beam and 2D structure using MSEC and Genetic Algorithm.[52] Another damage localization indicator named as Modal Strain Energy based Damage Indicator (MSEBI) was proposed for damage localization and then fused with Particle Swarm Optimization algorithm to quantify the damage severity[53,54]. Generally MSECR value gets higher value for Damaged elements and its neighbors so in order to improve the efficiency of damage localization data fusion techniques for multiple modes were developed and validated[55,56].

2.2 Frequency base Methods

Frequency based methods are further categorized into two types.

- Direct /Iterative Methods
- Optimization base Methods

The recent developments on these methods will be discussed which will highlight the importance of these approaches.

2.2.1 Direct/Iterative Methods

Frequency based damage detection methods are easier to detect damage in any structure as frequency measurement in any experimental modal setup is more accurate and does not require much effort [69]. Any damage detection algorithm which uses natural frequency for damage identification will be preferred over other methods. A damage identification method based on natural frequency was first proposed which provided a rough estimate for damage.[70*4].there are many advantages of frequency based damage identification methods over mode other methods as discussed by [71*5].An iterative method for damage quantification is formulated which uses natural frequency for this purpose [72*70] later on this method was extended to damage localization as well [73*71]. These methods are validated on 1-D beam structures and 2-D planar frames. Extension of this technique 3-D offshore platform is another milestone achieved [74*72] The major advantage of IMSE method is it overcomes the limitations of incomplete measured modes and noise contamination.

2.2.2 Optimization based Methods

Developed a damage detection technique coupling FRF with BAT Algorithm ,minimizing the objective function based on intact and damaged structure natural frequency[75]. Proposed a damage detection technique using change in natural frequency and Modal scale Factor (MSF) to minimize an objective function through PSO and BAT algorithm[76]. worked on crack location and depth estimation in an inverse problem using Particle Swarm Optimization (PSO) to minimize an objective function based on natural frequency of structure[77]. Developed a damage identification methodology using natural frequency and mode shape. Structural sparsity is utilized through l1 regularization method to estimate the localized damage severity[78]. presented a frequency based finite element model updating technique which incorporates the power spectral density function for damage identification in plate and shell structures [79].

2.3 General problems and possible scope of work

This literature review highlights the importance of damage algorithms as every structureaccumulates duringits service life and in most of the cases safety is subjected to human life. Considering the importance of Structural Health Monitoring (SHM) in every domain, many techniques are proposed ,validated and applied on different structures. This research work develops a damage detection algorithm which accurately identifies, localize and quantifies the damage in a Fixed-Fixed beam as its find its application in bridges.Its a robust damage identification techniques which uses few natural frequencies to identify, locate and estimate the damage severity accurately with reduced computational and time cost.

Chapter 3

Methodology

METHODOLOGY

The damage detection problem we are dealing requires an elaborative approach for damage identification , localization and quantification. The proposed methodology includes develops the basis for damage identification using FRF and a beta (ß) indicator is estimated based on measured and analytical FRF response of structure. Higher the value of beta (ß) for any element or DOF, higher will be the possibility of damage at that location. This input from damage localization indicator (ß) will help to estimate the damage in already localized damage location in the structure.

The newly developed damage detection technique is validated on a Cantilever beam using experimentally measured natural frequencies for beam structure. Similarly numerical studies are conducted for a Fixed-Fixed for damage identification in the structure. This damage detection approach will be applied and discussed here with mathematical formulation and experimental results obtained from experimental testing of Cantilever beam. Methodology for damage detection is divided in three steps

- Damage Identification
- Damage Localization
- Damage Quantification

3.1 Damage Identification

Damage identification phase includes extraction of vibration testing parameters. These parameters are natural frequency and mode shapes of structure. This methodology is mainly focused on natural frequency &FRF of damaged structure to for overall damage detection in structure. In this specific section natural Frequency & FRF will be discussed for implementation in this methodology.

3.1.1 Natural Frequency

Every structure has its own geometry and material characteristics either it’s a bridge ,building ,aircraft or an automotive.Vibrations in any structure are sometimes desired and sometimes fatal to the lives. Whenever any structure vibrates, there is a certain frequency of its oscillation which is dependent on its geometric and material characteristics. Natural Frequency can be single or multiple but these natural frequencies help to design an overall structure in a better manner. There is a limit of vibration in any structure ,above which structure enters in its resonance frequency domain, where higher resonance for a long period may result in Fatigue , failure or any sort of damage to the structure.

There is a certain Damping ratio associated with natural Frequency as already mentioned ,vibrations in a controlled limit are beneficial and exceeding that limit may be harmful to structural health. Collapse of Tricoma bridge in 1940 and aircraft structural failure emphasis on importance of natural frequencies of structure and to mold its design for better load carrying and flight dynamics characteristics in both cases . Structural damage and failure is shown in Fig 3.1(a)

Fig 3.1-(a) Structural Failure of Tricoma Bridge in 1940

Figure 3.1- (b) Structural Failure of Aircraft during Flight

3.1.2 Frequency Response Function (FRF)

Vibrating testing of any structure results in a certain output which requires transformation in frequency domain. FRF is one of the tool used in modal testing to obtain results in frequency domain.

A Frequency response function (FRF) can be divided into its real and imaginary part with output in the form of its magnitude and phase. During design phase of any structure FRF is performed to obtain natural frequencies of structure. This FRF is analytical in design phase and can be measured either in prototype phase of structure. FRF is basically the response of structure in which every peak shows the natural frequency for structure. Any external excitation is applied to the structure in form of force and response can be in form of displacement, acceleration, velocity or frequency. FRF of any structure is critical to its sustainability as prediction of right FRF helps to develop structural damage detection approach and any change in FRF corresponds to change in its stiffness and subsequently life of the structure.

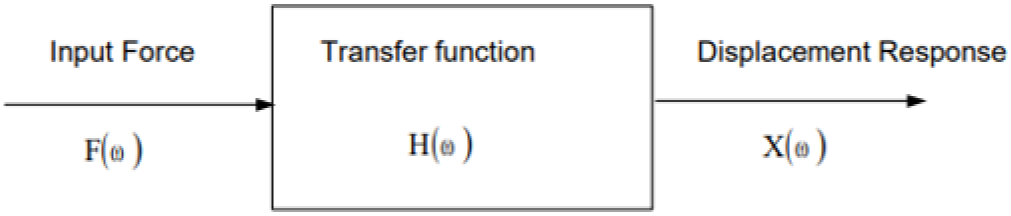


Figure 3.2 - Frequency function Model

Here F(ω) presents the external excitation force, H(ω) corresponds to Transfer function applied and X(ω) is the Displacement response.

