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Vibration Analysis of Cracked Beam using Intelligent Technique

P. M. P. SAIRAM[1], Y. SAI KRISHNA[2]
[1]PG Scholar, Dept of Civil Engineering, DJR College of Engineering &Technology, AP, India,
Email: pmpsairam01@gmail.com.
[2]Associate Professor, Dept of Civil Engineering, DJR College of Engineering &Technology, AP, India,
Email: sai.dashing@gmail.com.

Abstract: Structural systems in a wide range of Aeronautical, Mechanical and Civil Engineering fields are prone to damage and deterioration during their service life. So an effective and reliable damage assessment methodology will be a valuable tool in timely determination of damage and deterioration in structural members. Interest in various damage detection methods has considerably increased over the past two decades. During this time many detection methods founded on modal analysis techniques have been developed. Non-destructive inspection techniques are generally used to investigate the critical changes in the structural parameters so that an unexpected failure can be prevented. These methods concentrate on a part of the structure and in order to perform the inspection, the structure needs to be taken out of service. Since these damage identification techniques require a large amount of human intervention, they are passive and costly methods. A crack in a structural member introduces local flexibility that would affect vibration response of the structure. i.e., a crack causes a reduction in the stiffness and an increase in the damping of the structure. These changes of physical properties cause a reduction in the natural frequencies and a deviation in the mode shape. Therefore it is possible to predict the crack depth and crack location by measuring changes in the vibration parameters. Changes in the natural frequencies are more often considered than deviation of mode shapes, since frequencies can be measured more easily than mode shapes, and they are less seriously affected by experimental errors. This property may be used to detect existence of a crack together with its location and depth in the structural member. In this analysis the first three natural frequencies obtained from theoretical analysis and finite element analysis are trained in fuzzy logic controller and genetic algorithm controller to obtain the crack location and crack depth. Both types of fuzzy inference system i.e., Mamdani FIS and Takagi-Sugeno FIS are used for the prediction of crack depths and crack locations. It has been observed Mamdani FIS provides reasonable results with a relatively simple structure, and also due to the intuitive and interpretable nature of the rule base. The obtained results show that the T-S FIS presented provides a suitable functional approximation with a low computational load. Genetic algorithm is a type of evolutionary algorithm which is used to search the best fit (crack depth and crack location) for a set of natural frequencies. GA produces results which are in good agreement with that of the data table. But the exhaustive search and stochastic nature is its weakness. So in this work pattern search algorithm is also used to make the search global and quicker so that all the points in the solution space may be evaluated for the fitness value. When the GA is used with pattern search algorithm, produces more efficient results with significantly low computational time and further provides a robust tool for real time fault diagnosis applications. In summary this investigation is a step towards to forecast the characteristics of the damage using the Artificial Intelligence techniques and compare their results. The results from different analyses are compared among themselves. Finally the results from the fuzzy controller and the genetic algorithm controller are validated by doing experimental analysis.

Keywords: Damage, Vibration, Natural Frequency, Crack Depth, Crack Locations, Mamdani FIS, Takagi-Sugeno FIS, Genetic Algorithm, Pattern Search Algorithm.

I. INTRODUCTION

Many structural applications worldwide have been in use for tens or even hundreds of years. Their failure could lead to tragic consequences and therefore structures have regular costly inspections. During the last decades vibration based damage detection methods have attracted the most attention due to their simplicity for implementation. A brief description about the techniques that have been applied for fault diagnosis has been given in this chapter. At first framework and agenda in the field of vibration analysis of damaged structures has been defined. The second part of this chapter describes the purpose of this research. Finally the details of each chapter of the thesis for the current investigation have been explained in the third part of this chapter.

A. Framework and Agenda

Engineering structures deteriorate due to its regular usage over time. This process can be initiated or even accelerated due to environmental effects and adverse load configurations. The safety of a deteriorated structure can be ensured with structural health monitoring (SHM). With the methods of SHM, the performance of a structure is controlled. Usually, deterministic threshold values are taken as performance criteria for the monitoring process. The exceeding from these values during the monitoring process indicates a further increase of damage or deterioration and should lead to immediate measures. The highest safety could be achieved if the monitoring strategy covers the complete structure. Usually, this is not possible due to the related costs. Therefore optimal and cost effective maintenance strategies are required. Structural damage identification using dynamic parameters of the structure has become an important research area. The standard procedure of performing routine maintenance and replacing parts before they have actually used up their life is inefficient and increases the cost of the structure. For example currently 27 % of an average aircraft's life cycle cost is spent on inspection and repair. The strong need to develop effective damage identification techniques for Damage in engineering systems is defined as intentional or unintentional changes to the material and geometric properties of these systems, including changes to the boundary conditions and system connectivity, whi ch adversely affect the current and future performance of that system. Beams are one of the most commonly used structural elements. Beams are a major part of many different types of construction projects, be they residential, commercial or public like buildings, bridges and factories. Damages may occur in beam-like structures due to different type of loads. It has also been observed that the presence of cracks in machine elements like shafts also lead to operational problem as well as premature failure. A shaft is a means of transferring energy therefore, any type of failure in one, such as fatigue cracks, causes serious damage to the system. The damage may lead to plant shutdown and great economical loss. Thus, many attempts in recent years have been made to deal with shaft crack detection methods.

