VIBRATION ANALYSIS OF CRACKED BEAM USING INTELLIGENT TECHNIQUE

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Vibration Analysis of Cracked Beam using Intelligent Technique

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by

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I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

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Certificate

This is to certify that the thesis entitled, "Vibration Analysis of Cracked Beam using Intelligent Technique", being submitted by Mrs. Sasmita Sahu to the Department of Mechanical Engineering, National Institute of Technology, Rourkela, for the partial fulfillment of award of the degree Master of Technology (Research), is a record of bona fide research work carried out by her under my supervision and guidance.

This thesis in my opinion, is worthy of consideration for award of the degree of Master of Technology (Research) in accordance with the regulation of the institute. To the best of my knowledge, the results embodied in this thesis have not been submitted to any other University or Institute for the award of any degree or diploma.

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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.

Key Words: damage, vibration, natural frequency, crack depth, crack locations, Mamdani FIS, Takagi-Sugeno FIS, Genetic algorithm, pattern search algorithm.

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a_1	= depth of crack
A	= cross-sectional area of the beam
A_i i = 1to 12	= unknown coefficients of matrix A
B	= width of the beam
B_1	= vector of exciting motion
C_u	$= (\frac{E}{\rho})^{1/2}$
C_y	$= (\frac{EI}{\mu})^{1/2}$
E	= Young's modulus of elasticity of the beam material
F_i i = 1,2	= experimentally determined function
i, j	= variables
J	= strain-energy release rate
$K_{1,i}$ i = 1,2	= Stress intensity factors for P_i loads
$\overline{K}_u$	$= \frac{\omega L}{C_u}$
$\overline{K}_y$	$= \left(\frac{\omega L^2}{C_y}\right)^{1/2}$
K_{ij}	= local flexibility matrix elements
L	= length of the beam
L_1	= location (length) of the crack from fixed end
M_i i=1,4	= compliance constant
P_i i=1,2	= axial force (i=1), bending moment (i=2)
Q	= stiff-ness matrix for free vibration.
Q_1	= stiff-ness matrix for forced vibration
rcd	= Relative crack depth
rcl	= Relative crack location
fnf	= Relative first natural frequency
snf	= Relative second natural frequency

tnf	= Relative third natural frequency
u_i , i=1,2	= normal functions (longitudinal) $u_i(x)$
x	= co-ordinate of the beam
y	= co-ordinate of the beam
Y_0	= amplitude of the exciting vibration
y_i ,i=1,2	= normal functions (transverse) $y_i(x)$
W	= depth of the beam
?	= natural circular frequency
ß	= relative crack location $\frac{L_1}{L}$
µ	= A?
?	= mass-density of the beam
$?_1$	= relative crack depth $\frac{a_1}{W}$
V	= Aggregate (union)
Λ	= Minimum (min) operation
∀	= For every
fnf_{fld}	= First natural frequency of the field
snf_{fld}	= Second natural frequency of the field
tnf_{fld}	= Third natural frequency of the field
fnf_x	= Relative first natural frequency
snf_x	= Relative second natural frequency
tnf_x	= Relative third natural frequency

$x_1, x_2, x_3, ..., x_j, ..., x_m$ =output variables defined on reference sets T-S FIS

$X_1, X_2, X_3, ..., X_j, ..., X_m$ = Reference sets

y	=output variable
Y	= output reference set
R_k	= kth if-then rule

$f(x_1, x_2, ..., x_m)$ = is a linear function

w_k	=is the weight of R_k rule
x_j	=variables for pattern search algorithm
x_{jl}	=lower limit for the variable
x_{ju}	=upper limit for the variable
j	= 1; . . . N
M_j	=mesh points of the pattern search algorithm
η_{exp}	=expansion factor
η_{cont}	=contraction factor
$P_{current}$	=current point
P_{start}	=starting point

Chapter 1

Introduction

Chapter 1

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.

1.1 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 structural health monitoring and damage detection at the earliest possible stage is prevalent throughout the civil, mechanical, and aerospace engineering industries.

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, which 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.

The general interest in timely assessment of damage in structures and with the advent of modern computing techniques, the health monitoring has received a considerable attention since last three decades. The process of damage detection consists of mainly three stages as: (1) detecting, (2) locating and (3) quantifying the extent of damage. Most researchers have proposed methods for the detection of existence of structural damage via monitoring the structural responses. However, it is difficult to find the location and extent of damage. In recent years, there has been a considerable demand for more accurate techniques to detect and locate damage, particularly in large structures.

