"VIBRATION ANALYSIS OF FAULTY BEAM USING FUZZY LOGIC TECHNIQUE"

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By

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CERTIFICATE

This is to certify that the project entitled, "**VIBRATION ANALYSIS OF FAULTY BEAM USING FUZZY LOGIC TECHNIQUE**" submitted by '**Ms. Nikita Hotwani'** in partial fulfilments for the requirements for the award of Bachelor of Technology Degree in Mechanical Engineering at National Institute of Technology, Rourkela (Deemed University) is an authentic work carried out by her under my supervision and guidance.

To the best of my knowledge, the matter embodied in the report has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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10th May 2009 (NIKITA HOTWANI)

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ABSTRACT

The method of detecting crack location and its intensity in beam structures by fuzzy logic techniques and using ALGOR for finite element analysis has been considered in this project. The fuzzy logic controller used here comprises of three input parameters and two output parameters. Gaussian and triangular member ship functions are used for the fuzzy controller. The input parameters to the fuzzy- Gaussian controller and fuzzy- triangular controller are relative deviation of first three natural frequencies. The output parameters of the fuzzy inference system are relative crack depth and relative crack location. At the beginning theoretical analyses have been outlined for cracked cantilever beam to calculate the vibration parameters such as natural frequencies. A set of boundary conditions are considered involving the effect of crack location. A series of fuzzy rules are derived from vibration parameters which are finally used for prediction of crack location and its intensity. The comparison is made between Gaussian and triangular membership functions by calculating deviation from expected values of crack depth and crack location. Then finite element analysis of cracked beam has been done using ALGOR software where input files have been given through designing software. The proposed approach has been verified by comparing with the results obtained from fuzzy logic technique and finite element analysis.

CHAPTER 1

GENERAL INTRODUCTION

1.1. INTRODUCTION:

Cracks present in machine parts affect their vibrational behaviour like the fundamental frequency and resonance. The amplitude of vibration increases and the occurrence of resonance shifted as crack length increases. Structural failure refers to loss of the load-carrying capacity of a component or member within a structure or of the structure itself. Structural failure is initiated when the material is stressed to its strength limit, thus causing fracture or excessive deformations. When this limit is reached, damage to the material has been done, and its load-bearing capacity is reduced permanently, significantly and quickly. In a well-designed system, a localized failure should not cause immediate or even progressive collapse of the entire structure. Ultimate failure strength is one of the limit states that must be accounted for in structural engineering and structural design. Therefore intensive research has been going on amongst the scientists and engineers to find an effective methodology to predict the location and intensity of damage beforehand.

So in this paper we have presented two different approaches. First approach refers to:

1.2. Fuzzy Logic:

Fuzzy logic is a form of multi-valued logic derived from fuzzy set theory to deal with reasoning that is approximate rather than precise. In contrast with binary sets having binary logic, also known as crisp logic, the fuzzy logic variables may have a membership value of only 0 or 1. Just as in fuzzy set theory with fuzzy logic the set membership values can range (inclusively) between 0 and 1, in fuzzy logic the degree of truth of a statement can range between 0 and 1 and is not constrained to the two truth values {true (1), false (0)} as in classic predicate logic. And when linguistic variables are used, these degrees may be managed by specific functions, as discussed below. Fuzzy logic has been applied to diverse fields, from control theory to artificial intelligence, yet still remains controversial among most statisticians, who prefer Bayesian logic, and some control engineers, who prefer traditional two-valued logic

1.3. Why use fuzzy logic (FL)?

FL offers several unique features that make it a particularly good choice for many control problems.

1) It is inherently robust since it does not require precise, noise-free inputs and can be programmed to fail safely if a feedback sensor quits or is destroyed. The output control is a smooth control function despite a wide range of input variations.

2) Since the FL controller processes user-defined rules governing the target control system, it can be modified and tweaked easily to improve or drastically alter system performance. New sensors can easily be incorporated into the system simply by generating appropriate governing rules.

3) FL is not limited to a few feedback inputs and one or two control outputs, nor is it necessary to measure or compute rate-of-change parameters in order for it to be implemented. Any sensor data that provides some indication of a system's actions and reactions is sufficient. This allows the sensors to be inexpensive and imprecise thus keeping the overall system cost and complexity low.

4) Because of the rule-based operation, any reasonable number of inputs can be processed (1-8 or more) and numerous outputs (1-4 or more) generated, although defining the rulebase quickly becomes complex if too many inputs and outputs are chosen for a single implementation since rules defining their interrelations must also be defined. It would be better to break the control system into smaller chunks and use several smaller FL controllers distributed on the system, each with more limited responsibilities.

5) FL can control nonlinear systems that would be difficult or impossible to model mathematically. This opens doors for control systems that would normally be deemed unfeasible for automation.

1.4.How is fuzzy logic used?

1) Define the control objectives and criteria: What am I trying to control? What do I have to do to control the system? What kind of response do I need? What are the possible (probable) system failure modes?

2) Determine the input and output relationships and choose a minimum number of variables for input to the FL engine (typically error and rate-of-change-of-error).

3) Using the rule-based structure of FL, break the control problem down into a series of IF X AND Y THEN Z rules that define the desired system output response for given system input conditions. The number and complexity of rules depends on the number of input parameters that are to be processed and the number fuzzy variables associated with each parameter. If possible, use at least one variable and its time derivative. Although it is possible to use a single, instantaneous error parameter without knowing its rate of change, this cripples the system's ability to minimize overshoot for a step inputs.

4) Create FL membership functions that define the meaning (values) of Input/Output terms used in the rules.

5) Create the necessary pre- and post-processing FL routines if implementing in S/W, otherwise program the rules into the FL H/W engine.

6) Test the system, evaluate the results, tune the rules and membership functions, and retest until satisfactory results are obtained.

In fuzzy logic technique the crack location and depth are determined using three natural frequencies as input. The fuzzy logic controller used here comprises of three input parameters and two output parameters. Gaussian and triangular member ship functions are used for the fuzzy controller. The input parameters to the fuzzy- Gaussian controller and fuzzy- triangular controller are relative deviation of first three natural frequencies. The output parameters of the fuzzy inference system are relative crack depth and relative crack location. At the beginning theoretical analyses have been outlined for cracked cantilever beam to calculate the vibration parameters such as natural frequencies. A set of boundary conditions are considered involving the effect of crack location. A series of fuzzy rules are derived from vibration parameters which are finally used for prediction of crack location and its intensity. The comparison is made between Gaussian and triangular membership functions by calculating deviation from expected values of crack depth and crack location.

Now second approach refers to:

1.5 Finite Element Analysis:

Finite Element Analysis (FEA) was first developed in 1943 by R. Courant[1], who utilized the Ritz method of numerical analysis and minimization of variational calculus to obtain approximate solutions to vibration systems. Shortly thereafter, a paper published in 1956 by M. J. Turner et.al.[2] established a broader definition of numerical analysis. The paper centred on the "stiffness and deflection of complex structures".

FEA consists of a computer model of a material or design that is stressed and analyzed for specific results. It is used in new product design, and existing product refinement. A company is able to verify a proposed design will be able to perform to the client's specifications prior to manufacturing or construction. Modifying an existing product or structure is utilized to qualify the product or structure for a new service condition. In case of structural failure, FEA may be used to help determine the design modifications to meet the new condition. There are generally two types of analysis that are used in industry: 2-D modeling, and 3-D modeling. While 2-D modeling conserves simplicity and allows the analysis to be run on a relatively normal computer, it tends to yield less accurate results. 3-D modeling, however, produces more accurate results while sacrificing the ability to run on all but the fastest computers effectively. Within each of these modeling schemes, the programmer can insert numerous algorithms (functions) which may make the system behave linearly or non-linearly. Linear systems are far less complex and generally do not take into account plastic deformation.

Non-linear systems do account for plastic deformation, and many also are capable of testing a material all the way to fracture

1.6 How Does Finite Element Analysis Work?

FEA uses a complex system of points called nodes which make a grid called mesh.This mesh is programmed to contain the material and structural properties which define how the structure will react to certain loading conditions. Nodes are assigned at a certain density throughout the material depending on the anticipated stress levels of a particular area. Regions which will receive large amounts of stress usually have a higher node density than those which experience little or no stress. Points of interest may consist of: fracture point of previously tested material, fillets, corners, complex detail, and high stress areas. The mesh acts like a spider web in that from each node, there extends a mesh element to each of the adjacent nodes. This web of vectors is what carries the material properties to the object, creating many elements.

A wide range of objective functions (variables within the system) are available for minimization or maximization:

- Mass, volume, temperature
- Strain energy, stress strain
- Force, displacement, velocity, acceleration
- Synthetic (User defined)

There are multiple loading conditions which may be applied to a system.

- Point, pressure, thermal, gravity, and centrifugal static loads
- Thermal loads from solution of heat transfer analysis
- Enforced displacements
- Heat flux and convection
- Point, pressure and gravity dynamic loads

Each FEA program may come with an element library, or one is constructed over time. Some sample elements are:

- Rod elements
- Beam elements
- Plate/Shell/Composite elements
- Shear panel

- Solid elements
- Spring elements
- Mass elements
- Rigid elements
- Viscous damping elements

1.7 Types of Engineering Analysis:

Structural analysis consists of linear and non-linear models. Linear models use simple parameters and assume that the material is not plastically deformed. Non-linear models consist of stressing the material past its elastic capabilities. The stresses in the material then vary with the amount of deformation as in.

Vibrational analysis is used to test a material against random vibrations, shock, and impact. Each of these incidences may act on the natural vibrational frequency of the material which, in turn, may cause resonance and subsequent failure.

Fatigue analysis helps designers to predict the life of a material or structure by showing the effects of cyclic loading on the specimen. Such analysis can show the areas where crack propagation is most likely to occur. Failure due to fatigue may also show the damage tolerance of the material.

Heat Transfer analysis models the conductivity or thermal fluid dynamics of the material or structure. This may consist of a steady-state or transient transfer. Steady-state transfer refers to constant thermo properties in the material that yield linear heat diffusion.

1.9 Applications of FEA:

FEA has become a solution to the task of predicting failure due to unknown stresses by showing problem areas in a material and allowing designers to see all of the theoretical stresses within. This method of product design and testing is far superior to the manufacturing costs which would accrue if each sample was actually built and tested.

Here cracked beam has been analyzed through finite element method using software known as ALGOR. This software package has several applications in mechanical event simulation and computational fluid dynamics. Here it is used for finite element analysis of natural frequency modal of cracked beam where the input is been given from CATIA designing software. The mesh is generated in the input modal and then after specifying boundary conditions it is analyzed in FEA editor which finally gives output in three modes natural frequencies.

CHAPTER 2

LITERATURE SURVEY

Different researchers have discussed damage detection of vibrating structures in various ways. They are summarized below.

The method of crack localization and sizing in a beam has been obtained from free and forced response measurements by Karthikeyan et al.[3]. This method has been illustrated through numerical examples. The prediction for the crack location and size are in agreement taking the noise and measurement error in to account. A combined analytical and experimental study has been conducted by Wang and Qiao [4] to develop efficient and effective damage detection techniques for beam-type structures. The uniform load surface (ULS) has been employed in this study due to its less sensitivity to ambient noise. In combination with the ULS, two new damage detection algorithms, i.e., the generalized fractal dimension (GFD) and simplified gapped-smoothing (SGS) methods, has been proposed. Both methods are then applied to the ULS of cracked and delaminated beams obtained analytically, from which the damage location and size are determined successfully. Based on the experimentally measured curvature mode shapes, both the GFD and SGS methods are further applied to detect three different types of damage in carbon/epoxy composite beams. Damage detection in vibrating beams or beam systems has been done by Fabrizio and Danilo [5] by discussing the amount of frequencies necessary to locate and quantify the damage uniquely. Two different procedures of damage identification are used, which mainly take advantage of the peculiar characteristics of the problem. Cases with pseudo experimental and experimental frequencies are solved.

