INVESTIGATION THE RELATION OF CRACK MODES WITH RESONANCES EXCITATION IN BEAM STRUCTURE

NOOR FARIZA BINTI SAARI

B040710003

This thesis is submitted in partial fulfillment of the requirements for the award of Bachelor of Mechanical Engineering (Structure and Materials)

Faculty of Mechanical Engineering
Universiti Teknikal Malaysia Melaka

May 2011

Supervisor Declaration

‘I * hereby declare that I have read
this report and the views of this work
is inadequate in terms of scope and quality for the award
Bachelor of Mechanical Engineering (Structure and Materials)‘

Signature : ………………………..
Supervisor’s name (1) : ………………………..
Date : ………………………..

Signature : ………………………..
Supervisor’s name (2) : ………………………..
Date : ………………………..

Declaration

"I declare that this thesis is the result of my own except for a summary and excerpts of each of them I have explained the source"

Signature: …………………………..
Author: Noor Fariza binti Saari
Date: …………………………..

I would like to dedicate this work to my parents, En. Saari bin Mohamed and Pn. Zahurin binti Yaakub and also siblings for their supports and made me happy at all times.

ACKNOWLEDGEMENT

I would like to thank to my Supervisor, Dr. Ruztamreen bin Jenal for his guidance, advises and supports throughout this study. His brilliant ideas and suggestions had taught me how to do a research and achieve my research objectives.

Not forgotten to my beloved friends for your supports, comments and helps and lovely thanks to my parents and siblings for their infinite supports and encouragements.

ABSTRACT

In order to obtain the most useful damage detection, the crack related to resonance in beam structure need to be enhanced. It is required that the structure must safely work during its service life. But damage initiates a breakdown period on the structure. Cracks in a structure may be hazardous due to static or dynamic loadings, so that crack or damage detection plays an important role for structural health monitoring application. Beam type structures are being commonly used in construction and machinery industries. Studies based on structural health monitoring for crack detection deal with change in natural frequencies and mode shapes of beam. By this study, its aims are to determine the most effective vibration mode excitation produce the most effective crack edge and to apply the finite element modeling to analyze vibration response from cracked and uncracked beam. The study focuses to simulation approach by developing model of cracked and uncracked beam for modal analysis by using finite element method. The material property of beam is aluminum caused by its homogeneous mechanical properties. By this approach, it presents that the behavior of crack mode is due to three different crack modes with low frequency vibration. When, the beam is excited, the contact surface of crack will move away from the origin position. Thus, we can investigate the movement that interacts with the crack surface corresponding to the crack modes which are opening/closing, sliding and shearing.

ABSTRAK

Dalam rangka untuk mendapatkan tahap pengesanan keretakan yang paling efisien, iaitu keretakan yang berkaitan dengan resonans dalam struktur perlu dipertingkatkan. Hal ini sangat diperlukan kerana struktur sesuatu bahan mestilah berkeadaan baik selama tempoh penggunaannya. Tetapi kerosakan akan memulakan tempoh kerosakan pada sesuatu struktur. Keretakan dalam struktur mungkin berbahaya disebabkan oleh beban yang statik atau dinamik. Oleh itu, keretakan atau pengesanan kerosakan memainkan peranan penting untuk aplikasi pemantauan kesihatan dalam struktur. Struktur jenis 'beam' memang biasa digunakan dalam industri pembinaan dan mesin. Kajian berdasarkan pemantauan kesihatan dalam struktur adalah untuk mengesan keretakan berdasarkan perubahan frekuensi dan bentuk mod getaran. Dengan kajian ini, ianya bertujuan untuk menentukan eksitasi mod getaran yang efisien dan secara langsung menghasilkan keretakan yang paling berkesan dan menggunakan pemodelan elemen yang terhingga untuk menganalisis respon getaran dari struktur yang menpunyai keretakan dan tiada keretakan. Penelitian ini difokuskan pada pendekatan simulasi dengan model 'beam' yang retak dan tiada retak untuk menganalisis modal dengan menggunakan kaedah unsur terhingga. Aluminium digunakan disebabkan oleh sifat-sifat homogen mekanikal. Dengan pendekatan ini, ia menunjukkan bahawa sifat mod retak adalah berdasarkan 3 mod retak yang berbeza dengan getaran frekuensi yang rendah. Dengan demikian, kita dapat menyiasat gerakan yang berinteraksi dengan permukaan retak yang bersesuaian dengan mod retakan yang membuka / menutup, meluncur dan mericih.