II. LITERATURE REVIEW

Existence of structural damage in structural elements like beams and shafts leads to the modification of the vibration modes. A crack in a structural member introduces local flexibility that would affect vibration response of the structure. This property may be used to detect existence of a crack together its location and depth in the structural member. Thus, an analysis of periodical frequency measurements can be used to monitor the structural condition. During this time many detection methods founded on modal analysis techniques have been developed. In the following paper some of the techniques which have been used in damage detection of structural members by different researchers have been described.

A. Introduction

Structural damages may occur in a beam used in a bridge or in a rotating machine shaft, in all situations safety is the main requirement. Beams are one of the most commonly used structural elements in numerous engineering (civil, mechanical and aerospace) applications and experience a wide variety of static and dynamic loads. Failure of any of the structural element may appear in the form of a hazardous accident. To avoid these situations there should be continuous health monitoring. Cracks are among the most encountered damage types in the structures. A direct procedure is difficult for crack identification and unsuitable in some particular cases, since they require minutely detailed periodic inspections, which are very costly. In order to avoid these costs, recently researchers have adopted an alternative and more efficient procedure in crack detection through vibration analysis. Some of these techniques which have been used in the current research work are given in the following section.

B. Damage Detection using Finite Element Method

The cracked beam problem has attracted the attention of many researchers in recent years. Various kinds of analytical, semi-analytical and numerical methods have been employed to solve the problem of a cracked beam. A common method is to use the finite element method (FEM).In this section, some of the authors work to derive new FEM formulas and analysis of the dynamic behavior of the cracked beam to overcome the existing shortcomings is produced. Lee et al. [1] have developed a method to find the lowest four natural frequencies of the cracked structure by F.E.M. and the approximate crack location is obtained by using Armon's Rank-ordering method that uses the above four natural frequencies. Guo et al. [2] have proposed and described a method for shaft crack detection which formulates the shaft crack detection as an optimization problem by means of finite element method and utilizes genetic algorithms to search the solution. Owolabi et al. [3] have reported in his paper a part of an ongoing research on the experimental investigations of the effects of cracks and damages on the integrity of structures. Sahin et al. [4] have introduced in his research different damage scenarios by reducing the local thickness of the selected elements at different locations along finite element model (FEM) for quantification and localization of damage in beam-like structures. Al-Qaisia et al. [5] have utilized the reduction of Eigen frequencies and sensitivity analysis to localize a crack in a non-rotating shaft coupled to an elastic foundation. The shaft was modeled by the finite element method and coupled to an experimentally identified foundation model. With a view to detect, quantify, and determine their extents and locations. Zheng et al. [6] have found the natural frequencies and mode shapes of a cracked beam using the finite element method and ‘overall additional flexibility matrix’, instead of the ‘local additional flexibility matrix’. Compared with analytical results, the new stiffness matrix obtained using the overall additional flexibility matrix can give more accurate natural frequencies than those resulted from using the local additional flexibility matrix. Behzad et al.have calculated natural frequencies for abeam with open edge crack using theoretical and finite element analysis. Nahvi et al. [8] have developed an analytical, as well as experimental approach to the crack detection in cantilever beams by vibration analysis.

III. ANALYSIS OF DYNAMIC CHARACTERISTICS OF BEAM WITH SINGLE TRANSVERSE CRACK

Significant uncertainties are present in predicting structural deterioration and loading over time. There are varieties of prediction models. In order to ensure satisfactory long term safety and performance, both preventive and corrective maintenance inventions need to be carried out in a timely and adequate manner in order to mitigate progressive deterioration and for correcting major structural defects. Therefore, there is the need to understand the dynamic characteristics of cracked structures to save the structure before hand by detecting the crack location and its intensity. When a structure suffers damage, its dynamic properties change. Specifically, damage due to the crack can cause a stiffness reduction, with an inherent reduction in natural frequencies, an increase in modal damping, and a change in the mode shapes.