The crack can be simulated by an equivalent spring, connecting the two segments of the beam, as stated by Narkis[6]. Analysis of this approximate model results in algebraic equations which relate the natural frequencies of beam and crack characteristics. These expressions are then applied to studying the inverse problem—identification of crack location from frequency measurements. It is found that the only information required for accurate crack identification is the variation of the first two natural frequencies due to the crack, with no other information needed concerning the beam geometry or material and the crack depth or shape. The proposed method is confirmed by comparing it with results of numerical finite element calculations. The local effect of softening at the crack location can be simulated by an equivalent spring connecting the two segments of the beam as investigated by Wang et al.[4].The model uses the transfer matrix method in conjunction with the Bernoulli-Euler theories of beam vibration, modal analysis and fracture mechanics principle to derive characteristic equation, which relates the natural frequencies. The proposed approach is verified by simulation results. Least square identification method, Kalman filtering method and adaptive filtering method have been adopted by Nian *et al.* [7] to diagnose structural fault.

The equation of motion and corresponding boundary conditions has been developed by Behzad et al. [8] for forced bending vibration analysis of a beam with an open edge crack. A uniform Euler-Bernoulli beam and the Hamilton principle have been used in this research. The crack has been modelled as a continuous disturbance function in displacement filed which is obtained from fracture mechanics. They have stated that there is an agreement between the theoretical results and those obtained by the finite element method.

The natural frequencies have been obtained by Loya et al.[9] for bending vibrations of Timoshenko cracked beams with simple boundary conditions. The beam is modeled as two segments connected by two mass less springs (one extensional and another one rotational). This model promotes discontinuities in both vertical displacement and rotation due to bending, which are proportional to shear force and bending moment transmitted by the cracked section, respectively. Their results show that their method provides simple expressions for the natural frequencies of cracked beams and it gives good results for shallow cracks. An extensive study has been made on diagnosis of fracture damage in structure by Akgun et al.[10].The concept of 'fracture hinge' has been developed analytically and the same has been applied to a cracked section for detecting fracture damage in simple structures. It has been verified experimentally that the structural effect of a cracked section can be represented by an equivalent spring loaded hinge. A fuzzy finite element method has been used by Chen[11] for vibration analysis of imprecisely defined systems by using a search-based algorithm. The approach enhances the computational efficiency in fuzzy operations for identifying the system dynamic responses. A fuzzy arithmetical approach has been used by Hanss and Willner[12] for the solution of finite element problems involving uncertain parameters. Fuzzy finite element method for static analysis of engineering systems has been done by Rao [13] using an optimization-based scheme taking fuzzy parameters, geometry and applied loads into consideration. The mobile robot navigation control system has been designed by Parhi[14] using fuzzy logic. Fuzzy rules embedded in the controller of a mobile robot enable it to avoid obstacles in a cluttered environment that includes other mobile robots. A fuzzy finite element approach has been used by Akpan et al.[15] for modeling smart structures with vague or imprecise uncertainties. Application of neural networks, genetic algorithms and fuzzy logic for the identification of cracks in shafts by using coupled response measurements ' by Saridakis et al.[16] considered the dynamic behaviour of a shaft with two transverse cracks characterized by three measures: position, depth and relative angle. The eigen frequencies and the response of the cracked shaft in specific points are used in order to define an objective function based on the differences between numerical and experimental results. Towards this goal, five different objective functions are proposed and validated; two of these are based on fuzzy logic. More computational intelligence is added through a genetic algorithm, which is used to find the characteristics of the cracks through artificial neural networks that approximate the analytical model. Both the genetic algorithm and the neural networks contribute to a remarkable reduction of the computational time without any significant loss of accuracy. The final results show that the proposed methodology may constitute an efficient tool for real-time crack identification. The use of Ritz method for damage detection of reinforced and post-tensioned concrete beams has been done by Gharighoran et al.[17]. Damage-induced changes in modal characteristics can be detected using experimental modal analysis. Here, based on changes in natural frequency, mode shapes, and damping ratios, a methodology for detecting damage location and severity was presented. Experimental modal analysis was performed on the undamaged and damaged beams. The natural frequency and mode shapes were used to determine the location of damage. The approach is developed at an element level with a conventional finite element (FE) model by Ritz method, which is called Ritz damage detection method (RDDM). The numerical results showed that the exact location and severity of damage for different simulated damage scenarios could be efficiency found by the present methodology. An extensive work has been done on Improved beam finite element for the stability analysis of slender transversely cracked beam columns by Matjaž Skrinar[18] who presented a new geometrical stiffness matrix for a transversely cracked beam-column with linear distribution of axial compressive force. This matrix can be utilized in a beam finite element model of the structure for analyzing ultimate buckling load, according to the Euler's elastic flexural buckling theory. The results obtained using the presented matrix are further compared with values from large 2D finite element models, where a complete detailed description of the crack was achieved using the discrete approach. The newly presented matrix and the previously presented stiffness matrix for analysis of transverse displacements, present an efficient tool not only for buckling analysis of cracked beam structures but also for a better description of the structure regarding the inverse identification of cracks.

The detection of cracks in functionally graded material (FGM) structural members using the *p*-version of finite element method by Yu et al.[19] has been a significant subject due to their increasing applications in various important engineering industries. The *p*-version of finite element method is employed to estimate the transverse vibration characteristics of a cracked FGM beam. The influences of crack size, crack location and material gradient on the natural frequencies of a cracked cantilever FGM beam are studied. To identify the crack parameters, the frequency contours with respect to crack location and size are plotted and the intersection of contours from different modes indicates the predicted crack location and size.In the ambient vibration tests using statistical modal filtering by Bahlous et al.[20], operation disturbances can be avoided and the measured response is representative of the actual operating conditions of the structures which vibrate due to natural excitation. The proposed damage identification method is intended for moderate degrees of damage and requires vibration data relative to the current and reference states of the structure as well as a parametric finite element model. It is based on a residual generated from a modal filtering approach by the calculation of the error between the measurements at the current state and their projections onto the incomplete modal basis of the structure as identified at reference state.

The measurement of fatigue damage based on the natural frequency for spot-welded joints has been done by Shang[21]. According to the observation of fatigue fractography for the spot-welded joints, cracking behaviour was modelled for specimens of different dimensions using 3D FEA of a progressively growing crack that began at the joining surface, progressed to the outside surface, and finally broke. Thus, a new damage variable was proposed to measure fatigue damage using natural frequency nonlinear behaviour, and a nonlinear fatigue damage model was developed. Nonlinear vibration of beams made of functionally graded materials (FGMs) containing an open edge crack is studied by Kitipornchai et al. [21] based on Timoshenko beam theory and von Kármán geometric nonlinearity. The cracked section is modeled by a massless elastic rotational spring. It is found that unlike isotropic homogeneous beams, both intact and cracked FGM beams show different vibration behavior at positive and negative amplitudes due to the presence of bending–extension coupling in FGM beams.

The study by Begambreand et al.[22]proposes a new PSOS-model based damage identification procedure using frequency domain data. The formulation of the objective function for the minimization problem is based on the Frequency Response Functions (FRFs) of the system. A novel strategy for the control of the Particle Swarm Optimization (PSO) parameters based on the Nelder–Mead algorithm (Simplex method) is presented; consequently, the convergence of the PSOS becomes independent of the heuristic constants and its stability and confidence are enhanced. The formulated hybrid method performs better in different benchmark functions than the Simulated Annealing (SA) and the basic PSO (PSO_b). Two damage identification problems, taking into consideration the effects of noisy and incomplete data, were studied. In these cases, the damage location and extent were successfully determined. There was study done by Rao et al.[23]presents fractal finite element based continuum shape sensitivity analysis for a multiple crack system in a homogeneous, isotropic, and two dimensional linear-elastic body subjected to mixed-mode (modes I and II) loading conditions. The salient feature of this method is that the stress intensity factors and their derivatives for the multiple crack system can be obtained efficiently since it only requires an evaluation of the same set of fractal finite element matrix equations with a different fictitious load.

Skrinar[18] formulates the finite element of a beam with an arbitrary number of transverse cracks. The derivations are based on a simplified computational model, where each crack is replaced by a corresponding linear rotational spring, connecting two adjacent elastic parts. The stiffness and geometrical stiffness matrices thus take into account the effect of flexural bending deformation caused by the presence of the cracks. Damage detection methods based on model updating method have usually been developed as single objective optimization problems which have been studied by Perera et al.[24]. The application of genetic algorithms for solving multiobjective optimization constitutes an emergent research area nowadays. In this paper, some multiobjective GAs based on aggregating functions and Pareto optimality are compared. A solution to the free vibration problem of a stepped column with cracks is presented by Kukla[25]. The open cracks occur at step changes in the cross-section of the column or at the intermediate points of the uniform segments. The cracks in the column are represented by mass less rotational springs. The approach pertains to the vibration of columns consisting of an arbitrary number of uniform segments.

Identification of an open crack in a beam using a *posterior* error estimator of the frequency response functions with noisy measurements has been proposed by by Faverjon[26]. This paper presented a robust damage assessment technique for the non-destructive detection and size estimation of open cracks in beams. The damage detection, based on the constitutive relation error updating method, is used for the identification of the crack's location and size in a simply-supported beam..Structural damage detection with statistical analysis from support excitation has been studied. The unit impulse response (UIR) functions obtained from a structure under support excitation are used to identify local structural damages. A new damage localization index is proposed and the mean values of the identified parameters are taken as the damage severity. Finally, a nine-bay three-dimensional frame structure is analyzed numerically and experimentally using the proposed technique.

A new crack detection method is proposed by Xiang et al.[27], for detecting crack location and depth in a shaft. Rotating Rayleigh-Euler and Rayleigh-Timoshenko beam elements of B-spline wavelet on the interval (BSWI) are constructed to discretize slender shaft and stiffness disc, respectively. According to linear fracture mechanics theory, the localized additional flexibility in crack vicinity can be represented by a lumped parameter element. The first three measured frequencies are used in crack detection process and the normalized crack location and depth are detected by means of genetic algorithm. In the research by X. Fang, H. Luo, J. Tang, exploration of the structural damage detection using frequency response functions (FRFs) as input data to the back-propagation neural network (BPNN). Various training algorithms, such as the dynamic steepest descent (DSD) algorithm and the fuzzy steepest descent (FSD) algorithm, have shown promising features (such as improving the learning convergence speed), their performance is hinged upon the proper selection of certain control parameters and control strategy. In this paper, a tunable steepest descent (TSD) algorithm using heuristics approach, which improves the convergence speed significantly without sacrificing the algorithm simplicity and the computational effort, is investigated The analysis results on a cantilevered beam show that, in all considered damage cases (i.e., trained damage cases and unseen damage cases, single damage cases and multiple-damage cases), the neural network can assess damage conditions with very good accuracy.

An analytical as well as experimental approach to crack detection in cantilever beam has been established by Nahvi et al.[28](2005). An experimental setup is designed in which cantilever beam is excited by hammer and the response is obtained using accelerometer attached to the beam. To avoid non-linearity it is assumed that crack is always open. To identify the crack contours of the normalized frequency in terms of normalized crack depth and location are plotted. A minimization approach is applied for identifying the cracked element within the cantilever beam. A method for identification of crack in a beam is demonstrated by using genetic algorithm(GA) based on changes in natural frequencies by HORIBE et al.[29] (2007). To calculate the natural frequencies of the beam, a p- FEM code, which is based on parametric three dimensional, is developed because accuracy of analysis is important. By using GA square sum of residuals between the measured data and calculated data is minimized in the identification process and thus the crack is identified. E.Viola et al.[30](2002) formulated cracked beam element for structural analysis. These shape functions for rotational and translational displacements are also used to develop the consistent mass matrix for the cracked beam element. The crack effect of stiffness matrix and consistent mass matrix was investigated and graphically represented. The experimental vibration behaviour of a free-free beam with a breathing crack is simulated by Sinha et al.[31](2002) for a sinusoidal input force using a simple FE model for a crack in a beam. The present simulation was compared with an earlier study and found to be more realistic.