There are several ways to deal with the structural integrity evaluation. There is a consensus that it is necessary to establish inspection procedures which systematically evaluate the structural integrity. The main techniques may be separated as non-destructive and destructive testing. In particular, detection techniques based on non-destructive testing (NDT) has been preferable due to low cost and operational aspects related to the use of the analyzed structure. There are methods for damage detection based on sensitivity and statistical parameters. Some methods are based on dynamic characteristics of structures such as natural frequencies.

Considering the crack as a significant form of such damage, its modeling is an important step in studying the behavior of damaged structures. Knowing the effect of crack on stiffness, the beam or shaft can be modeled using either Euler-Bernoulli or Timoshenko beam theories. The beam boundary conditions are used along with the crack compatibility relations to derive the characteristic equation relating the natural frequency, the crack depth and location with the other beam properties. Beam type structures are commonly used in steel construction and machinery industries. The current study is based on crack detection for structural health monitoring in regard to change in natural frequencies and mode shapes of the beam.

Existence of structural damage in structural elements like beams and shafts leads to the modification of the vibration modes. These modifications are manifested as changes in the modal parameters, i.e., natural frequencies and mode shapes. Thus, an analysis of periodical frequency measurements can be used to monitor the structural condition. Since frequency measurements can be cheaply acquired and are often reliable, the approach could provide an inexpensive structural assessment technique.

1.2 Purpose of this Research

The occurrence of damage in a structure produces changes in its global dynamic characteristics such as its natural frequencies, mode shapes, modal damping, modal participation factors, and impulse response and frequency response functions. An understanding of these changes can lead to the detection, location, and the characterization of the extent of the damage. Such studies currently form the subject of active research in the ?eld of aerospace, mechanical and civil structural health monitoring. If interest is focused on determining the location of damage and the extent of damage, the analyst would require a satisfactory model for the structure in its undamaged state.

In the current research, a number of literatures published till now have been surveyed, reviewed and analyzed. It is felt that, the results presented by the researchers have not been utilized so far in a systematic way for engineering applications and much work is not done so far using these techniques (GA & PSA) which is provided in this research work. A systematic attempt has been made in the present study to investigate the dynamic behavior of cracked cantilever beam structure using theoretical analysis, finite element analysis, and experimental analysis and artificial intelligence techniques for damage diagnosis of cracked structure. The dynamic responses of the system are used for crack prediction.

The different steps used in the present analysis are as follows:

- First the Theoretical free vibration analysis of the cracked cantilever beam has been described.
- Finite element analysis of the crack is done.
- Finally the data obtained in the first two steps are trained in the designed controllers using Artificial intelligence techniques. These controllers predict the relative values of crack depth and crack location from the three inputs (relative values of first, second and third natural frequencies).
- Then Experimental analysis is done to validate the results from the designed controllers.

For analytical expressions for the dynamic responses of the cantilever beam, a single transverse crack has been considered. From the first three steps number of data are collected. All these analyses are done to make a data pool and for subsequent comparison among the results of the analyses.

The transverse crack introduces local flexibility at the vicinity of the crack location or decreases the stiffness of the material at that area. In all these analysis Euller-Bernoulli type of beam is considered for the shake of simplicity. Boundary conditions are derived from the strain energy equation using Castiglione’s theorem. The relative values for the first three natural frequencies are obtained from the theoretical, finite element analysis and experimental used as input parameters to the different controller for crack identification. The outputs from the controller are relative crack depth and relative crack location.

1.3 Layout of the work

The present work as outlined in this thesis is broadly divided into nine chapters. Following the introduction, Chapter two presents the literature review of previous work on structural vibration and its analysis, effect of different parameters on dynamic response of cracked structures, dynamic characteristics of beam with transverse crack, crack detection by artificial intelligence technique such as fuzzy logic, genetic algorithm and other techniques.

Chapter three analyses the dynamics characteristics of beam with a transverse crack using the expression of strain energy release rate and strain energy density function. The local flexibilities generated due to the presence of crack have been evaluated. The free vibration analysis has been performed to compute the vibration characteristics of the cracked cantilever beam.