A. Dynamic Characteristics of a Cantilever Beam with a Transverse Crack

A systematic approach has been produced in this section for finding out the expressions for the calculation of natural frequencies of cracked cantilever beam with a transverse crack and to observe the effect of crack on natural frequencies.

B. Theoretical Vibration Analysis

The presence of a transverse surface crack of depth ‘a1’ on beam of width ‘B’ and height ‘W’ introduces a local flexibility, which can be defined in matrix form, the dimension of which depends on the degrees of freedom. Here a 2x2 matrix is considered. A cantilever beam is subjected to axial force (P1) and bending moment (P2).

IV. ANALYSIS OF DYNAMIC CHARACTERISTICS OF BEAM USING FINITE ELEMENT METHOD

A. Introduction

The Finite Element Method has developed into a key, indispensable technology in the modeling and simulation of advanced engineering systems in various fields like housing, transportation, communications and so on. In building such advanced engineering systems, engineers and designers go through a sophisticated process of modeling, simulation, visualization, designing, prototyping, testing and lastly fabrication. The process is often iterative in nature, meaning that some of the procedures are repeated based on the results obtained at a current stage, so as to achieve an optimal performance at the lowest cost for the system to be built.

B. Methods used in FEM

The behavior of a phenomenon in a system depends upon the geometry or domain of the system, the property of the material or medium and the boundary, initial and loading conditions. It is therefore, in general, very difficult to solve the governing differential equation via analytical means. In practice, most of the problems are solved using numerical methods. Among these, the methods of domain discretization championed by the Finite Element Method are the most popular due to its practicality and versatility which can also be used to find out the natural frequencies of a cracked structural element. This chapter describes the systematic approach for the Finite element analysis. The procedure of computational modeling for finding out the natural frequencies of the cracked beam using the Finite Element Method broadly consists of four steps:

- Modeling of the geometry
- Meshing (discretization)
- Specification of material property
- Specification of boundary, initial and loading conditions.

C. Finite Element Formulation

The beam with a transverse edge crack is clamped at left end, free at right end and has uniform structure with a constant rectangular cross-section of 800 mm X 38 mm X 6 mm. The Euler-Bernoulli beam model is assumed for the finite element formulation. The crack in this particular case is assumed to be an open crack and the damping is not being considered in this theory. Only single edged crack is considered for the formulation.

D. Applications of Finite Element Method

In the finite element analysis of the cracked cantilever beam having V-shaped single crack is taken into account. The length and cross-sectional area of the beam are 800 mm, and 38 X 6 mm^2, respectively. As per the material properties the modulus of elasticity (E) is 70,000 Mpa, the density (?) is 2700 kg/m^3. Different crack configurations of same depth and at different locations (from different distance from the fixed end) are prepared to find out how the crack affects the dynamic behavior of the beam. Here crack depth and crack location both were varied, and the variation in the first three natural frequencies were noted down.

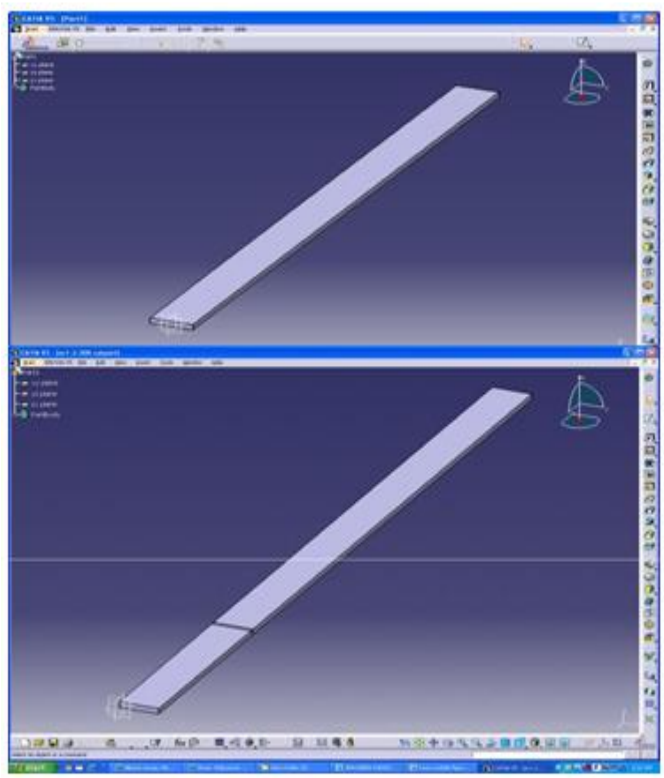

Fig1. Model of the beam without crack and with crack.