Introduction of a new finite element spectral element of a Timoshenko beam for modal and elastic wave propagation analysis was proposed by Krawczuk et al. [32](2002). The method was suitable for analysing wave propagation problems as well as for calculating model parameters of the structure. The influence of crack parameters, especially of the changing location of the crack, on the wave propagation was examined which finally allows one to indicate the crack location in precise way. An analytical study on the free and forced vibration of inhomogeneous Euler–Bernoulli beams containing open edge cracks has been proposed by Yang et al. [33](2007). The beam is subjected to an axial compressive force and a concentrated transverse load moving along the longitudinal direction. The rotational spring model is used to model the crack causing sectional flexibility. Analytical solutions of natural frequencies and dynamic deflections are obtained for cantilever, hinged–hinged, and clamped–clamped beams whose material properties follow an exponential through-thickness variation.

Defects influence in a negative way the service life of structures. Thus, detection of them even at a very small size is a very important point of view to guarantee structural safety and to safe costs. The objective of this study is to obtain information about the location and depth of cracks in cracked beams. For this purpose, the vibrations as a result of impact shocks were analyzed. The signals obtained in defect-free and cracked beams were compared in the frequency domain. The results of the study suggest to determine the location and depth of cracks by analyzing the from vibration signals. Experimental results and simulations obtained by the software ALGOR are in good agreement.

CHAPTER 3

THEORETICAL ANALYSIS

3.1 Local flexibility of a Cracked Beam Under Bending and Axial Loading:

The presence of a transverse surface crack of depth 'a_1' 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 (P_1) and bending moment (P_2), shown in figure 1a, which gives coupling with the longitudinal and transverse motion.

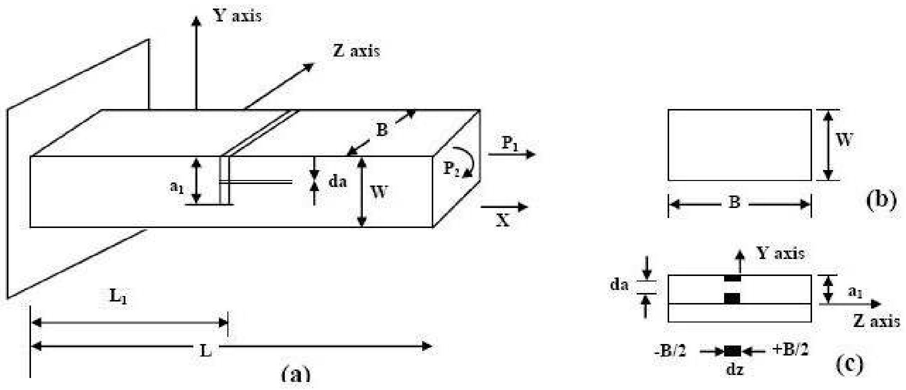


Figure 1: Geometry of beam, (a) Cantilever beam, (b) Cross-sectional view of the beam. (c) Segments taken during integration at the crack section

Fig 1. Parhi et al.[34]

The strain energy release rate at the fractured section can be written as (Tada *et al.*1973);

J = ($K_{I1} + K_{I2})^2$/ E' , where 1/ E' = (1- v^2)/E ,for plain strain condition

= 1/E , for plane stress condition

K_{I1} and K_{I2} are the stress intensity factors of mode I (opening of the crack) for load P_1 and P_2 respectively the value of stress intensity factors from previous studies (Tada *et al.*1973) are;

$$K_{I1} = \frac{P_1}{BW}\sqrt{\pi a}\ \left(F_1\left(\frac{a}{W}\right)\right)$$

$$K_{I2} = \frac{P_2}{BW^2}\sqrt{\pi a}\ \left(F_2\left(\frac{a}{W}\right)\right)$$

Where expressions for F_1 and F_2 are as follows

$$F_1\left(\frac{a}{W}\right) = \left(\frac{2W}{\pi a} tan\left(\frac{\pi a}{2W}\right)\right)^{0.5} \left\{\frac{0.752 + 2.02(a/W) + 0.37(1 - \sin(\pi a/2W))^3}{\cos\left(\frac{\pi a}{2W}\right)}\right\}$$

$$F_2\left(\frac{a}{W}\right) = \left(\frac{2W}{\pi a} tan\left(\frac{\pi a}{2W}\right)\right)^{0.5} \left\{\frac{0.923 + 0.199(1 - \sin(\pi a/2W))^4}{\cos\left(\frac{\pi a}{2W}\right)}\right\}$$

Let U_t be the strain energy due to crack, then from Castigliano's theorem, the additional displacement along the force P_i is:

$$\mathrm{ui} = \frac{\partial U_t}{\partial \mathrm{Pi}} \tag{1}$$

The strain energy will have the form

$$U_t = \int_0^{a_1} \frac{\partial U_t}{\partial a} da = \int_0^{a_1} J\, da \tag{2}$$

Where J = $\frac{\partial U_t}{\partial a}$ the strain energy density function.

From equations (1) and (2), thus we have,

$$\mathrm{ui} = \frac{\partial}{\partial \mathrm{Pi}}\left[\int_0^{a_1} J\, da\right] \tag{3}$$

The flexibility influence coefficients C_{ij} will be, by definition,

$$C_{ij} = \frac{\partial u_i}{\partial P_j} = \frac{\partial^2}{\partial P_i \partial P_j} \int_0^{a_1} J(a)\, da \tag{4}$$

To find out the final flexibility matrix we have to integrate over the breadth B,

$$C_{ij} = \frac{\partial u_i}{\partial P_j} = \frac{\partial^2}{\partial P_i \partial P_j} \int_{-B/2}^{+B/2} \int_0^{a_1} J(a)\, da\, dz \tag{5}$$

Put the value of strain energy rate from above, equation (5) modifies as,

$$C_{ij} = \frac{B}{E'} \frac{\partial^2}{\partial P_i \partial P_j} \int_0^{a_1} (K_{I1} + K_{I2})^2\, da \tag{6}$$

Putting,

$\xi = (a/W)$ and $d\xi = (da/W)$

We get,

$da = W\, d\xi$ and when $a=0$; $\xi=0$; $a= a_1$, $\xi = a/W = \xi_1$

From the above condition equation (6) converts to

$$C_{ij} = \frac{BW}{E'} \frac{\partial^2}{\partial P_i \partial P_j} \int_0^{\xi_1} (K_{11} + K_{12})^2 \, d\xi \tag{7}$$

From the equation (7) calculating C_{11}, C_{12} ($=C_{21}$) and C_{22} we get,

$$C_{11} = \frac{BW}{E'} \int_0^{\xi_1} \frac{\pi a}{B^2 W^2} 2(F_1(\xi))^2 \, d\xi$$
$$= \frac{2\pi}{BE'} \int_0^{\xi_1} \xi (F_1(\xi))^2 \, d\xi \tag{8}$$

$$C_{12} = C_{21} = \frac{12\pi}{E'BW} \int_0^{\xi_1} \xi F_1(\xi) F_2(\xi) \, d\xi \tag{9}$$

$$C_{22} = \frac{72\pi}{E'BW^2} \int_0^{\xi_1} \xi F_2(\xi) F_2(\xi) \, d\xi \tag{10}$$

Converting the influence co-efficient into dimensionless form

$$\overline{C_{11}} = C_{11} \frac{BE'}{2\pi} \qquad \overline{C_{12}} = C_{12} \frac{E'BW}{12\pi} = \overline{C_{21}} \; ; \; \overline{C_{22}} = C_{22} \frac{E'BW^2}{72\pi}$$

The local stiffness matrix can be obtained by taking the conversion of compliance matrix i.e.

$$K = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}^{-1}$$

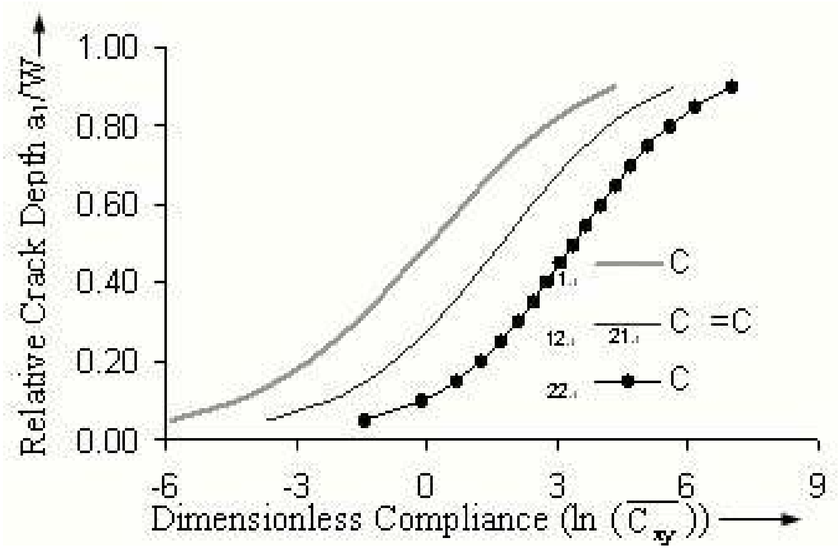


Figure 2. Variation of dimensionless compliances to that of relative crack depth. Parhi et al.[34]

3.2 Analysis of vibration characteristics of the cracked beam:

3.2.1 Free Vibration:

A cantilever beam of length ‘L’ width ‘B’ and depth ‘W’, with a crack of depth ‘a1’ at a distance ‘L’ from the fixed end is considered shown in figure 1. Taking $u_1(x, t)$ and $u_2(x, t)$ as the amplitudes of longitudinal vibration for the sections before and after the crack and$y_1(x, t)$, $y_2(x, t)$ are the amplitudes of bending vibration for the same sections shown in figure 3.

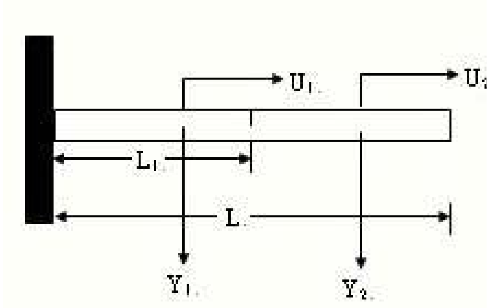


Figure 3. Beam Model

The normal function for the system can be defined as

$$\bar{u}_1(\bar{x}) = A_1 \cos(\bar{K}_u \bar{x}) + A_2 \sin(\bar{K}_u \bar{x}) \quad (11a)$$

$$\bar{u}_2(\bar{x}) = A_3 \cos(\bar{K}_u \bar{x}) + A_4 \sin(\bar{K}_u \bar{x}) \quad (11b)$$

$$\overline{y_1}(\bar{x}) = A_5 \cosh(\overline{K_y}\bar{x}) + A_6 \sinh(\overline{K_y}\bar{x}) + A_7 cos(\overline{K_y}\bar{x}) + A_8 sin(\overline{K_y}\bar{x}) \quad (11c)$$

$$\overline{y_2}(\bar{x}) = A_9 \cosh(\overline{K_y}\bar{x}) + A_{10} \sinh(\overline{K_y}\bar{x}) + A_{11} cos(\overline{K_y}\bar{x}) + A_{12} sin(\overline{K_y}\bar{x})$$

Where,

$$\bar{x} = \frac{x}{L}, \bar{u} = \frac{u}{L}, \bar{y} = \frac{y}{L}, \ \beta = \frac{L_1}{L}$$

$$\bar{K}_u = \frac{\omega L}{C_u}, C_u = \left(\frac{E}{\rho}\right)^{1/2}, \bar{K}_y = \left(\frac{\omega L^2}{C_y}\right)^{1/2}, C_y = \left(\frac{EI}{\mu}\right)^{1/2}, \mu = A\rho$$