In chapter four Finite element analysis of the cracked cantilever beam is described. For this analysis Euler-Bernoulli beam model is assumed. The crack is assumed to be an open crack and the damping is not being considered in this theory. Here crack depth and crack location both were varied and the variation in the first three natural frequencies were noted down.

Chapter five defines the concept of the fuzzy logic and outlines the technique used to design an intelligent fuzzy logic controller for prediction of relative crack depth and relative crack locations using the variation in the first three natural frequencies. Both Mamdani and Takagi-Sugeno FIS have been used to design the controller. The results obtained from the developed fuzzy controller have been validated with the results from the theoretical, finite element and experimental analysis.

In chapter six Analysis of Genetic Algorithm controllers is depicted. In this chapter both Genetic Algorithm and Pattern search methods are described.

Genetic Algorithms has three major applications, namely, intelligent search, optimization and machine learning. In this current work GA has been used as an intelligent search tool based on the fitness of the individuals, which is determined by a fitness function. In this investigation Pattern Search Algorithm is also used with GA for the prediction of crack depth and crack location. Generally, PS has the advantage of being very simple in concept, easy to implement and computationally efficient algorithm.

In chapter seven the details of the developed experimental set-up for vibration analysis along with the specifications of the different equipment used are presented. Finally the experimental results are discussed. Chapter eight summarizes the findings of all chapters discussed above. Contributions, conclusions of this research and future directions for further investigation have been discussed in the ninth chapter.

Chapter 2

Literature Review

Chapter 2

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.

2.1 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.

2.2 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. [7] 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. Demosthenous et al. [9] have produced in his paper an investigation of a beam crack identification method by using the standard finite element formulation. A new concept of nonlinear output frequency response functions (NOFRFs) has been introduced by Peng et al. [10] to detect cracks in beams using frequency domain information. The NOFRF concept is used to analyze the crack induced nonlinear response of a beam represented by a finite model. Hari Prasad et al. [11] have investigated the accuracy of predicting the dynamic response by finite element modeling of structures with cracks. Lee et al. [12] have presented a simple method to identify multiple cracks in a beam, by modeling the cracks as rotational springs and the forward problem is solved using the finite element method. Bejarano et al. [13] have developed a novel real-time monitoring diagnostic method of determining the position and depth of a transverse open crack on a rotating shaft. Vibration parameters were obtained first from a simulation employing the Finite Element method.

Dimarogonas [14] has described and analyzed a non linear system where the local stiffness matrix of the cracked section of the shaft leads to a coupled system, while for an uncracked shaft the system is decoupled. Naik et al. [15] have presented the full formulation for a crack model for analyzing the triply coupled free vibration of both Timoshenko (short) and Euler–Bernoulli (long) shaft beams based on compliance approach in the presence of a planar open edge crack in an arbitrary angular orientation with a reference direction. Al-Bedoor et al. [16] have presented an experimental study on the dynamic response of an overhung rotor with a propagating transverse crack. The effects of a propagating transverse crack and side load on the dynamic response of an overhung rotor are investigated in order to identify vibration signatures of a propagating crack in rotating shafts. Xiaoqing et al. [17] have described an analytical approach for the detection of a beam with multiple cracks. The method is based on the bending vibration theory of Euler-Bernoulli beam and the cracks are treated as mass less rotational springs, by which the cracked beam is separated into a number of segments of perfect beams. Parhi et al. [18] have analyzed fault detection in a cracked beam using Theoretical, finite element and experimental analyses for identification of the crack depths and their positions in a beam containing multiple transverse cracks. Wu et al. [19] have presented a general summary and review of state-of-the-art and development of vibration-based structural damage detection.

Various structural damage detection methods based on structural dynamic characteristic parameters are summarized and evaluated. The principle of intelligent damage diagnosis and its application prospects in structural damage detection are introduced, and the development trends of structural damage detection are also put forward.

2.3 Fuzzy Logic System for damage detection in a beam

Haziness is always present in any realistic process. This vagueness may come up from the analysis of the data inputs and in the directives used to describe the relationships between the informative attributes. Fuzzy logic grants an inference structure that allows the human reasoning capacities to be applied to artificial knowledge-based structures. Fuzzy logic gives a means for adapting linguistic strategy into control actions and thus offers a high-level computation. The Fuzzy Inference engine can be used as a controller for damage detection in structural elements. Some of the works of the researchers using this technique is provided in this section.