TABLE OF CONTENTS

CHAPTER **TITLE** **PAGE**

DECLARATION ii
DEDICATION iii
ACKNOWLEDGEMENT iv
ABSTRACT v
ABSTRAK vi
TABLE OF CONTENTS vii
LIST OF TABLE ix
LIST OF FIGURE x

CHAPTER 1 **INTRODUCTION**

1.1Overview 1
1.2 Objectives 5
1.3 Scope 5
1.4 Problem Statement 6
1.5 Chapter Outline 8

CHAPTER 2. DAMAGE DETECTION BY USING NONLINEAR ACOUSTIC EFFECT

2.1 Theory of Vibration 10

  2.1.1 Vibration 10

  2.1.2 Classification of Vibration 11

  2.1.3 Vibration Mode 12

2.2 Mode Shape 12

2.3 Crack 16

  2.3.1 Classification of cracks 16

2.4 Structural Damage Detection 18

  2.4.1 Fracture/ crack mode 18

2.5 Crack Detection Method 24

  2.5.1 Modal Analysis 24

  2.5.2 Finite Element Method 28

CHAPTER 3 FINITE ELEMENT MODELLING

3.1 Introduction 31

3.2 Flow Chart of Methodology 32

3.3 Flow Chart- General Step of Finite Element Method (ABAQUS) 33

  3.3.1 Modal Analysis by FE Method 34

    3.3.1.1 Uncracked beam 34

    3.3.1.2 Cracked beam 37

  3.3.2 Traansient Dynamic Analysis by FE Method 39

    3.3.2.1 Crack Edge Divergence 40

CHAPTER 4 ANALYSIS OF NATURAL FREQUENCIES

4.1 Introduction 43
4.2 Natural Frequencies based on FE Method 44
    4.2.1 Uncracked beam 44
    4.2.2 Cracked beam 46
4.3 Crack Depth versus Frequency Shifting 48
4.4 Summary 50

CHAPTER 5 TRANSIENT DYNAMIC ANALYSIS

5.1 Introduction 51
5.2 Crack Edge Divergence 52
    5.2.1 Effect of Modal Excitation on Crack Edge Divergence 56
5.3 The effective vibration mode that corresponds to crack modes 59
5.4 Summary 60

CHAPTER 6 CONCLUSION AND RECOMMENDATION

6.1 Summary of Research 61
6.2 Conclusion 62
6.3 Recommendation 63

REFERENCES 64

APPENDICES **Appendix A** 67

Appendix B 69

LIST OF TABLE

BIL	TITLE	PAGE
3.1	Material Properties of the Aluminium beam model for FE analysis	37
4.1	Natural frequencies for the uncracked aluminium beam based on the FE method	44
4.2	Natural frequency for uncracked and cracked beam from FE Method	47
4.3	Frequency shift (%) for cracked beams	47
5.1	Results of crack edge divergence of various crack depth	53-55