3.2 Damage Localization

First phase of proposed damage detection technique provides the basis for damage localization, measured and analytical FRF will be used as an input for damage localization in Fixed-Fixed and Cantilever beam.

3.2.1 Damage Indicator for Damage localization

Damage in any structure results in change in its dynamic characteristics e.g Natural Frequency, Mode Shapes and Damping Ratios. These Dynamic changes effect structural Stiffness, ass & Flexibility matrices of structure. .

Dynamic Response of structure is Dynamic Equation for an n DOF System can be expressed as follows

$$[M]\ddot{a}(t) + [C]\dot{a}(t) + [K]a(t)c = f(t) \qquad (1)$$

Where

$[M]_{n\times n}$= Mass Matrix

$[C]_{n\times n}$=Damping Matrix

$[K]_{n\times n}$=Stiffness Matrix)

Vibration based damage identification techniques (VBDIT) use change in natural frequency and mode shapes for damage detection in structure. Basic dynamic response equation for n DOF system can be expressed as Eq. 1

$$[M]\ddot{a}(t) + [C]\dot{a}(t) + [K]a(t)\mathrm{c} = f(t) \qquad (1)$$

For an external force and displacement $f(t) = \{F(\omega)\}e^{j\omega t}anda(t) = \{a(\omega)\}e^{j\omega t}$, and damaped free condition FRF is expressed as

$$[H(\omega)] = [(-\omega^2[M] + [K])]^{-1}(2)$$

The analytical and measured FRFs is presented as $[H(\omega)]$ & $[H(\omega)^*]$
where $[K]^* = ([H] + \omega^2[M])$ (3)
It is assumed that mass of structure remains constant and stiffness changes

$$[\triangle K] = [H]^{-1} - [H]^{-1*} \qquad (4)$$

When multiplied by $[H]^*$,Eq. 4 gives:

$$[H]^*[\triangle K] = [H]^*([H]^{-1} - [H]^{-1*}) \qquad (5)$$

Based of analytical and measured FRF, beta(β) will be calculated as:

$$\beta(1,i) = ([H]^*_{1n}) * [H]^{-1} - [I](1,i) \qquad (6)$$

Damage indicated in the first step is localized by Damage indicator beta (β). Higher the value of beta (β),higher will be the possibility of damage in structure. Equation (10) will be used here for damage localization which uses the analytical and measured FRF for structure. This Damage indicator provides the basis for damage quantification in the next step.

3.3 Damage Quantification

3.3.1 Iterative modal strain energy method

Damage severity will be estimated for damaged elements identified from Frequency Response Function. Eigen Analysis Equations for Intact & damaged structures are written as follows.

$$[K]\Phi_i = \lambda_i [M]\Phi_i \qquad (7)$$

$$[K]^* \Phi_i^* = \lambda_i^* [M]^* \Phi_i^* (8)$$

Φ_i = Mode shape for Intact structure

Φ_i^* = Mode shape for Damaged structure

λ_i = N$atural$ Frequency for Intact structure

λ_i^* = N$atural$ Frequency for Damaged structure

Since M*=M and Damage is characterized by reduction in their stiffness and damage is identified for local elements from Frequency Response Function. Global Stiffness matrix will be written as linear combination of local Stiffness matrix for each element.

$$[K]^* = [K] + \sum_{n=1}^{Nd} \alpha_n K_{ln} (9)$$

Here Nd is the total number of Damaged Elements while α_n and l_n show the damage severity coefficient and the number of damaged Element. Damage Causes the reduction in stiffness for local stiffness of each damaged element which effects the overall stiffness of structure[ ]. Damage Severity relation derived from Eigen equation is as follows

$$\sum_{n=1}^{Nd} \alpha_n \phi_i^t \, K_{ln} \phi_i^* = \frac{\lambda_i^*}{\lambda_i} - 1 \tag{10}$$

Structural modal Strain energy and Elemental Modal Strain energy changes due to damage which is applied here as an input for estimation of damage extent.

$$C_i = \phi_i^t \, K \, \phi_i^* \tag{11}$$

$$C_{n,i} = \alpha_n \phi_i^t K_{ln} \phi_i^* (12)$$

Using the equation (15) & (16), (14) can be written as follow

$$\sum_{n=1}^{Nd} \alpha_n C_{n,i} = b_i \tag{13}$$

Where

$$b_i = \frac{\lambda_i *}{\lambda_i} - 1 \tag{14}$$

For m equations (17) can be simplified as

$$C\alpha = b \tag{15}$$

$[C]_{m\times Nd}$=Modal Strain Energy Matrix

$[\alpha]_{Nd\times 1}$=Damage Severity Coefficient Matrix

$[b]\,]_{m\times 1}$=Natural Frequency Change Ratio

For m≥Nd, Least square solution method will be used to calculate Damage Severity Coefficient

$$\alpha = (C^T C^{-1}) \, C^T b \tag{16}$$

Equation (20) requires Mode shapes for Damaged Structure at Full coordinates which is difficult to obtain due to experimental Limitations so here for Damage estimation, initially zero damage is assumed for Fixed-Fixed beam and IMSE method is applied to accurately estimate the damage using measured Natural Frequency for Damaged beam.

$$\Phi_i^*(K^*, M) = \Phi_i^*\left([K] + \sum_{n=1}^{Nd} \alpha_n K_{ln}\right)(17)$$

Equation (20) & (21) will be used in for each Iteration of IMSE Method.

3.3.2 Iterative modal strain energy method

Step 1: initialize the solution with $\alpha^0=0$, calculate $\Phi_i^{*(0)}(K^*, M)$ where $K^*=K$.

Step 2: solve for α using $\Phi_i^{*(0)}$, First Iteration for IMSE Completes Here.

Step 3: Compute $\Phi_i^{*(k-1)}$ from $\alpha^{(k-1)}$, and estimate $\alpha^{(k)}$ using$\Phi_i^{*(k-1)}$, where k=2,3…

Step 4:if $|\alpha^{(k)} - \alpha^{(k-1)}| < r$ Damage Severity is estimated, otherwise move to step 3, where r=0.0001

3.3.3 Noise-Effect

In actual Measured Modal parameters differ by simulated FE parameters due to noise. In order to simulate this effect on dynamic response of structure, Modal Frequencies with Gussian Noise [] are used For implementation of Damage Detection Algorithm.

$$\omega_j^* = \omega_j\left(1 + n\gamma_j\right) \qquad (18)$$

Here$\boldsymbol{\omega_j^*}$**and**$\boldsymbol{\omega_j}$are the noise free and noise effected natural frequencies and $\boldsymbol{\gamma_j}$ represent the random number with standard deviation of 1 and of mean 0 , n shows the percentage of Noise

3.4 Damage detection algorithm

A damage detection algorithm is proposed based on approach developed in the earlier sections. This algorithm is applicable for single and multiple damage cases. Change in FRF will indicate the presence of damage in structure, damage will be localized based on damage indicator beta (β). In the next step single or multiple damage will be quantified using IMSE method.