A_{i} , (i= 1,12) constants are to be determined, constants are to be determined from boundary conditions. The boundary conditions of the cantilever beam in consideration are:

$$\bar{u}_1(0)=0; \quad \bar{y}_1(0)=0; \quad \bar{y}_1'(0)=0; \quad \bar{u}_2'(1)=0; \quad \bar{y}''_2(1)=0; \quad \bar{y}_2'''(1)=0$$

At the cracked section,

$$\bar{u}_1(\beta)=\bar{u}_2(\beta); \quad \bar{y}_1(\beta)=\bar{y}_2(\beta); \quad \bar{y}_1''(\beta)=\bar{y}_2''(\beta); \quad \bar{y}_1'''(\beta)=\bar{y}_2'''(\beta)$$

Also at the cracked section, we have:

$$AE\frac{du_1(L_1)}{dx} = K_{11}(u_2(L_1) - u_1(L_1)) + K_{12}\left(\frac{dy_2(L_1)}{dx} - \frac{dy_1(L_1)}{dx}\right)$$

Multiplying both sides of the above equation by AE/L$K_{l1}K_{l2}$we get

$$M_1 M_2 \bar{u}'(\beta) = M_2(\bar{u}_2(\beta) - \bar{u}_1(\beta)) + M_1(\bar{y}_2'(\beta) - \bar{y}_1'(\beta))$$

Similarly,

$$EI\frac{d^2y_1(L_1)}{dx^2}=K_{21}(u_2(L_1)-u_1(L_1))+K_{22}\left(\frac{dy_2(L_1)}{dx}-\frac{dy_1(L_1)}{dx}\right)$$

Multiplying both sides of the above equation by EI/L^2 $K_{21}K_{22}$, we get

$$M_3M_4\bar{y}_1''(\beta)=M_3(\bar{u}_2(\beta)-\bar{u}_1(\beta))+M_4(\bar{y}_2'(\beta)-\bar{y}_1'(\beta))$$

Where, $M_1=\frac{AE}{LK_{11}}, M_2=\frac{AE}{K_{12}}, M_3=\frac{EI}{LK_{22}}, M_4=\frac{EI}{L^2K_{21}}$

The normal functions equation 11, along with the boundary conditions as mentioned above yield the characteristic equation of the system as

$|Q| = 0$,

This determinant is a function of natural circular frequency (ω), the relative location of crack (β) and local stiffness matrix (K) which in turn is a function of relative crack depth(a_1/W).

3.2.2 Forced Vibration:

If the cantilever beam with transverse crack is excited at its free end by a harmonic excitation ($Y=Y_0$ sin (ω t)), the non-dimensional amplitude at the free end may be expressed as $\overline{y_2}(1) = y_0/L = \overline{y_0}$. Therefore the boundary conditions for the beam remain same as before as except the boundary condition which is modified as $\overline{y_2}(1) = \overline{y_0}$

The constants A_i, i=1, to 12 are then computed from the algebraic condition

Q_1 D=B_1 (13)

Q_1 is the (12 x 12) matrix obtained from boundary conditions as mentioned above,

D is a column matrix obtained from the constants,

B_1 is a column matrix, transpose of which is given by,

B_1^T = [0 0 0 y 0 0 0 0 0 0 0 0]

CHAPTER 4

DETECTION OF CRACK USING FUZZY LOGIC TECHNIQUE

4.1 Analysis of fuzzy controller:

The fuzzy controller developed has got six input parameters and two output parameters.

The linguistic term used for the inputs are as follows;

Relative first natural frequency = “fnf”; Relative second natural frequency = “snf”;

Relative third natural frequency = “tnf”;

The linguistic term used for the outputs are as follows;

Relative crack location = “rcl” and Relative crack depth = “rcd”

The Fuzzy controller used in the present text is shown in Figure 4a. The Triangular and Gaussian membership functions are shown pictorially. The linguistic terms for the Gaussian membership functions, used in the fuzzy controller, are described in the Table 1

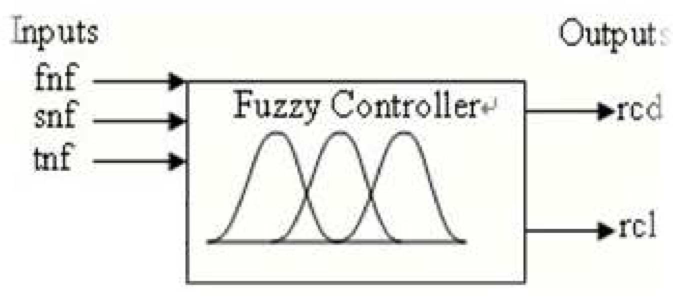
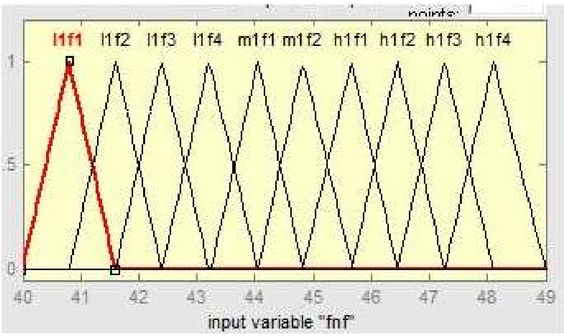


Figure 4a: Fuzzy Controller

4.2 Triangular Membership function:



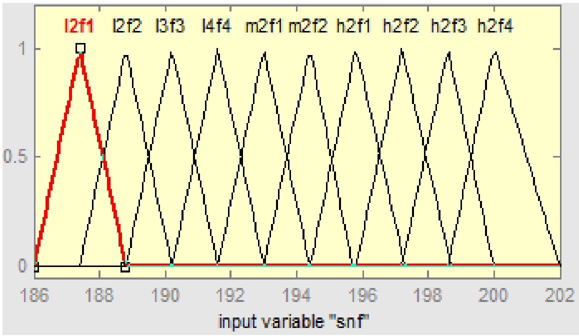


Fig 4b1: Membership functions for relative natural frequency for first mode of vibration

Fig 4b2: Membership functions for relative natural frequency for second mode of vibration

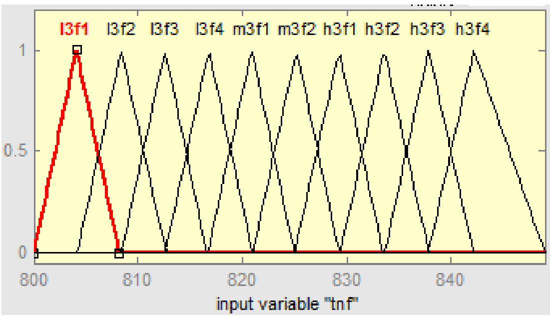


Figure 4b3: Membership functions for relative natural frequency for third mode of vibration

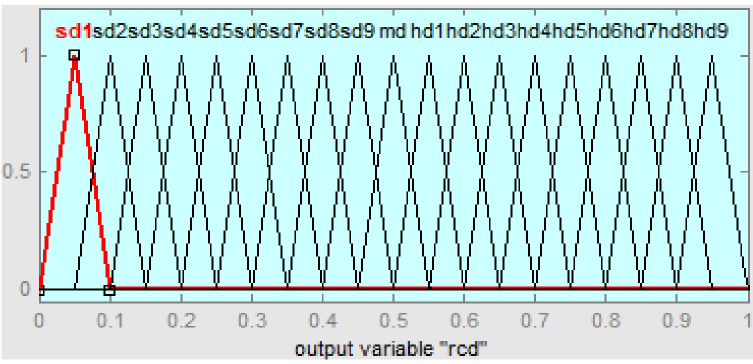


Fig 4b4: Membership functions for relative crack depth

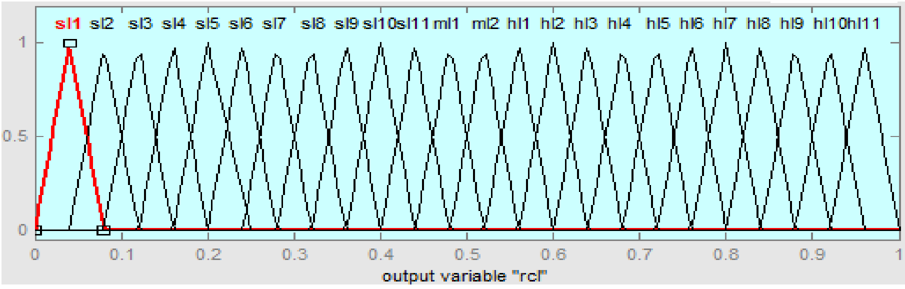
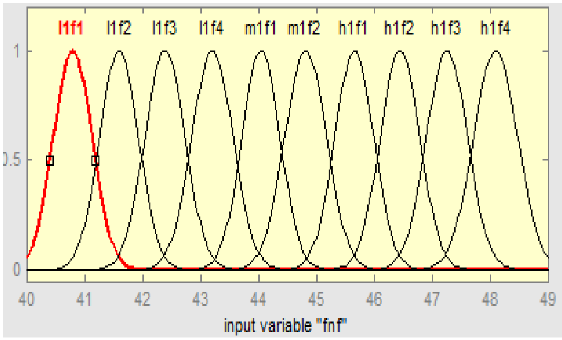


Fig 4b5: Membership functions for relative crack location

4.3 Gaussian Membership function:



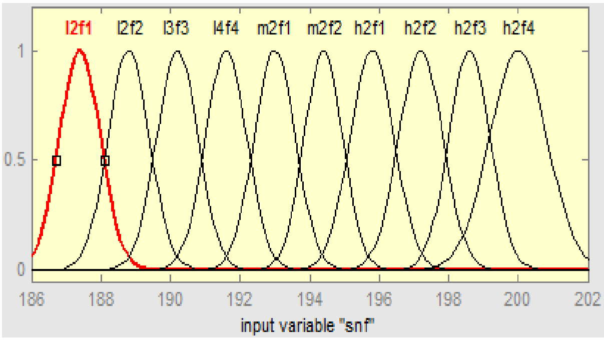


Fig 5a1: Membership functions for relative natural frequency for first mode of vibration

Fig 5a2: Membership functions for relative natural frequency for second mode of vibration

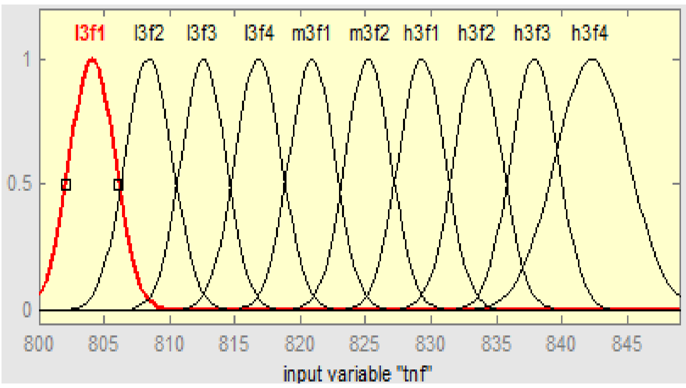


Fig 5a3: Membership functions for relative natural frequency for third mode of vibration