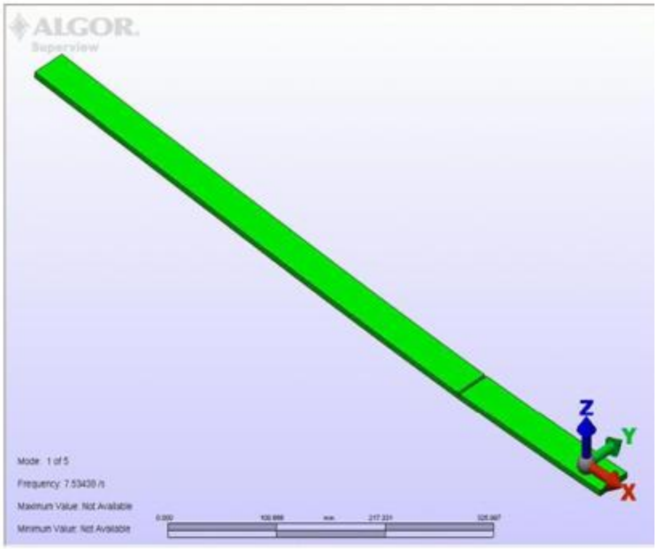

Fig2. First Mode of Vibration of the Cracked Beam after Finite Element Analysis.

V. ANALYSIS OF FUZZY LOGIC CONTROLLER FOR CRACK DETECTION

Fuzzy set theory provides a major newer paradigm in modeling and reasoning with uncertainty. Though there were several forerunners in science and philosophy, in particular in the areas of multivalued logic and vague concepts. Zadeh, a professor at Berkeley was the first to propose a theory of fuzzy sets and an associated logic, namely fuzzy logic. Essentially, a fuzzy set is a set whose members of the set may have degrees of membership between 0 and 1, as opposed to classical sets where each element must have either 0 or 1as membership value. A fuzzy system is an alternative to traditional notions of set membership and logic that has its origins in ancient Greek philosophy, and applications at the leading edge of Artificial Intelligence. Yet, despite its long-standing origins, it is a relatively new field, and as such leaves much room for development. This chapter will present the foundations of fuzzy systems, along with some of the more noteworthy objections to its use, with examples drawn from current research in the field of Artificial Intelligence. Ultimately, it will be demonstrated that the use of fuzzy systems makes a viable addition to the field of Artificial Intelligence. Here Fuzzy Logic is used for training of the datasets of the data table for the prediction of the relative crack depth and relative crack location. Basically, the fuzzy logic provides an inference organization that enables proper human reasoning capabilities that machines do not have. It uses fuzzy rules, which are a representation of expertise, wisdom or rules-of-thumb, often represented by rules containing "if-then" conditional statements or cases containing various fact patterns. Knowledge bases may also consist of representative objects (excited utterance) within a sub-class (rules against hearsay) and class (rules of evidence) of information. Knowledge bases typically focus on narrow issues, known as a domain, within a particular fact situation. The different steps used in a Fuzzy Inference System are described in the following flowchart.

VI. RESULTS AND DISCUSSIONS

In this chapter the results obtained from various analyses are discussed and the effects of cack parameters on the dynamic structure have been analyzed.

A. Discussions of results

This research work has been completed in following six steps. The steps are as follows: Literature review involves various researchers' works corresponding to this field. Analysis of the dynamic response of the cracked beam with a transverse single crack has been done. Finite element analysis of the cracked cantilever beam has been done to get the first three natural frequencies for various positions of crack depth and crack location. Analysis and design of fuzzy logic controller for the crack characteristic prediction has been developed. Genetic Algorithm and Pattern search Algorithm for crack detection are used. Experimental analysis has been performed to validate the results from different controllers. In literature review chapter various practice adapted by different researchers since last two decades for damage identification in structural elements have been given. Much structural health monitoring means used by different authors for damage detection in different sphere of engineering applications with the help of Artificial Intelligence techniques and other techniques have been discussed. In the third chapter the Theoretical analysis has been carried out. Vibration based methods use the fact that due to the presence of the crack, there is a change in the flexibility which affects the natural frequency of the cracked structure. Using Castiglione's theorem and strain energy density function, the flexibility matrix is derived.

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Author's Profile:

P.M.P Sairam received his B.Tech degree in Civil Engineering and pursuing M.Tech degree in Civil Engineering(structural) from DJR College of Engineering & Technology.

Y.Sai Krishna received his M.Tech degree and B.Tech degree in Civil Engineering . He is currently working as an Assoc Professor in DJR College of Engineering & Technology.