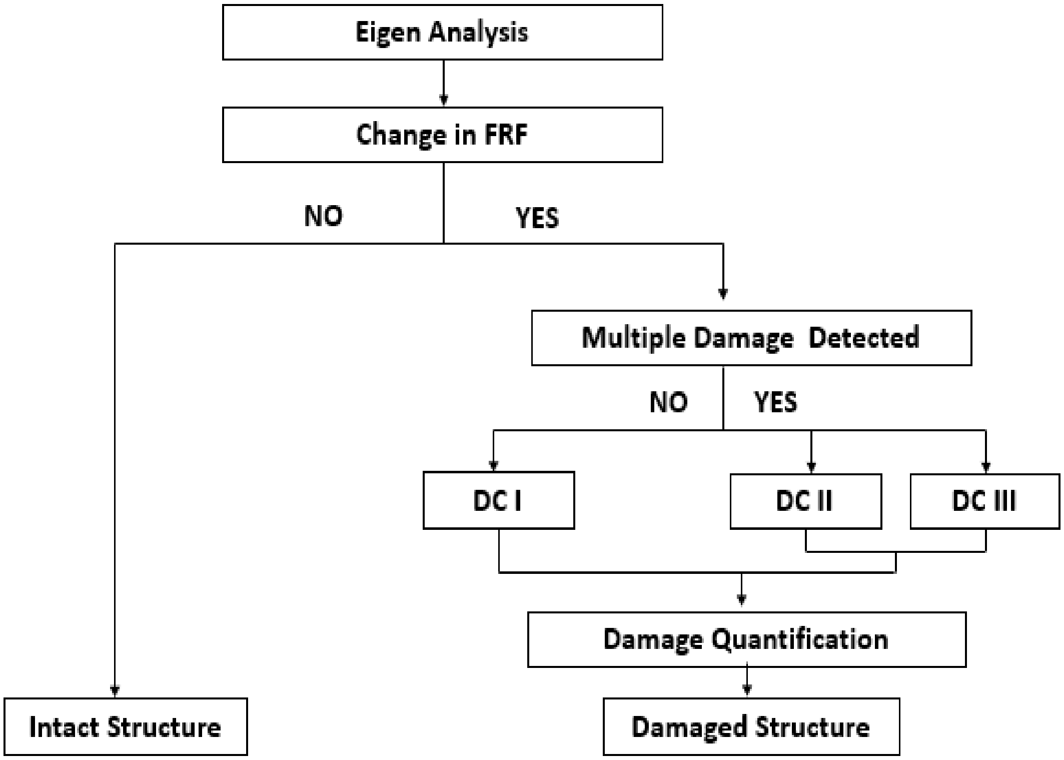


Figure 3.3 - damage detection algorithm for single or multipledamage

Chapter 4

Experimental Modal Testing

EXPERIMENTAL MODAL TESTING

Structural design demands higher strength and reliability with reduced cost. Static and dynamics response monitoring is very important at early stage of development of product. Vibration testing is performed to measure the vibrational parameters of designed structure. Dynamic Response of structure helps to assure the safe design of structure. It increases the importance of this integral part of product development in any research based setup. Dynamic response of structure includes dynamic parameters such as natural frequency, mode shapes , damping and resonance. Vibration testing setup includes a set of instrumentation to obtain these vibration testing or dynamic response parameters. It includes transducers, shakers or impact hammers. Transducers are calibrated device with reference to another transducers of certain calibration level, similarly excitation is induced using impact hammer as a certain level of force is induced to excite the structure or an electrical signal is generated and transformed into force. The difference between these two excitation mechanism is that either excitation is variable in case of impact hammer and is constant in case of shaker. Accelerometers are used to measure the structural response and Transient signal is transformed in frequency domain as FRF. Vibrational testing setups based on impact hammer and shaker are shown in Figure 4.1&4.2.