LIST OF FIGURE

BIL	TITLE	PAGE
1.1	Three basic crack modes (a), (b) and (c) of fatigue crack in beam	4
2.1	The Mode Shape of Cantilevered I- Beam	13
2.2	Three basic mode of fracture	19
2.3	Finite element modeling of the cracked beam	22
2.4	Testing using impact hammer	24
2.5	Using a shaker as exciter on steel beam	25
2.6	Photograph of the crack after the fatigue test	26
3.1	3D Model Beam	34
3.2	Step selected in natural frequency analysis	35
3.3	Meshed Model	36
3.4	Creating crack	38
3.5	Open crack with node A and B	39
3.6	The step of transient dynamic analysis	40
3.7	Load at the beam tip	41
3.8	(a) Nodal labeled	41
	(b) The assigned node A and B in XY Data	42
4.1	Mode shapes for the uncracked aluminum beam	45
4.2	Illustaration of fatigue crack	48
4.3	Percentage of frequency shift versus crack depth for aluminum beam at various vibration modes excitation from FE method	48
5.1	IIlustartion of fatigue crack with point A and B	52
5.2	The Amplitude of Crack Edge Divergence for excitation frequency corresponding to different vibration modes for various crack depth	56-58

CHAPTER 1

INTRODUCTION

1.1 Overview

It is required that structures must safely work during its service life. But, damages initiate a breakdown period on the structures. Cracks are among the most encountered damage types in the structures. Cracks in a structure may be hazardous due to static or dynamic loadings, so that crack detection plays an important role for structural health monitoring applications. Beam type structures are being commonly used in construction and machinery industries. In the literature, several studies deal with the structural safety of beams, especially, crack detection by structural health monitoring (SHM). Studies based on structural health monitoring for crack detection deal with change in natural frequencies and mode shapes of the beam.

In maintenance engineering, Structural Health Monitoring (SHM) is a common approach for maintaining the performance, safety and reliability of structures. It has been widely applied in various structures such as aircraft, bridges and offshore platforms. SHM refers to the process of damage detection and characterization of the damage for further maintenance strategies. It consists of various damage detection methods and damage monitoring systems that can measure the effects of damage on a structure's functionality or reliability.

The most common structural defect is the existence of a crack. Cracks are present in structures due to various reasons. The presence of a crack could not only cause a local variation in the stiffness but it could affect the mechanical behavior of the entire structure to a considerable extent. Cracks may be caused by fatigue under service conditions as a result of the limited fatigue strength. They may also occur due to mechanical defects. Another group of cracks are initiated during the manufacturing processes. Generally they are small in sizes. Such small cracks are known to propagate due to fluctuating stress conditions. If these propagating cracks remain undetected and reach their critical size, then a sudden structural failure may occur. Hence it is possible to use natural frequency measurements to detect cracks.

In recent years, the application of nonlinear effects from acoustic waves for damage detection has been extensively studied. This is due to the advantage of detecting micro damage or early signs of damage [3, 4] and the fact that nonlinear manifestation due to cracks is more easily detected than traditionally used linear measurement .In contrast with linear analysis, nonlinear analysis is a technique of analyzing wave signal outputs that are unrelated to the signal inputs (i.e. wave amplitude and speed, scattering coefficient) [3]. The most common nonlinear effects that highly dependent on the wave propagating medium are generation of side bands, amplitude dissipation, generation of harmonics and resonant waves shifting. It is a technique of exciting a test specimen with two frequency waves simultaneously and inspecting the harmonics and sidebands of the frequencies to detect damage.

In the present investigation a number of literatures published so far have been surveyed, reviewed and analyzed. Most of researchers studied the effect of single crack on the dynamics of structures. However in actual practice structural members such as beams are highly susceptible to transverse cross-sectional cracks due to fatigue. Therefore to attempt has been made to investigate the relation of crack modes with resonances excitation on a beam structure.

It is essential to analyze the modal parameters of a cracked beam in order to understand the behavior of movement of crack edges in a beam and beam surface responses to the low-frequency excitation. Modal analysis involves analytical analysis using Finite Element (FE) modeling. At each specified resonant frequency excitation, a structure will respond or vibrate to a unique structure deformation or curvature of surface known as mode shape. Each mode shape corresponds to a vibration mode.

Vibration analyses of uncracked and cracked aluminum beam using finite element (FE) method. The simulation results then are used to determine the behavior of crack modes due to crack surface interaction which respect to different direction x, y and z corresponding crack modes caused by the vibration. Both approaches are presented to demonstrate the behavior of the crack modes due to three different crack modes with the low frequency vibration. When the beam is excited, the crack will move away from the origin position, thus, we can investigate the movement that interact with the crack surface corresponding to the crack modes which are, opening/ closing crack, sliding crack or shearing crack. The illustration of crack modes can be seen from the Figure 1.1.