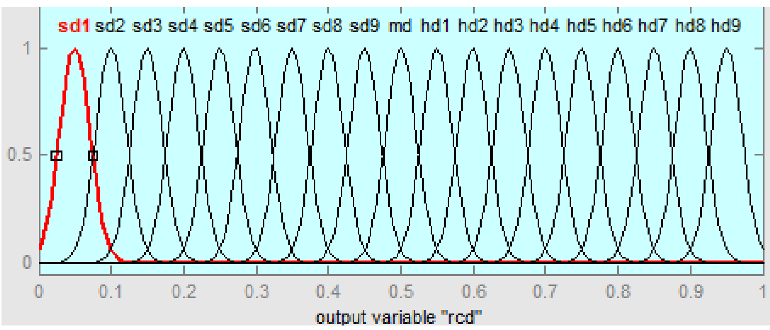


Fig 5a4: Membership functions for relative crack depth

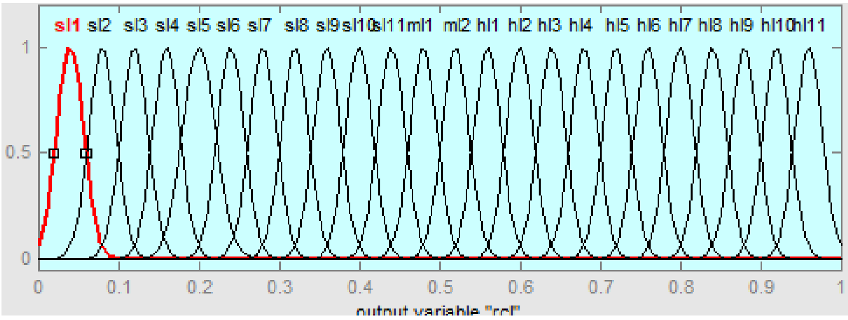


Fig 5a5: Membership functions for relative crack location

4.4 :Table 1: Description Of Fuzzy Linguistic terms

Membership functions name	**Description and Range of membership functions**
L1f1,l1f2,l1f3,l1f4	Low ranges of natural frequency for first mode of vibration in ascending order respectively
M1f1, m1f2	Medium ranges of natural frequency for first mode of vibration in ascending order respectively
H1f1,h1f2,h1f3,h1f4	High ranges of natural frequency for first mode of vibration in ascending order respectively
L2f1,l2f2,l2f3,l2f4	Low ranges of natural frequency for second mode of vibration in ascending order respectively
M2f1, m2f2	Medium ranges of natural frequency for second mode of vibration in ascending order respectively
H2f1,h2f2,h2f3,h2f4	High ranges of natural frequency for second mode of vibration in ascending order respectively
L3f1,l3f2,l3f3,l3f4	Low ranges of natural frequency for third mode of vibration in ascending order respectively
M3f1, m3f2	Medium ranges of natural frequency for third mode of vibration in ascending order respectively
H3f1,h3f2,h3f3,h3f4	High ranges of natural frequency for third mode of vibration in ascending order respectively
Sd1,sd2,.......,sd9	Small ranges of relative crack depth in ascending order respectively
Md	Medium range of relative crack depth in ascending order

Hd1,hd2,.....hd9	High ranges of relative crack depth in ascending order respectively
Sl1,sl2,sl3.......,sl11	Small ranges of relative crack location in ascending order respectively
Ml	Medium range of relative crack location in ascending order
Hl1,hl2,hl3......,hl11	High ranges of relative crack location in ascending order respectively

S.No.	Fnf	Snf	Tnf	triangular		gaussian	
				Rcd	Rcl	Rcd	Rcl
1.	48.9	201.9	848.9	.125	.74	.127	.74
2.	48	201	840	.125	.713	.125	.711
3.	47.9	200.8	846.5	.125	.686	.126	.685
4.	47.5	200	845	.135	.617	.13	.631
5.	47	199.9	840.5	.163	.527	.157	.534
6.	46.5	199.5	838.5	0.175	0.404	.178	.418
7.	45.3	198	839	0.2	0.24	.206	.317
8.	40	191	836	0.375	0.4	.377	.402
9.	46.8	199	839	0.175	0.45	.177	.449
10.	46.4	198.9	837	0.184	0.406	.184	.405
11.	45	198.7	827.5	0.5	0.5	0.3	.517
12.	45.8	198.2	829	0.3	0.7	0.281	0.648
13.	46.4	198.7	833.5	0.2	0.611	0.202	0.574
14.	44.6	197	823	0.328	0.456	0.326	0.458
15.	44.2	195	819	0.399	0.453	0.398	0.47
16.	43.9	193.9	820.6	0.394	0.512	0.391	0.513
17.	41.4	194.6	812.4	0.35	0.205	0.39	0.316
18.	40.9	192.6	810.7	0.491	0.316	0.489	0.314
19.	40.8	192	805	0.5	0.29	0.49	0.265
20.	40.2	186.2	800.5	0.5	0.08	0.5	0.0801

4.5 Table 2: Comparison between Triangular and Gaussian Membership functions

From above table it is clear that Gaussian membership functions gave more accurate result than triangular one so for comparison of fuzzy logic technique with finite element analysis would on the basis of Gaussian member ship functions.

CHAPTER 5

DETECTION OF CRACK USING FEA

5.1 FEA analysis using ALGOR:

ALGOR is a general-purpose multiphysics finite element analysis software package developed by ALGOR Incorporated for use on the Microsoft Windows and Linux computer operating systems. It is distributed in a number of different core packages to cater to specifics applications, such as mechanical event simulation and computational fluid dynamics. ALGOR's complete product line includes InCAD technology for direct CAD/CAE data exchange and full associativity with each design change in Solid Edge for use with any analysis type within FEMPRO, ALGOR's easy-to-use, single user interface. ALGOR's wide range of simulation capabilities includes static stress and Mechanical Event Simulation (MES) with linear and nonlinear material models, linear dynamics, fatigue, steady-state and transient heat transfer, steady and unsteady fluid flow, electrostatics, full multiphysics and piping. So for analysis in ALGOR we need to first generate CAD model and then this model is analysed in the software by generating mesh and giving boundary conditions. Following are the steps for full finite element analysis taking example of double crack model.

5.2 STEPS for FEA of cracked beam modal using ALGOR :

1. **Generation of model in a designing software (here CATIA):**

The cracked beam model having single and double cracks are generated in CAD software CATIA having different crack depths and crack location. For single crack 153 models and for double crack 1064 models are generated having crack depths varying from 0.05 to 4 mm and crack location from 50 to 700 mm. Figure below shown is an example of the model generated in CATIA.

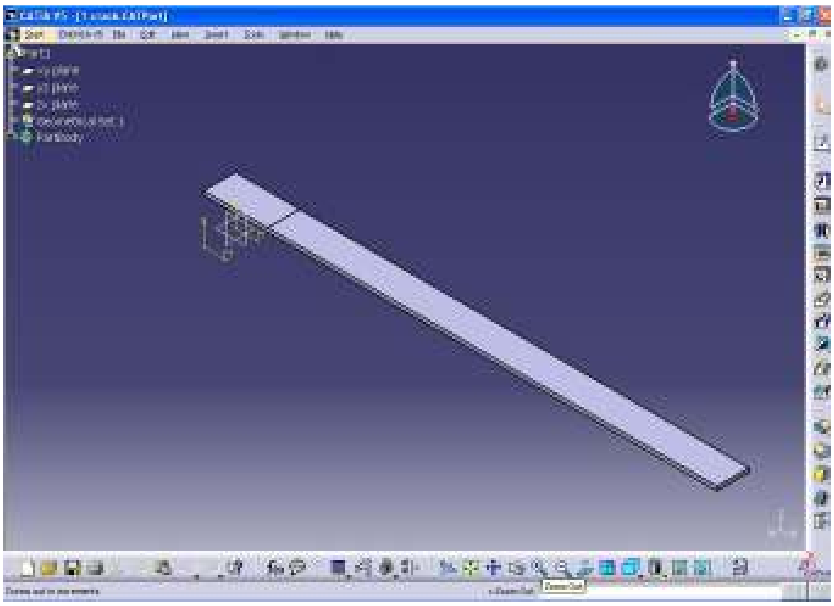


Fig 6a. Single crack model in CATIA

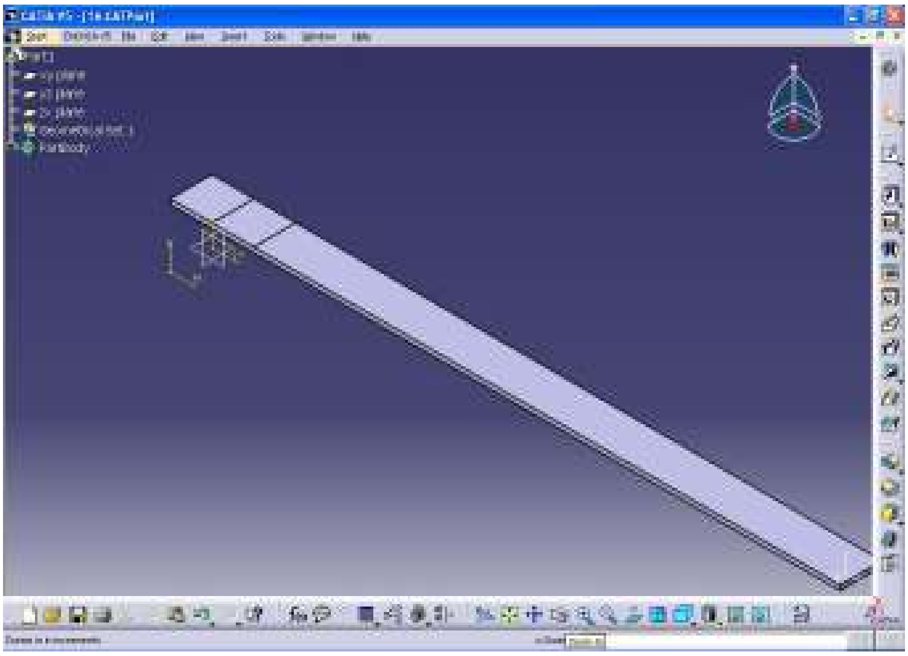


Fig 6b: Double crack model in CATIA

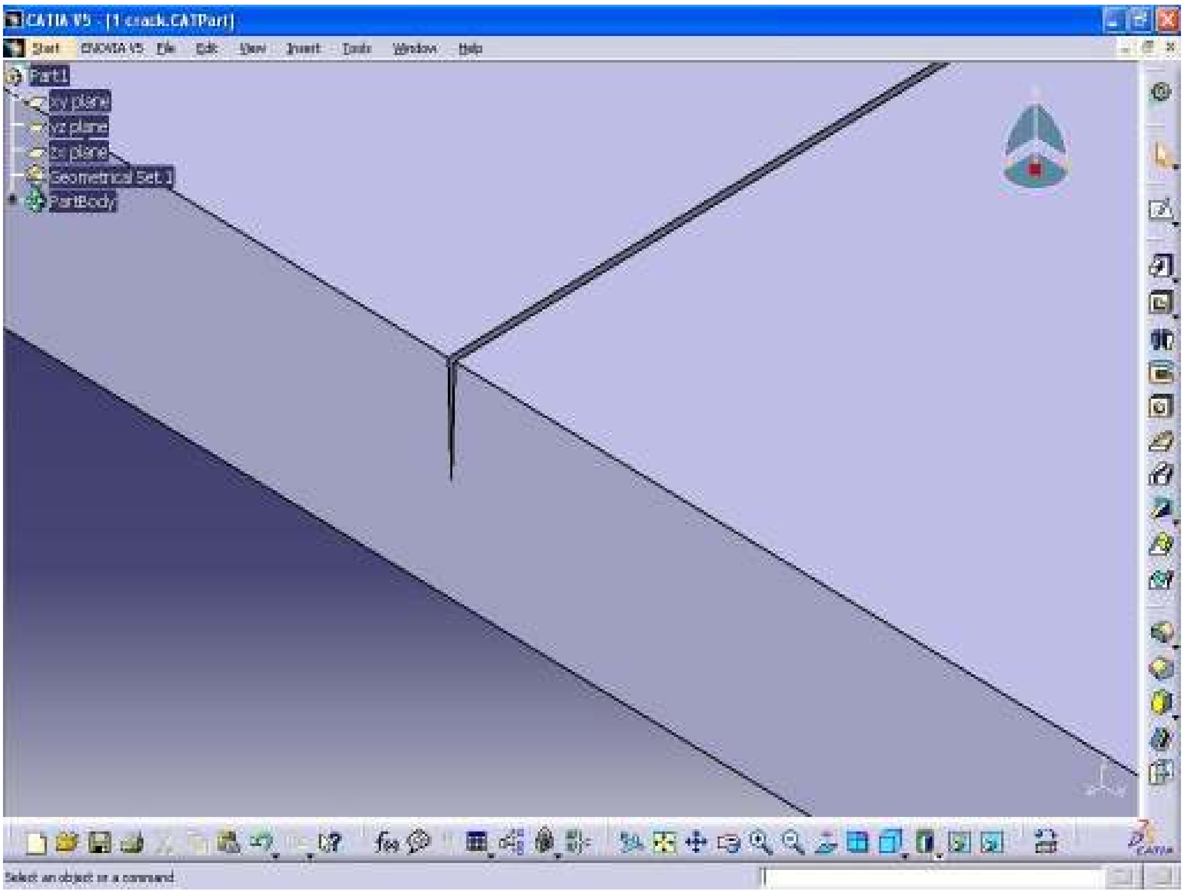
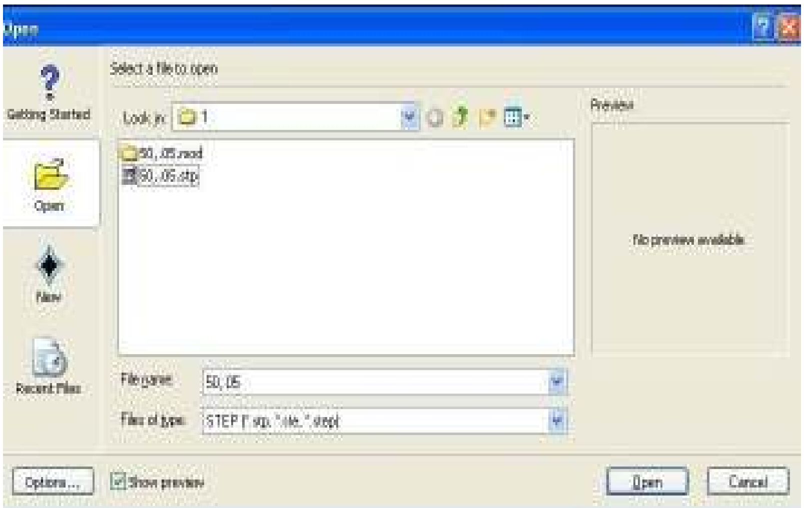