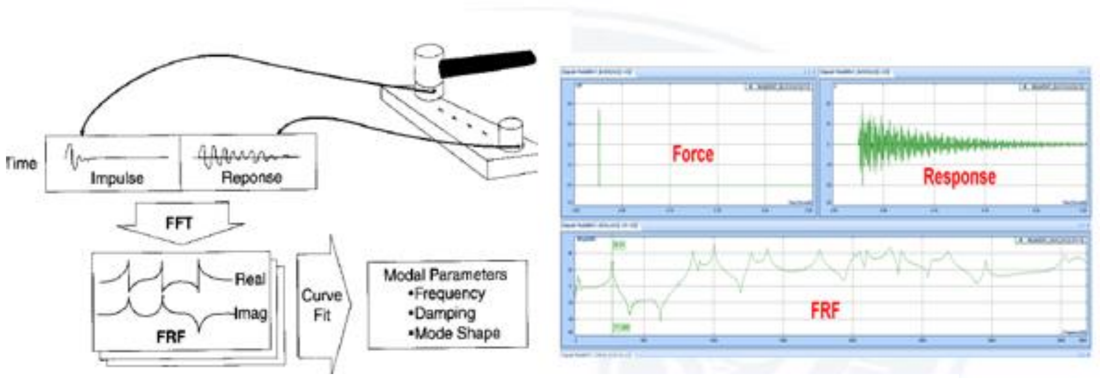


Figure 4.1 - Impact based Vibration Testing Setup

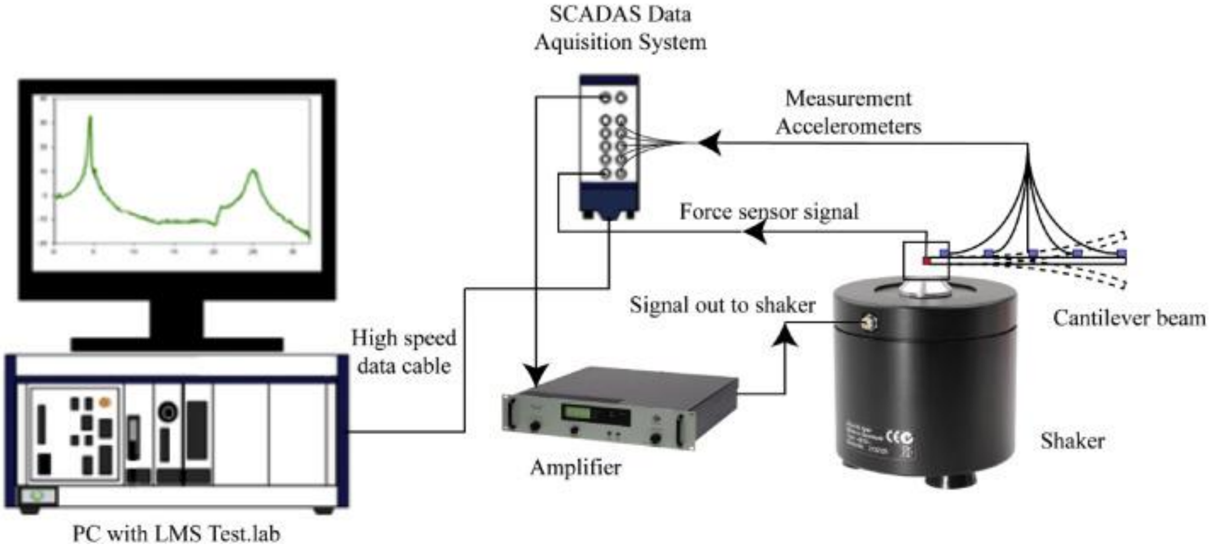


Figure 4.2 - Shaker based Vibration Testing Setup

4.1 Vibration Testing using Impact Hammer

In this research work, impact hammer based excitation setup is used for structural dynamic response measurement. This setup consists of an FFT analyzer for frequency response measurement based on externally applied load, providing an economical alternate for vibration testing of any structure. It proves to be efficient approach to obtain the vibration response of structure.

Impact based vibration testing setup includes following instrumentation which includes

- Impact Hammer
- Accelerometer
- FFT Analyzer
- Post Processing Modal Software

Impact hammer excites the structure with a load cell for applied force measurement. An accelerometer to measure the response at a position in the structure. FFT analyzer helps to transform the time based response into frequency domain. Similarly post processing software provides modal response for the structure. Structural specification in form of its geometry and material helps to determine the level of excitation required to obtain structural response , In impact testing structural response determines its characteristics such as natural frequency and mode shapes. This response is interpreted by modal testing software. In our experimental setup this response is interpreted in form of mode shapes and natural frequency by MESCOPE.

4.2 Cantilever beam Modal Testing

Experimental Modal Testing setup consists of four Aluminum 2024-T6 beam of length 600 mm with width and thickness of 50 & 5 mm and slit size of (1*2.5) mm^2 has following material properties as shown in TABLE I.

TABLE I. Material Properties for test beams

Property (Units)	**Value**
Young s Modulus (GPa)	73100
Density (Kg/m^^{3})	2780
Length (m)	0.6
Area (m)^^{2}	0.00254

4.2.1 Beam Testing Samples

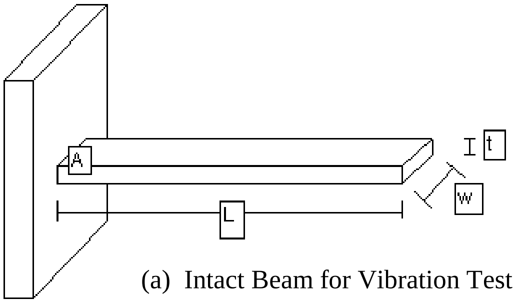
There are four cantilever beam samples considered for experimental testing geometrical specifications for each beam are shown in TABLE II .

TABLE II. Geometrical specification for test beams

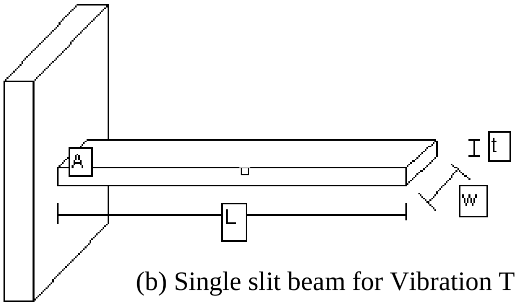
Structure	**Slit 1**	**Slit 2**	**Slit 3**
Intact	None	None	None

DCI	250 mm	None	None
DCII	125 mm	375 mm	None
DCIII	125 mm	175 mm	425 mm

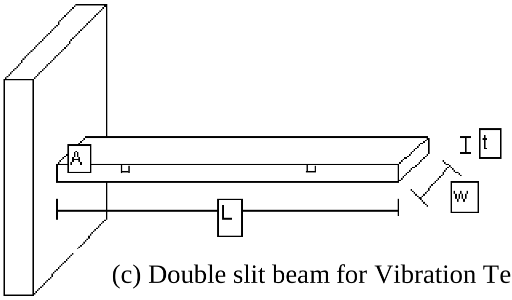
Slit location and size are determined based on literature studies regarding different vibrational testing setups. In future Depth of slit and shape of slit will be considered as topic of study for research in this domain. Beam samples are shown in Figure 4.3.



(a) Intact Beam for Vibration Testing



(b) Single slit beam for Vibration Testing



(c) Double slit beam for Vibration Testing

Figure 4.3 - Cantilever Beam Samples

4.3 Experimental setup for Cantilever beam modal testing

Experimental modal testing is used to measure the structural dynamic response. It provides results for FE Modal analysis validation. Modal parameters provide a correlation between Experimental and FE Modal analysis results.

Experimental modal parameters will be obtained in four stages.

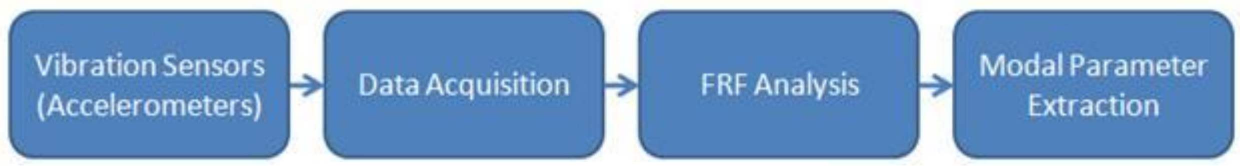


Figure 4.4 - Experimental Modal Analysis

4.3.1 Vibration Sensors (Accelerometers)

Vibration sensors such as accelerometers play a major role in accurate measurement of vibration response of structure. Location of sensor is important to measure the structural dynamic response. Excitation mechanism based on impact hammer or shaker excites the structure and vibration sensors should have frequency range and sensitivity to the dynamic response of structure for any testing setup. Proper selection of sensor and its location is vital to the effective vibration testing of structure.

Figure 4.5 - PCB Accelerometer and Impact Hammer for Measuring Vibration

4.3.2 Data Acquisition

Data acquisition hardware provides setup to obtain vibration signals. Dynamic signal Analyzer (DSAs) consists of 24- analog to digital converters (ADCs) . These DSAs are High resolution product with antialiasing filters which reduce the effect of noise and improve the measurement obtained. These DSAs power the accelerometers to obtain the vibrational response.