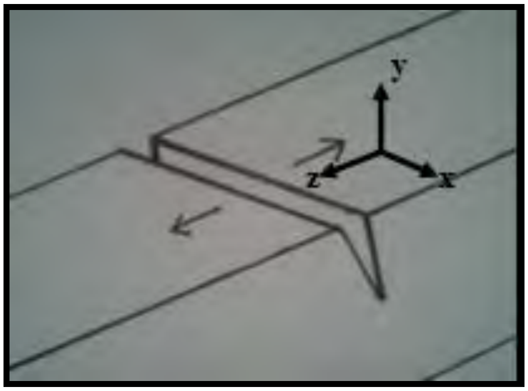

Figure 1.1 (a): Crack mode-I
(Opening / closing mode)

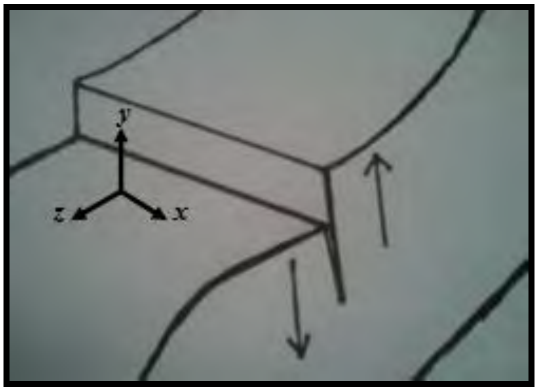

Figure 1.1 (b): Crack mode- II
(Sliding mode)

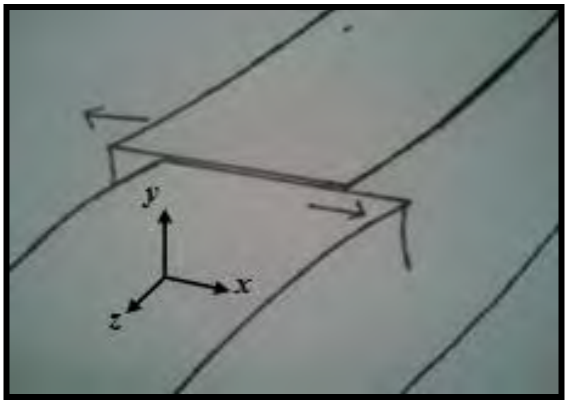

Figure 1.1 (c): Crack mode- III

(Tearing/ shearing mode)

Figure 1.1: Three basic crack modes (a), (b) and (c) of fatigue crack in beam

Whatever the explanation behind nonlinear effects, low-frequency excitation is a crucial element of nonlinear acoustic technique when used for crack detection. It is important to know what frequency and level of excitation is required to analyze the behavior of fatigue crack surface interaction either fully open/ close crack, sliding and shearing crack against natural frequency. By investigating the fatigue crack surface interaction modes, the crack edge divergence obtained will help to determine which mode of crack produce most effective nonlinear effect.

1.2 Objectives

In order to achieve the objectives, this project aims to:-

- To apply finite element modeling to analyze vibration responses of uncracked and cracked beam;
- To analyze the relation of crack depth with the crack modes in order to determine the most effective vibration that produces the largest divergence of fatigue crack edge.

1.3 Scope

This project focuses to:

- Develop crack interaction in beam model;
- Extract natural frequencies and mode shape by using FE modeling for uncracked and cracked beam;
- Analyze the relation between vibration mode and mode shape;
- Analyze the natural frequency shift against the vibration modes;
- Analyze the extracted natural frequencies for different crack depths;
- Select nodal to obtain the crack edge divergence respectively to 3 direction of crack modes;
- Analyze the obtained crack edge divergence;
- Select the most effective vibration mode which produces the largest crack edge divergence.