Ganguli et al. [20] have developed A fuzzy logic system (FLS) is developed for ground based health monitoring of a helicopter rotor blade. Structural damage is modeled as a loss of stiffness at the damaged location that can result from delamination. Sazonov et al.[21] have designed fuzzy expert system based on a finite element (FE) model of a simple beam and have provided reliable detection of damage for every tested damage scenario. Shim et al. [22] have presented a method to identify the location and depth of a crack in a structure. This method uses neuro fuzzy- evolutionary technique, that is, Adaptive-Network-based Fuzzy Inference System (ANFIS) solved via hybrid learning algorithm (the back-propagation gradient descent and the least-squares method) and Continuous Evolutionary Algorithms (CEAs) solving single objective optimization problems with a continuous function and continuous search space efficiently are unified. Pawar et al. [23] have used a finite element model of a cantilever beam to calculate the change in beam frequencies because of structural damage and a genetic fuzzy system is used to find the location and extent of damage. Shim et al.[24] have presented a method which uses a synthetic artificial intelligence technique, i.e. adaptive-network-based fuzzy inference system (ANFIS) solved via a hybrid learning algorithm (the back propagation gradient descent and the least-squares method) and continuous evolutionary algorithms (CEAs) solving single objective optimization problems with a continuous function and continuous search space efficiently are unified. Suresh et al. [25] have analytically computed the modal frequency parameters for various crack locations and depths using a fracture mechanics based crack model and made comparative study using the modular neural network architecture with two widely used neural networks, namely the multi-layer perceptron network and the radial basis function network. Fang et al. [26] have developed a back-propagation neural network (BPNN) used frequency response functions (FRFs) as input data to the network the structural damage detection. Song et al. [27] have proposed in his paper a fuzzy gain tuner to tune the gain in the positive position feedback control to reduce the initial overshoot while still maintaining quick vibration suppression. Lin et al. [28] have presented a novel resonant fuzzy logic controller (FLC) to minimize structural vibration using collocated piezoelectric actuator/sensor pairs. The effectiveness of the new fuzzy control design to a state-of-the-art control scheme is compared through the experimental studies. Nomura et al. [29] have proposed a method that includes two fuzzy active control systems, a fuzzy ensemble system, and a gating network. In this study, two fuzzy active control systems are constructed by applying particle–swarm optimization. Chandrashekhar et al.[30] have explored the effect of changes in the damage evaluation parameter (frequency) due to uncertainty in material properties and a fuzzy logic system (FLS) is developed with a new sliding window defuzzifier for damage detection. Lee et al. [31] have presented a simple method to identify multiple cracks in a beam using the vibration amplitudes by solving the inverse problem iteratively for the crack locations and sizes using the Newton–Raphson method and the singular value decomposition method. Nossair et al. [32] have developed a simulation platform of a flexible beam vibration using finite difference (FD) method is used to demonstrate the capabilities of the identification algorithms. These identification are done using (a) traditional Recursive Least Square (RLS) filter, (b) Genetic Algorithms (GAs) (c) Adaptive Neuro Fuzzy Inference System (ANFIS) model (d) General Regression Neural Network (GRNN) and (e)Bees Algorithm (BA). Zouzou et al. [33] have paper presents a practical implementation of a new strategy using the fuzzy logic for the detection and the diagnosis of broken shafts in electrical induction machine. Dash et al. [34] have presented a comprehensive review of methodologies and technologies in the domain of dynamic vibration of cracked structures. The methodologies mainly consist of energy methods, finite element methods, fuzzy inference techniques, neural networks, neuro-fuzzy adaptive techniques and genetic algorithms used for identifying the intensity and location of cracks. Parhi et al. [35] have presented comprehensive review of methodologies in the domain of dynamic vibration of cracked structures using energy methods, finite element methods, fuzzy inference techniques, neural networks, neuro-fuzzy adaptive techniques and genetic algorithms for identifying the intensity and location of cracks. Beena et al. [36] have developed a new algorithmic approach for structural damage detection based on the fuzzy cognitive map (FCM). The input concepts for the FCM are the frequency deviations and the output of the FCM is at five possible damage locations along the beam. Parhi and Das [37] have used the multiple adaptive-neuro-fuzzy inference system (MANFIS) methodology to diagnose the crack in the structure. The input layer is the fuzzy layer. The other layers are neural layers. The inputs to the fuzzy layer are relative deviation of the first three natural frequencies and relative values of percentage deviation for the first three mode shapes. The final outputs of the MANFIS controller are relative crack depth and relative crack location. Serra and Bottura [38] have proposed a Takagi–Sugeno (TS) fuzzy model. In this approach, the chosen instrumental variables, statistically uncorrelated with noise, are mapped to fuzzy sets, partitioning the input space in sub regions to define unbiased estimates of the TS fuzzy model consequent parameters in a noisy environment. Das and Parhi [39] have developed a fuzzy inference system for detection of crack location and crack depth of a cracked cantilever beam structure. The six input parameters to the fuzzy member ship functions are percentage deviation of first three natural frequencies and first three mode shapes of the cantilever beam. The two output parameters of the fuzzy inference system are relative crack depth and relative crack location. The developed fuzzy inference system can predict the location and depth of the crack in a close proximity to the real results.