Figure 4.6 - National Instruments Data Acquisition Hardware

4.3.3 FRF Analysis

Transfer function is obtained from excitation and response of structure. FRF of any structure is based on its magnitude and phase for a certain frequency range. Frequencies are obtained for a set of mode shapes to obtain the structural response. Magnitude of FRF shows the natural frequency in form of peaks and phase change for structural response. FRF based on magnitude and phase is shown in Figure 4.7.

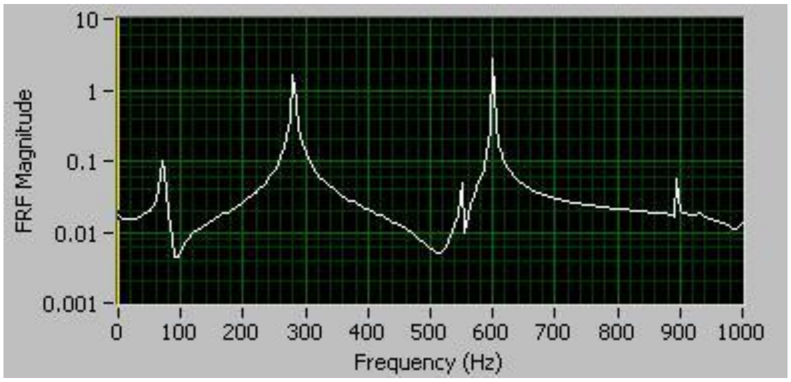


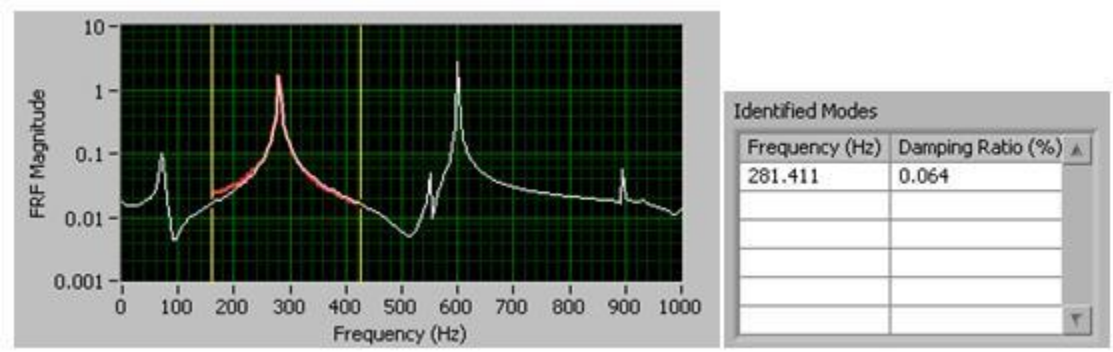
Figure 4.7 - FRF Results for a Test Scenario

4.3.4 Modal Parameter Extraction

Algorithms are developed for moda parameters extraction obtained from FRF of structural response. peak picking, least square complex exponential fit, frequency domain polynomial fit, and FRF synthesis are used to extract the modal parameters these algorithms find their application to a set of testing setups and frequency ranges. Each algorithm is flexible to testing conditions.

- **Peak picking** is used to obtain uncoupled and lightly damped modes in single-degree-of-freedom (SDOF) modal analysis method. This method is sensitive to any shift in frequency.
- **Least square complex exponential fit (LSCE)** uses time domain multiple-degree-of-freedom (MDOF) modal analysis. Major characteristics of this method is that it can be used for a wide range of frequencies and successfully applied for slightly damped modes.
- **Frequency domain polynomial fit (FDPI)** uses frequency domain MDOF modal analysis method for heavily damped modes in a narrow frequency band.

- **FRF synthesis** is compared with original FRF to validate the estimation of actual FRF and its accuracy is achieved more accurately and properly. This approach helps to obtain results more effectively.
- Specific mode is identified in result of algorithm applied. FDPI is used in the following figure for mode identification as it’s a narrow frequency range problem.



Identified Modes

Frequency (Hz)	Damping Ratio (%)
281.411	0.064

Figure 4.8 - Frequency Domain Polynomial Fit Test Results

Chapter 5

Results

RESULTS

5.1 Numerical Simulation for Fixed-Fixed Beam

A Fixed-Fixed Beam of length 2 m with Elastic modulus of 2.1e09 N/m^2 ,and area of 0.0014m^2 and Density of 7850 Kg/m^3 is considered for eigen analysis consisting of 12 Euler Bernoulli beam elements & 13 nodes with 2 DOF per node is shown in Fig.2. Natural frequencies for Intact and damaged structures are calculated and will be termed as analytical & measured frequencies. Three Damage cases are considered and simulated as shown in Table III.

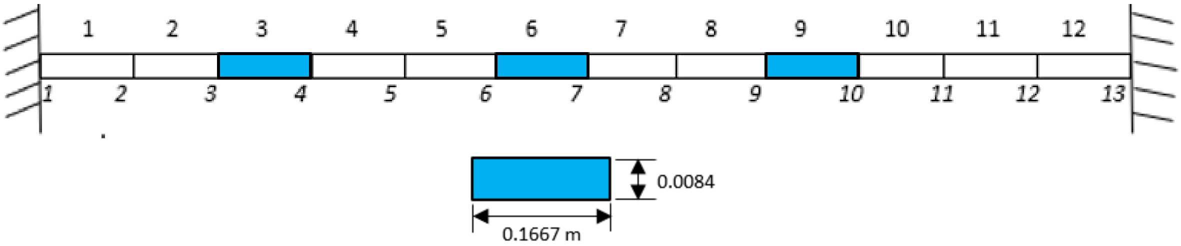


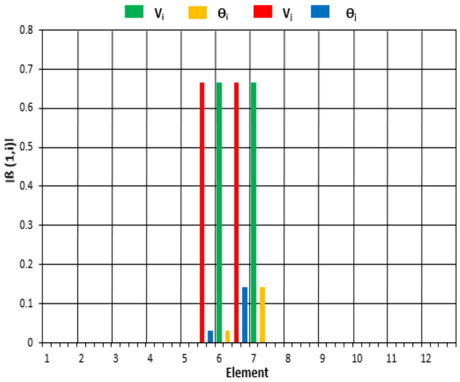
Figure 5.1 - FE Model of a Fixed-Fixed Beam