1.4 Problem Statement

The most common structural defect is the existence of fatigue crack. Cracks are present in structures due to various reasons. The presence of a crack could not only cause a local variation in the stiffness but it could affect the mechanical behavior of the entire structure to a considerable extent. Cracks may be caused by fatigue under service conditions as a result of the limited fatigue strength. They may also occur due to mechanical defects. Another group of cracks are initiated during the manufacturing processes. Generally they are small in sizes. Such small cracks are known to propagate due to fluctuating stress conditions. If these propagating cracks remain undetected and reach their critical size, then a sudden structural failure may occur. Hence it is possible to use natural frequency measurements to detect cracks. Since damage like fatigue cracks consists of three modes of interface interactions, the investigation of each natural frequency against nonlinear acoustic effects is necessary. This is because each frequency has a unique deformation shape that may have a unique contribution to the effects.

However, the mechanism of the nonlinear acoustic effects is not quite established and very limited in real engineering practice due to lack of understanding regarding the physical mechanism behind the nonlinear acoustic effects whereas all effects are crucial for incipient damage detection. This is a good sign that this method is a reliable tool for damage detection. However, it is more complicated to understand the physical mechanism nonlinear acoustic effects because there are many causes which may happen simultaneously where one of the behaviors is due to crack surface interaction. As strain level around the defect area increases, the causes of nonlinearity may increase. These include material hysteresis, non-uniform material stiffness, thermal elasticity, internally or externally induced thermal friction, boundary deformation, and others.

In order to reduce the above problem, there are many studies showing the effectiveness of mechanism of the nonlinear acoustic effects for enhancing damage detection. With the advancement of smart materials and technology, this technique of diagnosing defects has become more reliable and accurate. The advantages of new signal processing tools can also be used with this mechanism effects to analyze the measured data. By using the finite element method with the advancement of computing and software technology, the prediction of the nonlinear acoustic effects for any materials or structures has become easier, faster, and more reliable. Therefore, with the advance technology, we suppose to introduce the mechanism of the nonlinear acoustic effects that respect to the mechanism due to the fatigue crack surface interaction as a way for fatigue damage detection. Thus, from the above hypothesis, we decided to relate the relation of the crack surfaces interaction with low frequency vibration.

1.5 Chapter Outline

In order to achieve the objective, there are some chapters or steps that need to be considered to ensure that the project can be completed. In Chapter 2, the literature reviews about damage detection using nonlinear acoustic effect that have been reviewed by referring from books, article, and magazine or on the websites, journals and other resources. Besides, in this chapter, it reviews briefly about the mode shape, the classification of crack, the basic of crack modes and the analysis used for this research.

Meanwhile in Chapter 3, it discusses about the methodology that needs to be used in creating and developing uncracked and cracked beam for modal analysis and transient dynamic analysis. Both analyses are applied in FE method. In this chapter also explains the procedures and steps used to developing model, selecting the suitable steps, creating and assigning a crack and analyzing the results obtained in this FE method.

Furthermore, in Chapter 4, it presents the results and discussion of the analysis of natural frequencies based on FE method for uncracked and cracked beam. There are 10 modes of natural frequencies have been extract and each vibration modes present the shape mode of beam. Those extracted natural frequencies are then used directly in next analysis that will be discussed on Chapter 5.

Chapter 5 presents the results and the discussion about the transient dynamic analysis where its purpose to find the crack edge divergence corresponding to the direction *x*, *y* and *z*. Therefore, by analyzing this section, the most effective of vibration mode that produce the largest crack edge divergence can be determined. Finally, the conclusion and recommendation about the investigation of relation of crack mode with resonances excitation in beam structure are discussed in Chapter 6.

.

CHAPTER 2

DAMAGE DETECTION BY USING NONLINEAR ACOUSTIC EFFECT

In this chapter, literature review is done to explore the previous research related to low vibration excitation to the crack modes in beam structure. The focus is on various methods used for fatigue crack detection and all the information researches those are relevant with the title of project. Thus, by this literature review, the previous research which related to this approach will help to apply and guide on the further research.