2.4 Genetic Algorithm for Crack Detection in a Beam

The concept of Darwin's theory of evolution has been translated into algorithms to search for solutions to problems in a more "natural" way. This theory was first proposed by John Holland in 1975. First, different possible solutions, a fraction of good solution are selected, and the others are eliminated (survival of the fittest). The selected solutions undergo the processes of reproduction, crossover, and mutation to create a new generation of possible solutions (which are expected to perform to better than previous generation). This process of production of a new generation and its evaluation is repeated until there is convergence within a generation.

Because of their simplicity, ease of operation, minimal requirements, and parallel and global perspective, Genetic Algorithms have been applied successfully in a wide variety of problem domains. Some of these works are produced here.

Chaudhry et al**.** [43] have obtained frequency response data obtained from a piezoelectric actuator/sensor pair bonded to a composite/aluminum beam structure with a debond between the interface is used to train an artificial neural network by back propagation to identify the severity and presence of a delamination. Zang and Imregun [44] have dealt with structural damage detection using measured frequency response functions (FRFs) as input data to artificial neural networks (ANNs). He et al. [45] have proposed and described a genetic algorithm based method for shaft crack detection and formulated the shaft crack detection as an optimization problem by means of finite element method and utilizes genetic algorithms to search the solution. Comp et al. [46] have developed a genetic algorithm with real number encoding is applied to identify the structural damage by minimizing the objective function, which directly compares the changes in the measurements before and after damage. Krawczuk et al. [47] have presented in his paper the use of the wave propagation approach combined with a genetic algorithm and the gradient technique for damage detection in beam-like structures. Pawar et al. [48] have developed the genetic fuzzy system for a noise level of 0.20 in the data gives a fault isolation success rate of 99.81% when the first eight natural frequencies are used. Cheng et al. [49] have described in this paper a procedure for detecting structural damage based on a micro-genetic algorithm using incomplete and noisy modal test data. Rao et al.[50] have developed two-point crossover binary coded genetic algorithm (GA) with tournament selection approach is adopted in minimizing the objective and optimum set of stiffness reduction parameters are predicted. Marwala et al. [51] have used Genetic algorithm to solve for the missing input values. The proposed method is tested on a fault classification problem in a population of cylindrical shells. Hwang et al. [52] have developed an effective algorithm, which combined an adaptive real-parameter genetic algorithm with simulated annealing, is proposed to detect damage occurrence in beam-type structures. Perera et al. [53] have developed a non classical optimization approach involving the use of genetic algorithms (GAs) is proposed to localize damaged areas of the structure. Chen et al. [54] have proposed a vibration-based approach to detect crack damage for large structural systems by using the Hilbert—Huang transform(HHT).An optimization procedure is developed by genetic algorithm(GA) in order to determine the location of piezoelectric sensor for damage detection in a composite wing box. Pawar et al. [55] have investigated the effect of damage on beams with fixed boundary conditions using Fourier analysis of mode shapes in the spatial domain a neural network is trained to detect the damage location and size using Fourier coefficients as input. Taghi et al. [56] have developed a fault diagnosis method based on genetic algorithms (GAs) and a model of damaged (cracked) structure. The identification of the crack location and depth in the cantilever beam is formulated as an optimization problem, and binary and continuous genetic algorithms (BGA, CGA) are used to find the optimal location and depth by minimizing the cost function which is based on the difference of measured and calculated natural frequencies. Xian, Ming et al.[57] have developed a novel method of damage identification for beam using artificial neural network (ANN) based on statistical properties of structural dynamic responses is developed. Saridakis et al. [58] have first introduced a model for the coupling effect of bending vibrations on the cracked shaft and then used to identify the rotational angle of the crack. Then an efficient objective function is selected, one whose minimization leads to the determination of the crack characteristics. More computational intelligence is added through a genetic algorithm, which is used to find the characteristics of the crack. Panigrahi et al. [59] have formulated an objective function for the identification of macroscopic structural damage in a uniform strength beam using genetic algorithm and residual force method. Lehky et al. [60] have described a methodology of damage detection which is based on artificial neural networks in combination with stochastic analysis. The damage is defined as a stiffness reduction (bending or torsion) in certain part of a structure. Hyung et al. [61] have developed sequential approaches for damage detection in beams using time-modal features and artificial neural networks are proposed. Gunes and Tokan [62] have introduced a direct, efficient and derivative-free optimization tool with the applications on the antenna array synthesis in the antenna engineering. P Search is a nonrandom method which can be exploited as a direct searching tool for minimization of a function which is not necessarily differentiable, stochastic, or even continuous.