Table III. First Three Natural Frequencies (Hz) for Fixed-Fixed Beam

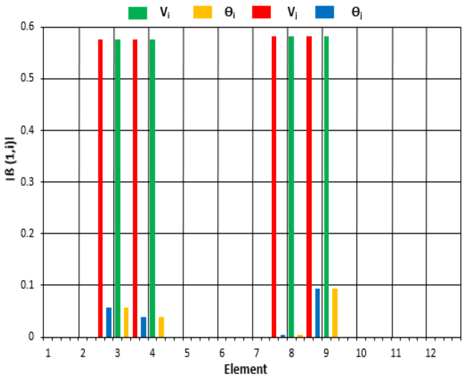
Structure	Damage Location (element)	Damage Severity (percentage)	Natural Frequency (Hz)		
			1st	2nd	3rd
Intact	No	Nil	37.22	102.60	201.21
DCI	6th	35 %	36.16	102.07	195.10
DCII	3rd& 8th	25 % & 30%	36.74	99.66	195.69
DCIII	3rd ,6th& 9th	40 % each	36.67	93.40	187.54

5.1.1 Damage localization Using FRF

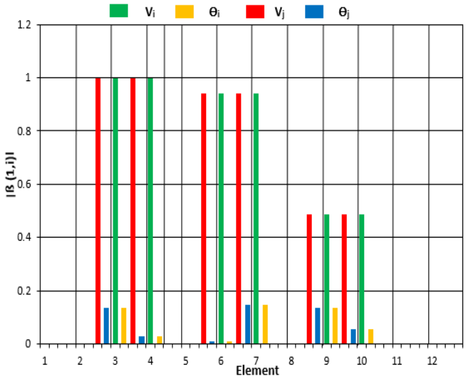
FRF for each damage case indicates presence of damage in the structure. Damage Localization indicator ß(1,i) uses (10) for damage location at element and its corresponding DOF



(a) Damage Indicator beta (ß) for DCI elements

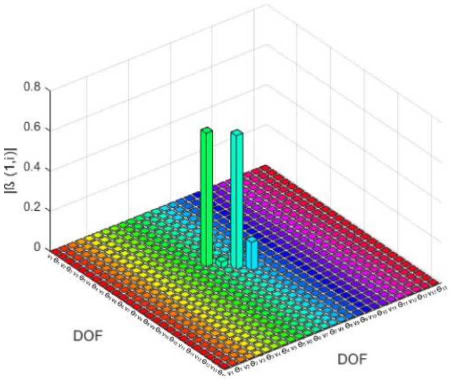


(b) Damage Indicator beta (ß) for DCII elements

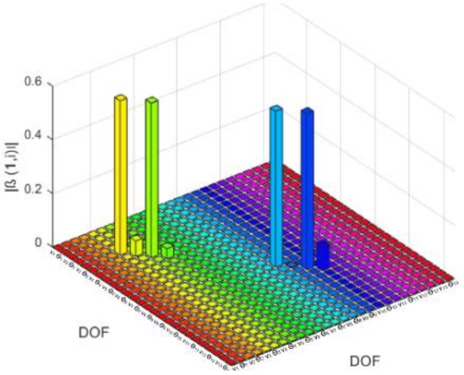


(c) Damage Indicator beta (ß) for DCIII elements

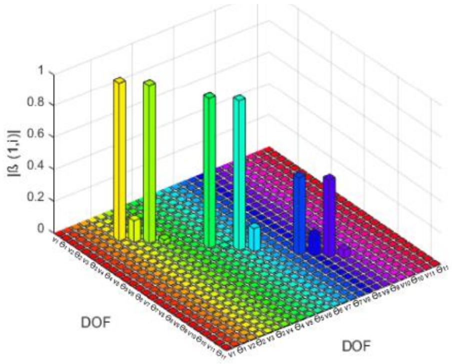
Figure 5.2 - Damage Indicator(ß) based on Elements for Beam



(a) Damage Indicator (ß) for DCI DOFs



(b) Damage Indicator (ß) for DCII DOFs

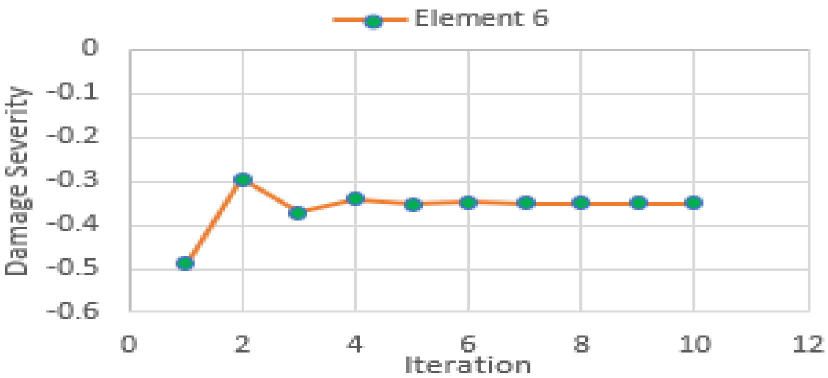


(c) Damage Indicator (ß) for DCIII DOFs

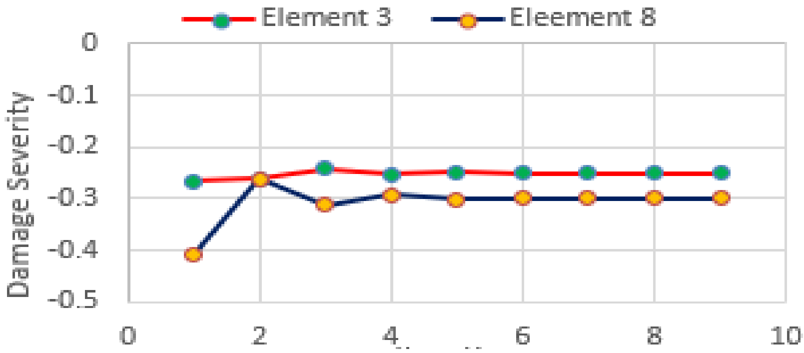
Figure 5.3 - Damage Indicator based on DOFs

5.1.2 Damage Quantification using Iterative Modal Strain Energy Method

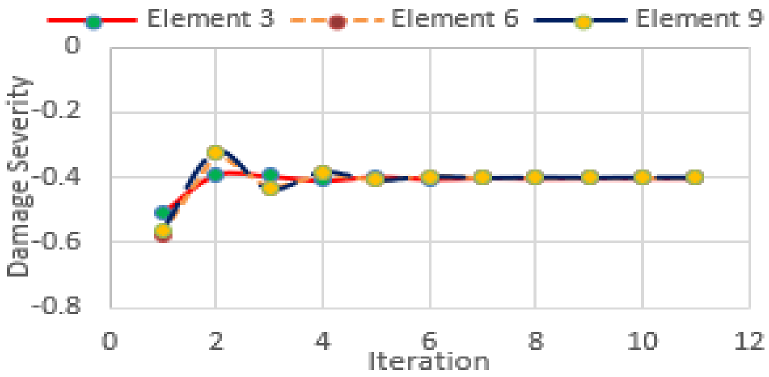
IMSE method utilizes the natural frequencies of Intact and Damaged structures. For a multiple damage case it requires only first Three natural frequencies for damage quantification.