When a structure suffers from damages, its dynamic properties can change, especially, crack damage can cause a stiffness reduction, with an inherent reduction in natural frequencies, an increase in modal damping, and a change of the mode shapes. For vibration analysis of cracked beams and possible crack detection, the fracture mechanics procedure is generally preferred [1].

2.1 Theory of vibration

2.1.1 Vibration

Vibration refers to mechanical oscillations about an equilibrium point. The oscillations may be periodic such as the motion of a pendulum or random such as the movement of a tire on a gravel road. Vibration is occasionally "desirable". For example the motion of a tuning fork, the reed in a woodwind instrument or harmonica, or the cone of a loudspeaker is desirable vibration, necessary for the correct functioning of the various devices. More often, vibration is undesirable, wasting energy and creating unwanted sound – noise. For example, the vibration motions of engines, electric motors, or any mechanical device in operation are typically unwanted. Such vibrations can be caused by imbalances in the rotating parts, uneven friction, the meshing of gear teeth, and others. Careful designs usually minimize unwanted vibrations [37].

Besides, mechanical vibration is the term used to describe the continuing periodic motion of a solid body at any frequency. When the rate of vibration of the solid body ranges between 20 and 20,000 hertz (Hz), it may also be referred to as an acoustic vibration, for if these vibrations are transmitted to a human ear they will produce the sensation of sound. The vibration of such a solid body in contact with a fluid medium such as air or water induces the molecules of the medium to vibrate in a similar fashion and thereby transmit energy in the form of an acoustic wave. Finally, when such an acoustic wave impinges on a material body, it forces the latter into a similar acoustic vibration. In the case of the human ear it produces the sensation of sound.

2.1.2 Classification of vibration

Vibration can be classified in several ways. Some of the important classifications are as follows:

- **Free and forced vibration**

If a system, after an internal disturbance, is left to vibrate on its own, the ensuing vibration is known as free vibration. No external force acts on the system. The oscillation of the simple pendulum is an example of free vibration. If a system is subjected to an external force (often, a repeatating type of force), the resulting vibration is known as forced vibration. The oscillation that arises in machineries such as diesel engines is an example of forced vibration. If the frequency of the external force coincides with one of the natural frequencies of the system, a condition known as resonance occurs, and the system undergoes dangerously large oscillations. Failures of such structures as buildings, bridges, turbines and airplane have been associated with the occurrence of resonance [2].

- **Undamped and damped vibration**

If no energy is lost or dissipated in friction or other resistance during oscillation, the vibration is known as undamped vibration. If any energy lost in this way, however, it is called damped vibration. In many physical systems, the amount of damping is so small that it can be disregrated for most engineering purposes. However, consideration of damping becomes extremely important in analyzing vibratory system near resonance.

- **Linear and nonlinear vibration**

If all the basic components of vibratory system—the spring, the mass and the damper- behave linearly, the resulting vibration is known as linear vibration. If the basic components behave nonlinearly, the vibration is called non linear vibration.

2.1.3 Vibration mode

A characteristic manner in which vibration occurs in a freely vibrating system, oscillation is restricted to certain characteristic frequencies; these motions are called normal modes of vibration. An ideal string, for example, can vibrate as a whole with a characteristic frequency, where L is the length of string between rigid supports, T the tension, and *m* the mass per unit length of the string. The displacements of different parts of the string are governed by a characteristic shape function. The frequency of the second mode of vibration is twice that of the first mode. Similarly, modes of higher order have frequencies that are integral multiples of the fundamental frequency [39].

2.2 Mode shape

A mode shape is a specific pattern of vibration executed by a mechanical system at a specific frequency. Different mode shapes will be associated with different frequencies. The experimental technique of modal analysis discovers these mode shapes and the frequencies. Besides, the mode shape is also defined with the central concern that underlies the notion of mode shapes which related to choice of coordinate system to formulate the equations of motion of vibrating structures. When we formulate equation of motion for multi-degree of freedom systems, it needs to begin by selecting a coordinate system.