Different researchers have also done vibration analysis using many different techniques which is also produced in the next section of this chapter. Some of these ideas are also used in this research work.

Sahu et al. [63] have used the influence coefficient method to find out the fundamental frequency of a cracked shaft with two open cracks rotating in a fluid medium. Das et al. [64] have used various innovative techniques like hierarchical knowledge reinforcement, genetic evolutionary concept, transform domain approach, tuning of sigmoid slope of neuron using fuzzy logic concept to incorporate into an FNN framework for designing highly efficient equalizer structures. Reddy et al. [65] have used radial basis function (RBF) neural networks for detection of structural damage in a helicopter rotor blade using rotating frequencies of the flap (transverse bending), lag (in-plane bending), elastic torsion and axial modes. Chaudhry et al. [66] have used frequency response data obtained from a piezoelectric actuator/sensor pair bonded to a composite/aluminum beam structure with a debond between the interface is used to train an artificial neural network by back propagation to identify the severity and presence of a delamination. Ruotolo et al. [67] have analyzed the vibrational response of a cracked cantilevered beam to harmonic forcing using the harmonic balance method. Yokoyama et al. [68] have investigated the vibration characteristics of a uniform Bernoulli-Euler beam with a single edge crack and the numerical results for the natural frequencies of cracked hinged-hinged and cantilever beam are shown to be in excellent agreement with available numerical and experimental data. Kasabov and Kozma [69] have given a general framework of developing hybrid, intelligent, and adaptive systems. This work develops multi modular, fuzzy neural network systems. Ishak et al. [70] have presented Numerical and Experimental studies for crack detection in beam employing transverse impact. Here adaptive multilayer preceptor networks (MLP) are used for inverse identification of crack parameters (i.e., crack location, depth and length) in the beams. Jack et al. [71] have used Artificial neural networks (ANNs) have been to detect faults in rotating machinery, using statistical methods to preprocess the vibration signals as input features and the performance of both types of classifiers in two-class fault/no-fault recognition examples and the attempts to improve the overall generalization performance of both techniques through the use of genetic algorithm based feature selection process. Haryanto et al. [72] have developed a computational method on damage detection problems in structures was developed using neural networks. The problem considered in this work consists of estimating the existence, location and extent of stiffness reduction in structure. Zhang et al. [73] have used GP to detect faults in rotating machinery. Feature sets from two different machines are used to examine the performance of two-class normal/fault recognition. The results are compared with a few other methods for fault detection: Artificial neural networks (ANNs) have been used in this field for many years, while support vector machines (SVMs) also offer successful solutions. Tian et al. [74] have produced a method of crack detection in beam which is provided by wavelet analysis of transient flexural wave. Kim et al. [75] have presented a practical method to non-destructively locate and estimate size of a crack by using changes in natural frequencies of a structure is by producing algorithm to locate and size cracks in beam-type structures using a few natural frequencies is outlined. Kalkat et al. [76] have designed a direct-coupled rotor system was designed to analyze the dynamic behavior of rotating systems in regard to vibration parameters. A neural network is designed for analyzing a system's vibration parameters. Angeli et al. [77] have developed On-line fault detection and isolation techniques. These methods include numerical methods, artificial intelligence methods or combinations of the two methodologies. Maity et al. [78] have applied in this study the basic strategy is to train a neural network to recognize the behavior of the undamaged structure as well as of the structure with various possible damaged states. Hsu [79] has numerically formulated axial loading and excitation force using the differential quadrature method (DQM) of clamped-free and hinged–hinged Bernoulli–Euler beams. Loutridis et al. [80] have proposed a new method for crack detection in beams based on instantaneous frequency and empirical mode decomposition by applying empirical mode decomposition and