(a) Damage Severity Estimator (α) for DC-I



(b) Damage Severity Estimator (α) for DC-II



(c) Damage Severity Estimator (α) for DC-III

Figure 5.4 - Damage Severity estimation for elements

For beam structure single & multiple damage cases FRFs indicate the presence of damage in all three damage cases. For DCI, ß indicator shows a higher value at 6th element and its corresponding DOFs. Similarly for DC II & DC III , there exists a higher value of ß at 3rd ,6th ,8th and 9th Element. This damage localization is used as an input for damage quantification in the damaged elements. For DCI, IMSE Method uses only first natural frequency of damaged structure. The damage severity estimator α is estimated within 10 iterations with a tolerance of 0.0001, similarly DCII & DCIII require first two and three natural frequencies to estimate the damage severity within 9 & 11 iterations.

5.2 Numerical Simulation & Experimental Validation for Cantilever Beam

A Cantilever beam of length 0.5 m with Elastic modulus of 73.1 e09 N/m^{2}with an area of 0.00025 m^2 and Density of 2780 Kg/m^3 is considered for eigen analysis consisting of 12 Euler Bernoulli beam elements & 13 nodes with 2 DOF per node is shown in Fig.2. Natural frequencies for Intact and damaged structures are calculated and will be termed as analytical & measured frequencies. Three Damage cases are considered and simulated as shown in Table III.

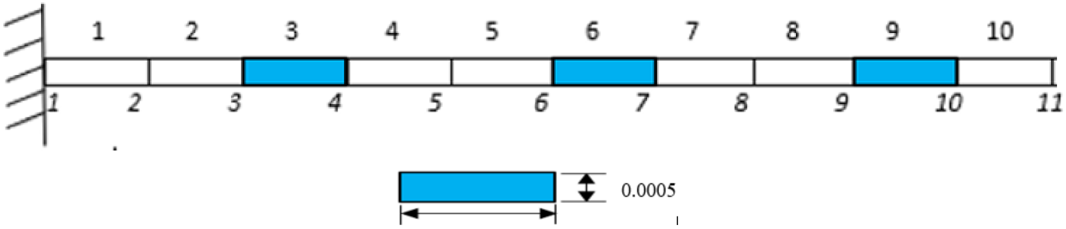


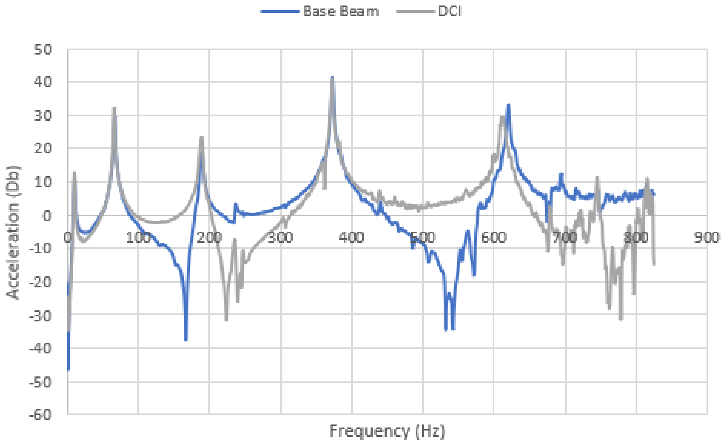
Figure 5.5 - FE Model of a Cantilever beam

Table IV. First Three Natural Frequencies (Hz) for Cantilever Beam

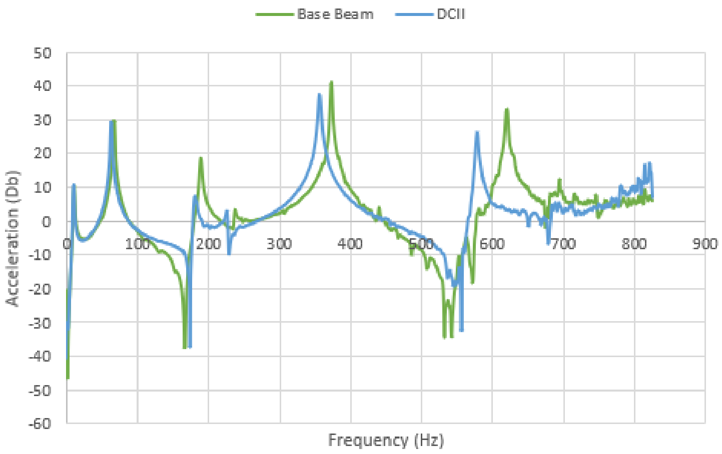
Structure	Damage Location (element)	Damage Severity (percentage)	Natural Frequency (Hz)		
			1st	2nd	3rd
Intact	No	Nil	37.22	102.60	201.21
DCI	6th	35 %	36.16	102.07	195.10
DCII	3rd& 8th	25 % & 30%	36.74	99.66	195.69
DCIII	3rd ,6th& 9th	40 % each	36.67	93.40	187.54

5.2.1 Damage Indication using Experimental FRFs

Experimental modal testing is conducted for three beam Samples and natural frequencies are measured for base beam and damaged beams. Frequency response Function for damaged beams are plotted against base beam which indicate the presence of damage.



(a) Measured FRF for Base and DC I beam samples

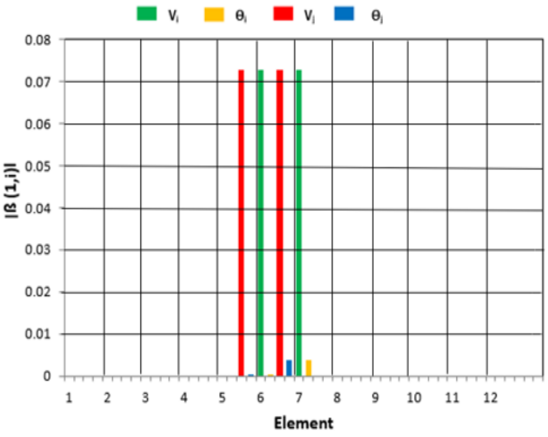


(b) Measured FRF for Base and DC II beam samples

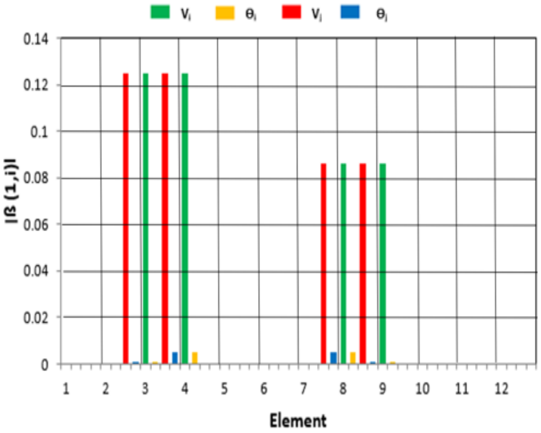
Figure 5.6 -Measured FRF for Intact and Damaged beams

5.2.2 Damage lo

FRF for each damage case indicates presence of damage in the structure. Damage Localization indicator ß(1,i) uses (10) for damage location at element and its corresponding DOF.