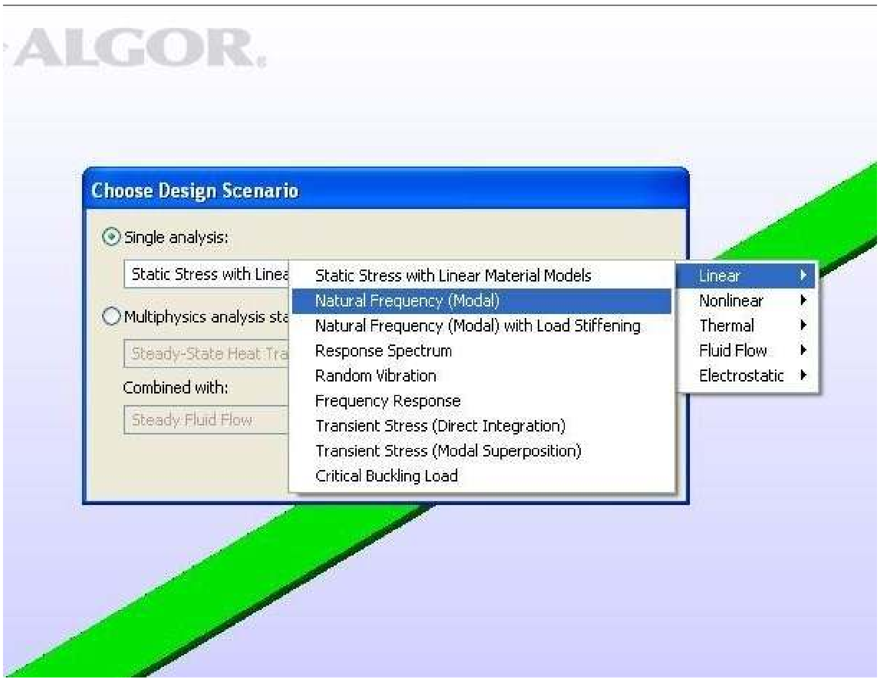
Fig 6c :Zoomed view of crack

Step 2: The file generated is saved in .stp format and given as input file for ALGOR software for finite element analysis

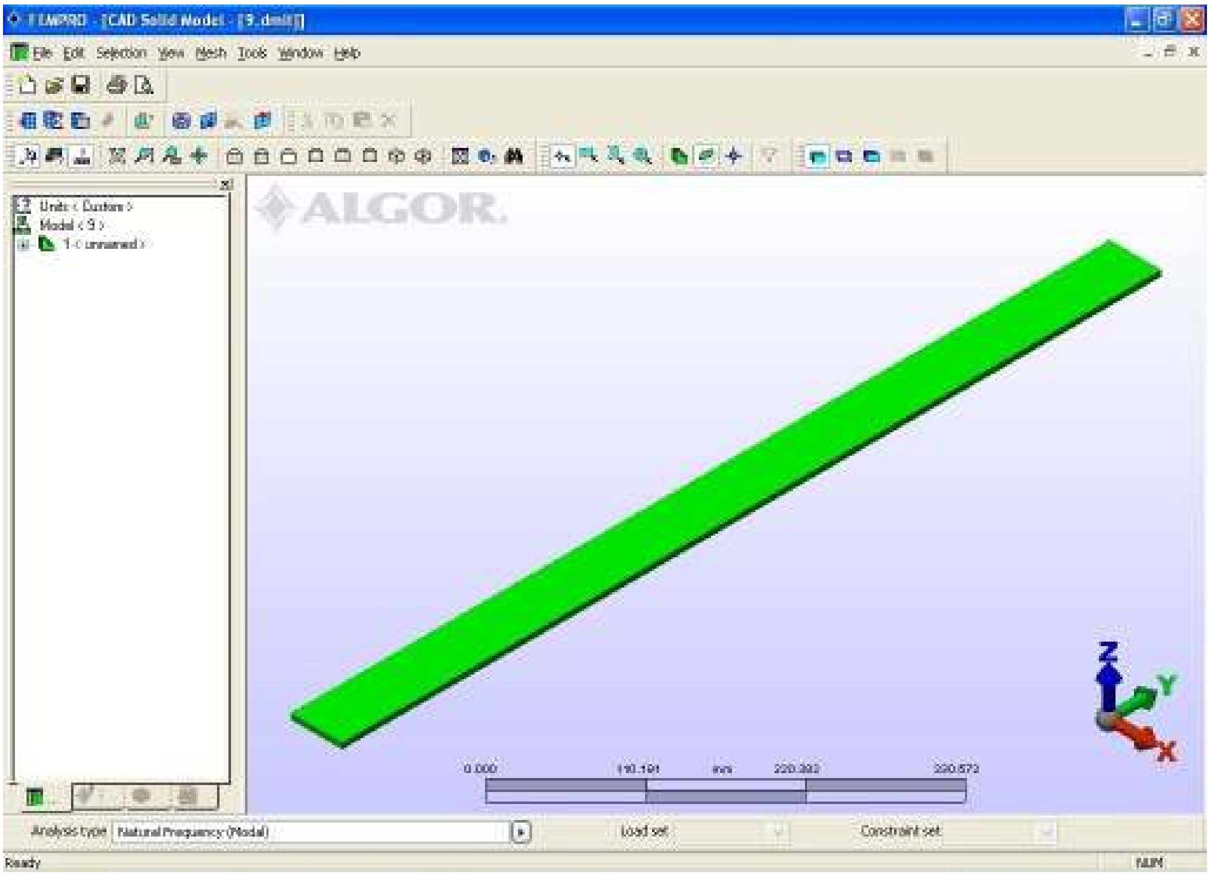
Step 3: The file is opened in FEMPRO which is part of ALGOR for finite element analysis as shown



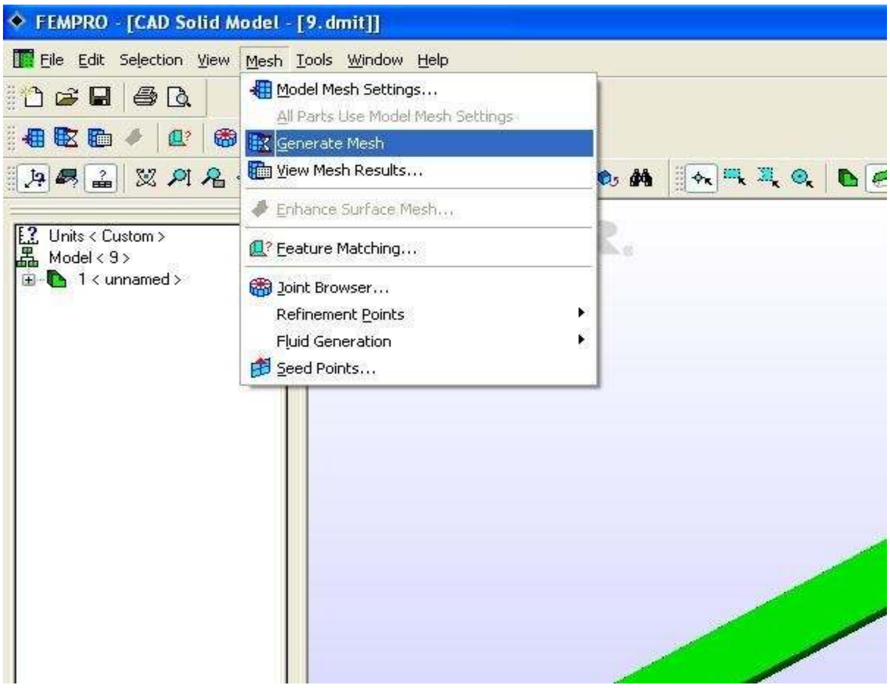
Step 4: Natural frequency modal is chosen for design scenario and mesh settings are shown in subsequent figure