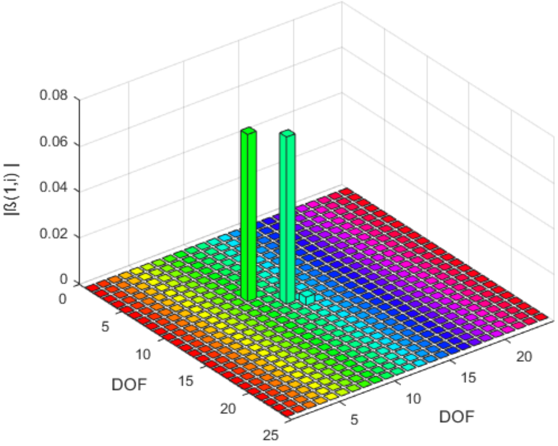


(a) Damage Indicator beta (ß)for DCI elements

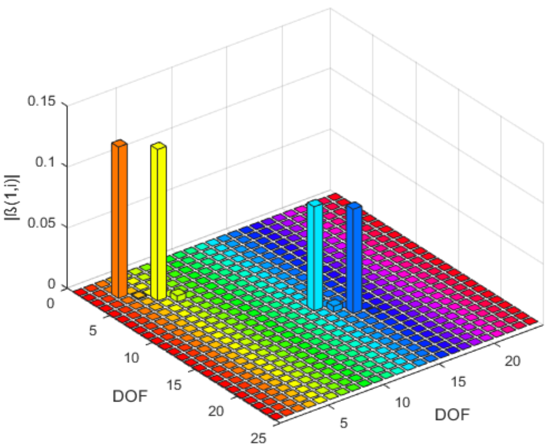


(b) Damage Indicator beta (ß)for DCII elements

Figure 5.7 - Damage Indicator(ß) based on Elements for Beam



(a) Damage Indicator (ß) for DCI DOFs

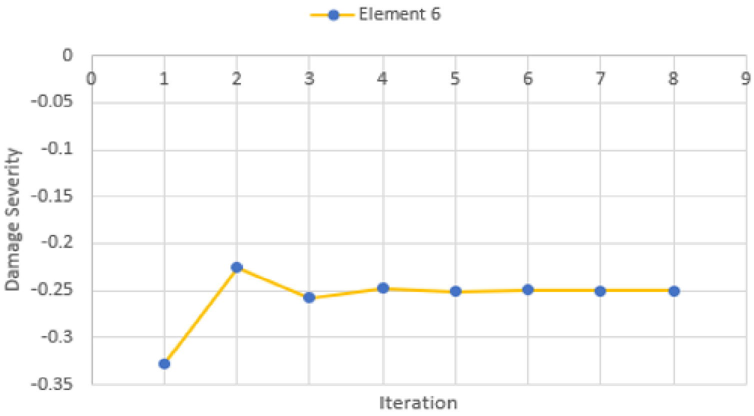


(b) Damage Indicator (ß) for DCII DOFs

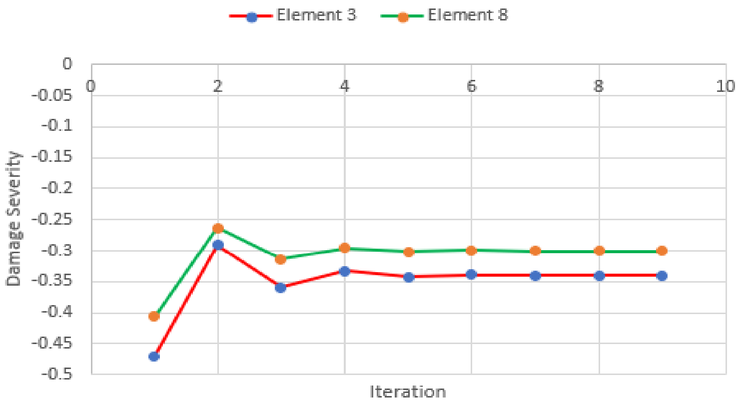
Figure 5.8 - Damage Indicator based on DOFs

5.2.3 Damage Quantification using Iterative Modal Strain Energy Method

IMSE method utilizes the natural frequencies of Intact and Damaged structures. For a multiple damage case it requires only first Three natural frequencies for damage quantification.



(a) Damage Severity Estimator (α) for DC-I



(b) Damage Severity Estimator(α) for DC-II

Figure 5.9 - Damage Severity estimation for elements

For beam structure single & multiple damage cases FRFsindicate the presence of damage in all three damage cases. For DCI, ß indicator shows a higher value at 6th element and its corresponding DOFs. Similarly for DC II, there exists a higher value of ß at 3rd and 8thElement. This damage localization is used as an input for damage quantification in the damaged elements. For DCI, IMSE Method uses only first natural frequency of damaged structure. The damage severity estimator α is estimated within 8 iterations with a tolerance of 0.0001, similarly DCII require first two natural frequencies to estimate the damage severity within 9 iterations.

Chapter 6

Conclusion and Future Work

CONCLUSION AND FUTURE WORK

6.1 Conclusion

A damage Detection Algorithm is developed which uses FRF as Damage indicator and uses its characteristics for damage localization. Damage severity is estimated by IMSE method which requires minimum input in form of few measured frequencies from damaged structure, overcoming the limitations of other modal strain energy methods which require mode shapes at full coordinates for damage localization and quantification. This approach is validated on a cantilever beam using Impact Hammer based modal testing results, A good correlation is developed between numerically simulated and experimentally measured modal parameters .This research work provides a structural damage assessment techniques which provides accurate damage identification , localization and quantification with higher convergence rate at reduce time and computational cost.

6.2 Future Work

As discussed in earlier sections, Structural damage detection is subjected to reliability of its assessment techniques ,this method provides a better approach for damage detection and validated by experimental results as well but a comparative study should be developed for its comparison with Structural health monitoring (SHM) techniques and the second prospect which should be explored is to couple this damage identification technique with some optimization algorithm to further improve its efficiency and performance.

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