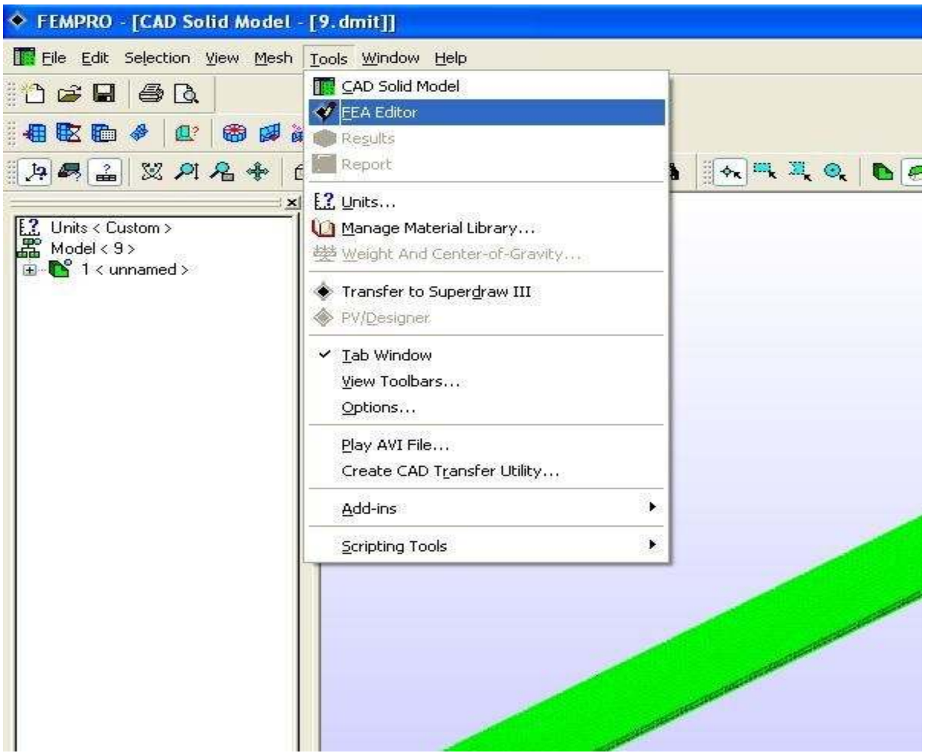
The modal is shown as below



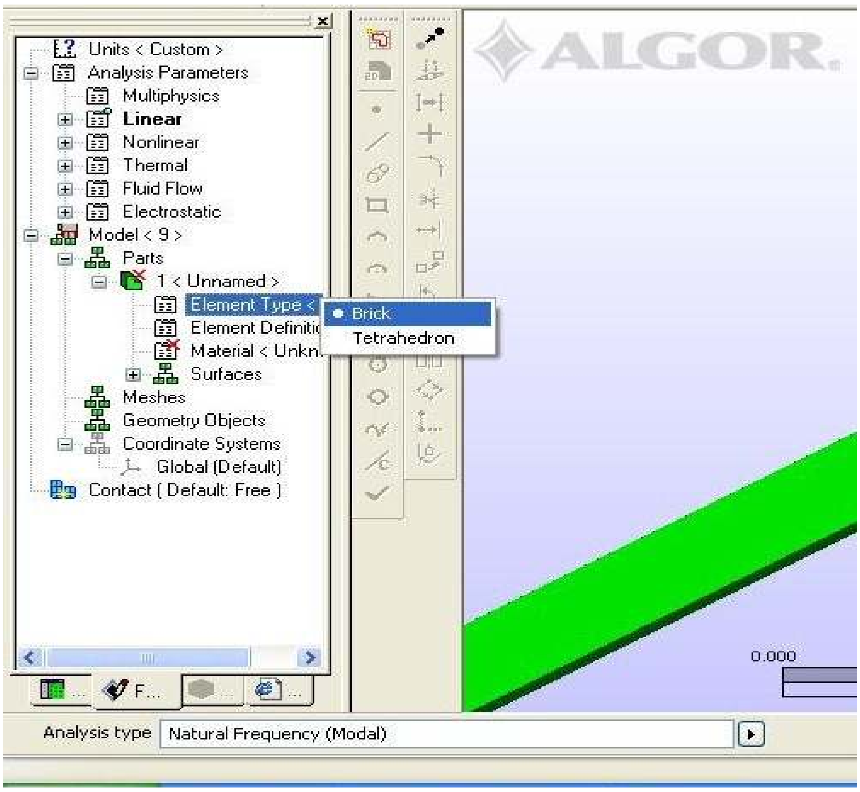
Step 5: Now mesh is generated as shown:



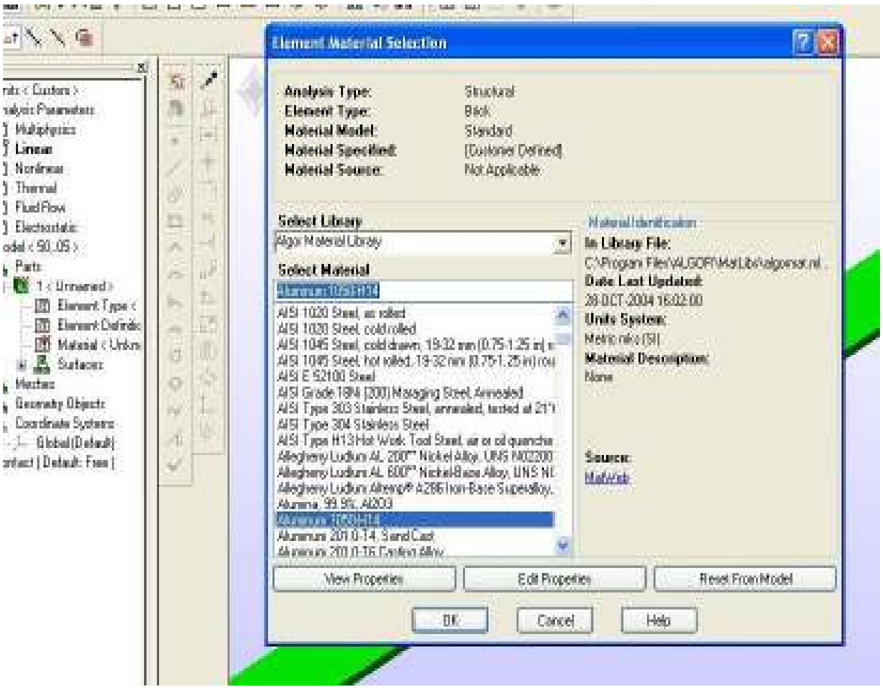
Step 6: After meshing is done FEA editor is opened



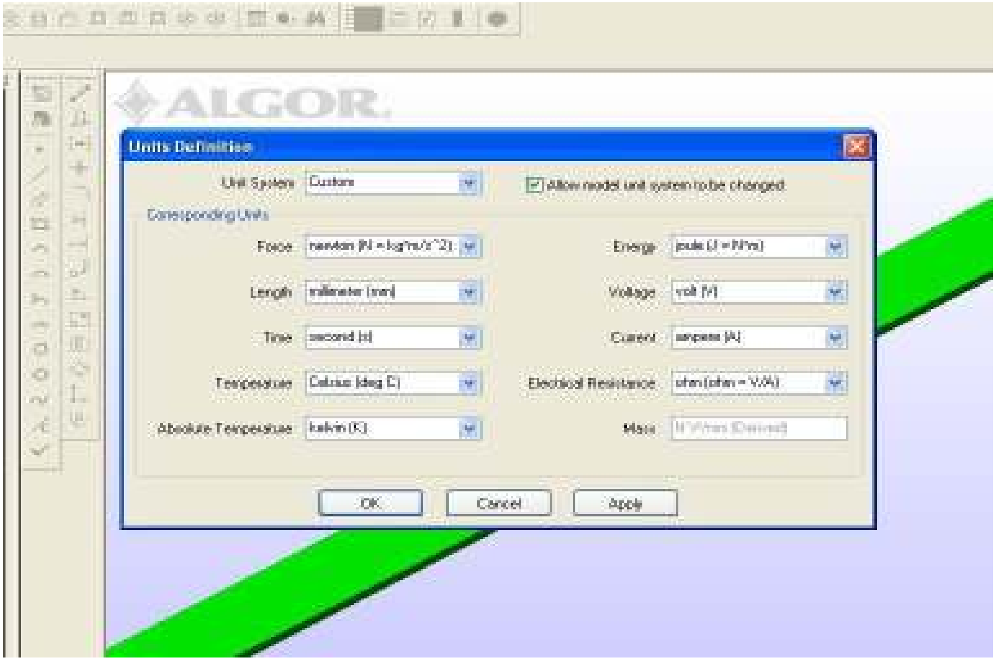
Step 7: Element type is set as brick type:



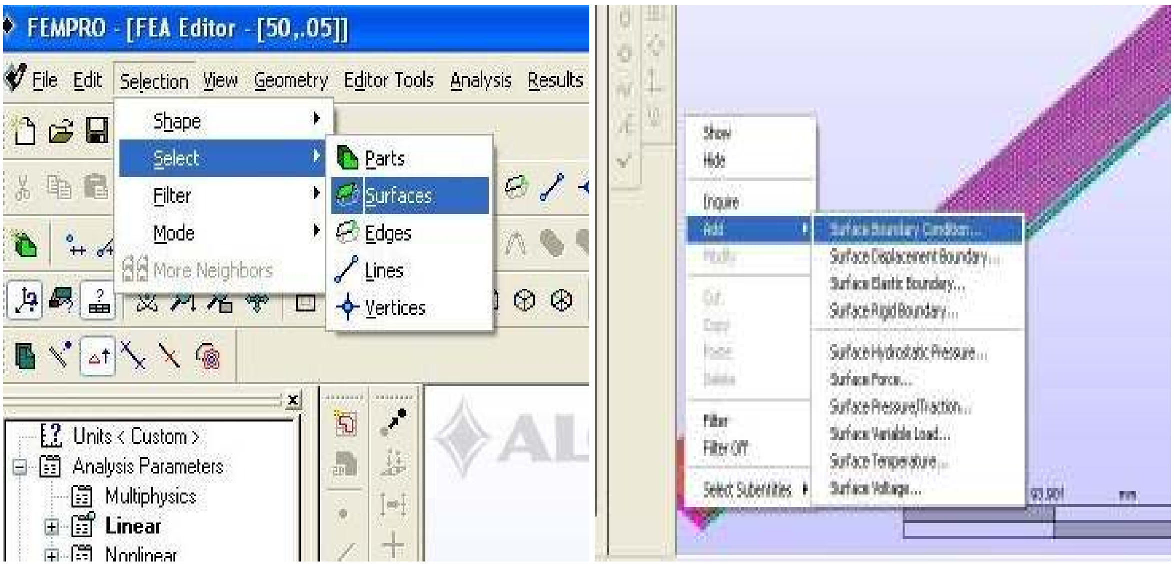
Step 7: Material is chosen as per requirement. Here Aluminium 1050-H14 is selected.



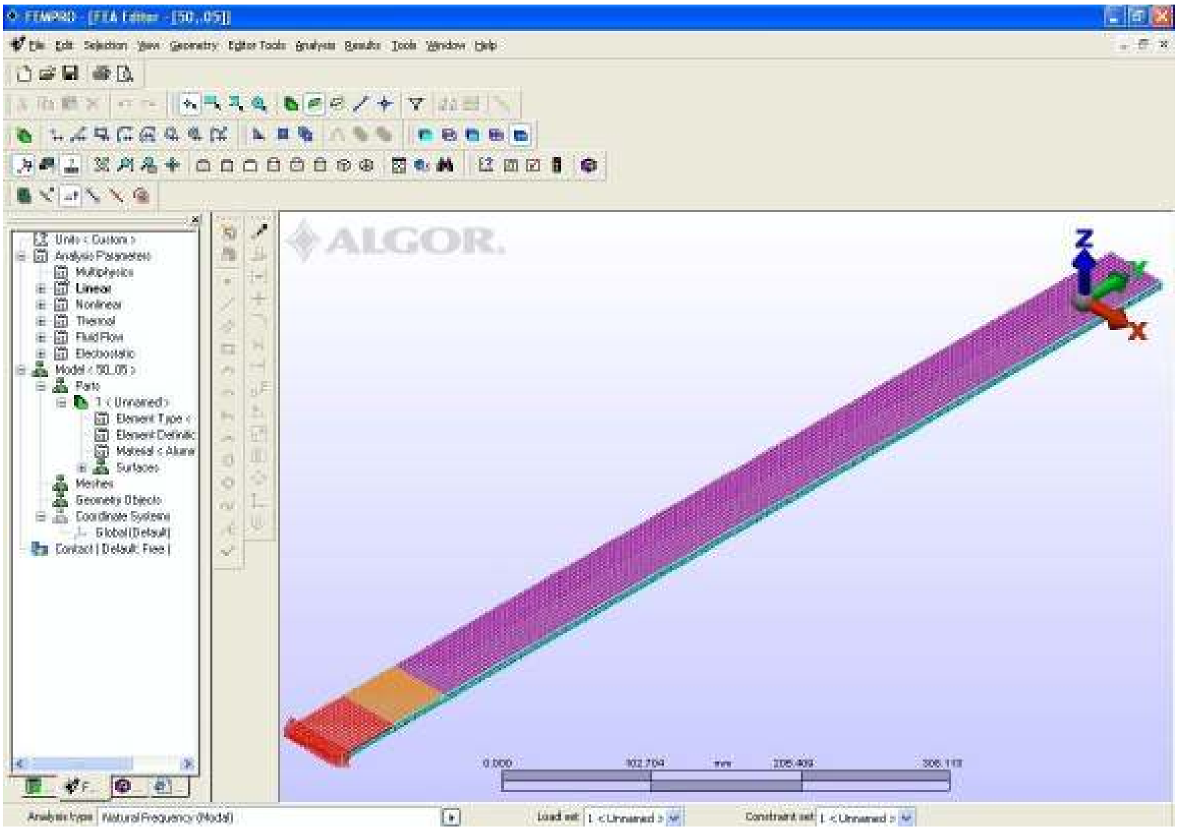
Step 8: Units are defined as:



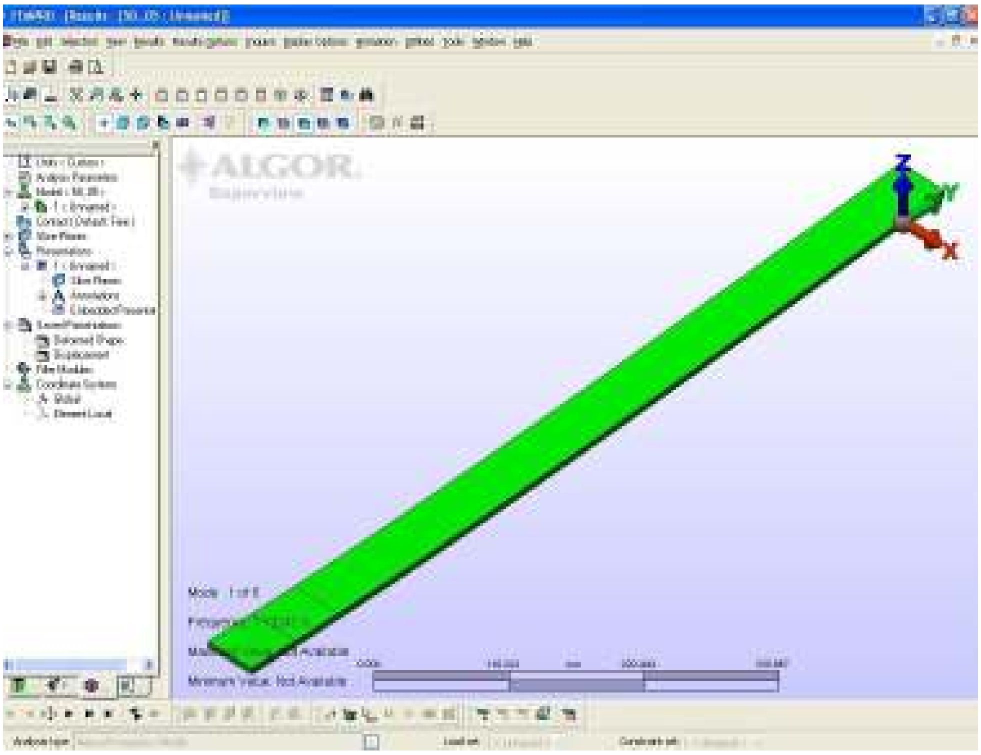
Step 9: Surfaces of modal is selected and surface boundary conditions are set



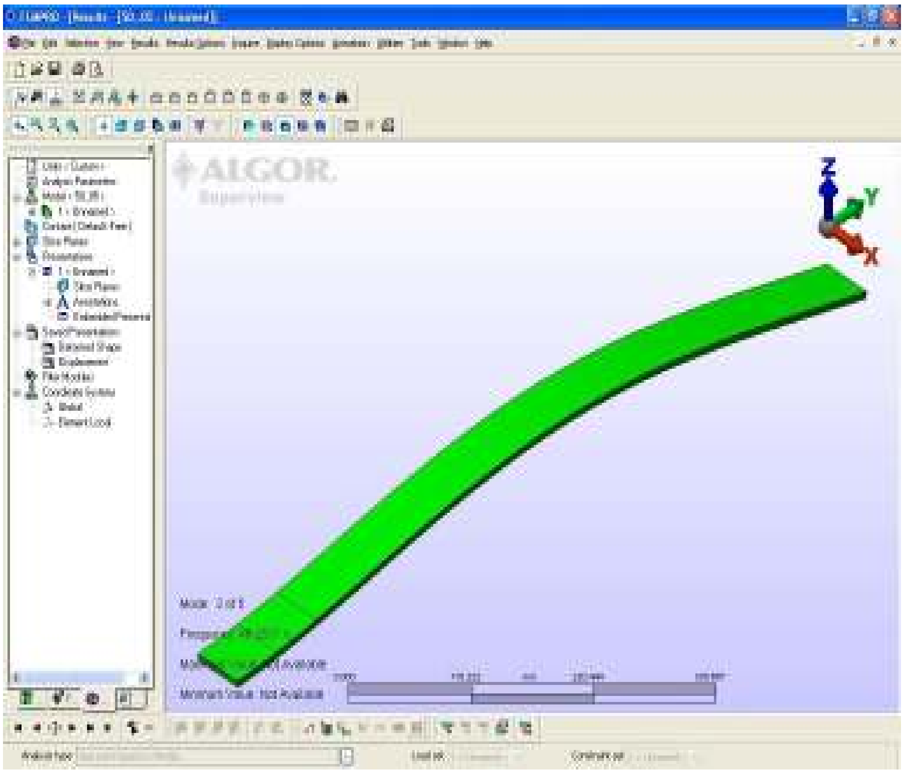
The modal would become like:



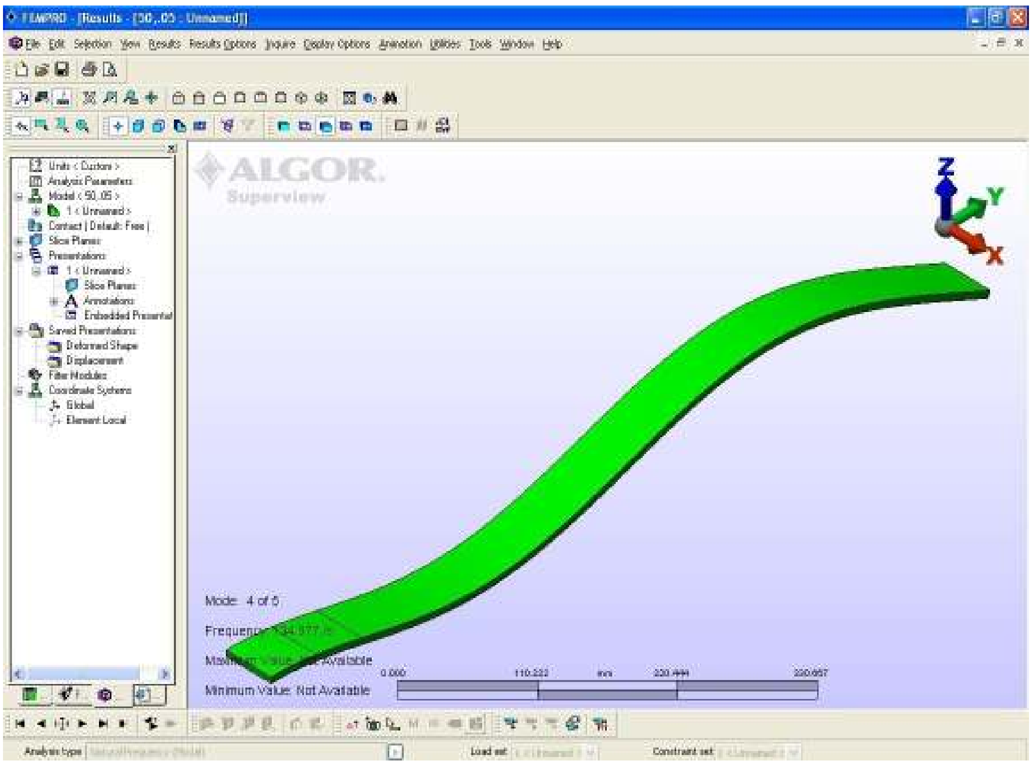
Step 10: Now we'll click perform analysis button in the toolbar and the three modes would be shown as below:



<u>First mode of vibration in cantilever beam</u>



Second mode of vibration in cantilever beam



Third mode of vibration in cantilever beam

5.3. Table 3: Comparison between FL and FEA:

Sl. No.	Fnf	Snf	Tnf	Fuzzy Gaussian membership function		ALGOR	
				Relative crack depth(rcd)	Relative Crack Location(rcl)	Relative crack depth(rcd)	Relative Crack Location(rcl)
1.	.997	.998	.999	.126	.739	.208	.125
2.	.996	.9976	.9987	.126	.737	.25	.0625
3.	.994	.9964	.998	.126	.726	.291	.0625
4.	.9915	.9949	.9972	.127	.687	.333	.0625
5.	.9884	.9931	.9962	.135	.618	.375	.0625
6.	.9845	.9908	.995	.176	.588	.416	.0625
7.	.9797	.9881	.9936	.175	.494	.458	.0625
8.	.9738	.9848	.9918	.19	.341	.5	.0625
9.	.9665	.9807	.9897	.27	.461	.541	.0625
10.	.9573	.9757	.9871	.271	.406	.583	.0625
11.	.9455	.9695	.9839	.4	.42	.625	.0625
12.	.9319	.9626	.9805	.373	.302	.666	.0625
13.	.977	.999	.983	.175	.498	.5833	.25
14.	.963	.9986	.973	.218	.569	.667	.25
15.	.9997	.9997	.9997	.127	.74	.125	.375
16.	.9982	.998	.9978	.126	.74	.292	.375
17.	.9831	.9813	.9799	.298	.724	.625	.375
18.	.998	.9825	.9851	.173	.476	.208	.5
19.	.999	.9996	.9996	.127	.74	.125	.625
20.	.996	.963	.970	.275	.507	.667	.625

CHAPTER 6

DISCUSSIONS:

Discussions based on the outputs of fuzzy controller used and information supplemented by finite element analysis are mentioned below. Firstly, fuzzy logic approach is considered. Since it was known that natural frequency decreases with the increase in relative crack depth. The linguistic form of fuzzy rules established for fuzzy membership functions used in the present fuzzy controller are given in table 1. Some of the sample examples of actual rules made for the fuzzy controller of the present investigation are listed in table 2. The present fuzzy controller uses Gaussian and triangular membership functions that are depicted and the outputs are also shown. The table shows comparison between outputs from Gaussian and triangular membership function.

Now considering the second approach in which finite element analysis of cantilever beam is done using ALGOR. Several steps have been shown to develop a natural frequency modal based on FEA which is explained through an example. It is clear from the analysis that natural frequency of three modes of vibration can be obtained precisely from this method.

The two approaches have been compared in table 3 which shows the relative crack depth and relative crack location are the two outputs. But in actual fuzzy takes inputs of first three natural frequencies giving output as relative crack depth and relative crack location whereas in ALGOR the inputs are crack depth and crack location and the first three natural frequencies are the outputs.

CHAPTER 7

CONCLUSIONS:

The present investigation based on the analytical results and discussions draws the following conclusions.

Significant changes in natural frequencies and mode shapes of the vibrating beam are observed at the vicinity of crack location.

The fuzzy controller is developed with Gaussian member ship functions is more accurate than triangular one. The inputs parameters to the fuzzy controller are first three natural frequencies. The outputs from the fuzzy controller are relative crack location and relative crack depth.

By comparing the fuzzy results from both membership functions it is observed that the developed Gaussian fuzzy controller can predict the relative crack location and relative crack depth in a very accurate manner.

The crack depth and crack location of a beam can be predicted by the developed fuzzy controller in nano seconds thereby saving a considerable amount of computational time.

The finite element analysis of the beam using ALGOR software package gave new approach for finding natural frequencies for a given crack depth and crack location.

Both approaches have advantages and disadvantages.

Fuzzy logic technique has advantage that after training it we can get crack depth and crack location at any inputs of three frequencies. But its results are not accurate as it is based on some training patterns. Whereas ALGOR gives more accurate values as the modal here is analysed in finite element wise but it is practically not applicable because natural frequencies can be evaluated practically but value of crack depth and crack location cannot be obtained from any measuring instrument because of their low values. The results obtained of all analyses are not much in agreement with each other.

So by comparing both the analyses we have noticed that they are not in much agreement but a new approach can be developed by combining the two approaches proposed i.e. the fuzzy Gaussian membership function can be trained on the basis of the outputs obtained from finite element analysis usinf ALGOR package. In this way fuzzy controller can be trained in accurate and better way as ALGOR gives results more precisely than fuzzy technique.

Further research can be made in the future to generate hybrid system of fuzzy controller and finite element analysis using ALGOR software package for more efficient results.

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