Hilbert transform and the instantaneous frequency of each oscillatory mode. Chang et al. [81] have presented a technique for structure damage detection based on spatial wavelet analysis. The innovation of the proposed paper is that both the positions and depths of multi-cracks can be estimated from spatial wavelet based method. Chen et al. [82] have presented an experimental investigation of the identification of crack location and size, by providing the first three natural frequencies through vibration measurements, curves of crack equivalent stiffness versus crack location are plotted. Fang et al. [83] have presented a method for the structural damage detection using frequency response functions (FRFs) as input data to the back-propagation neural network (BPNN). Taplak et al. [84] have presented a neural network predictor investigation for analyzing vibration parameters of a rotating system. Liu et al. [85] have presented a study compare the performance of crack detection using neural network (NN) and support vector machine (SVM) based on natural frequencies. The results show that the SVM is a powerful and effective method for crack identification. Li et al. [86] have proposed a damage detection method based on a continuous wavelet transform by using the flexural waves obtained from FEM or experiments. Sumant et al. [87] have proposed both theoretical and experimental method to detect the size and location of an edge-normal crack in a beam-like component by fixing discrete PZT patches at its top and bottom edges. Oberholster et al. [88] have presented a methodology for monitoring the on-line condition of axial-flow fan blades with the use of neural networks by utilizing on-line blade vibration signals measured on an experimental test structure. Yoon et al. [89] have investigated both analytically and experimentally influence of two open cracks on the dynamic behavior of a double cracked simply supported beam using the Hamilton's principle. Ramadas et al. [90] have discussed in this paper the detection, location and sizing of transverse cracks in a composite beam, by combining damage features of Lamb wave and vibration based techniques in artificial neural network (ANN) environment, using numerical finite element model. Saito et al. [91] have examined nonlinear vibration analysis of a rotating elastic structure with a crack. The approach employed in this study is a multi harmonic hybrid frequency/time-domain technique, which is an extension of the traditional harmonic balance method. Rosales et al. [92] have produced two approaches of crack detection by using the solution of the inverse problem with a power series technique (PST) and the use of artificial neural networks (ANNs). Khaji et al. [93] have developed an analytical approach for crack identification procedure in uniform beams with an open edge crack, based on bending vibration measurements and the proposed analytical method is also validated using numerical studies on cracked beam examples with different boundary conditions. Nagarajua et al. [94] have utilized a 3D wavelet (CWT) which clearly indicates both the time and frequency features of the crack. The inverse problem of crack identification has also been carried out using Artificial Neural Network (ANN). Zapicoa et al. [95] have used the Frequency Response Function to detect damages in metallic structures. The FRFs are used as input in an artificial intelligent system such as neural nets to detect damage. Das et al. [96] have presented the fault detection of a cracked cantilever beam using a hybrid artificial intelligence technique. The hybrid technique used here uses a fuzzy-neuro controller. The fuzzy-neuro controller has two parts. The first part is comprised of the fuzzy controller, and the second part is comprised of the neural controller. The results of the developed fuzzy-neuro controller and experimental method are in good agreement. Perennou et al. [97] have described an experimental method, using Michelson interferometry and Fourier transform, to determine phase variations on wave fronts after double passage through a wavy air-water interface. Wadhwani et al. [98] have provided a brief review of recent developments in the area of applications of ANN, Fuzzy Logic, and Wavelet Transform in fault diagnosis. Prime et al. [99] have presented experimental results from the vibration of a polycarbonate beam containing a crack that opens and closes during vibration. Several techniques were employed to detect and locate the crack making use of the nonlinearity. “Harmonic mode shapes” proved to be more sensitive to damage than conventional mode shapes. Quek et al. [100] have presented a local non-destructive evaluation technique for locating damage in a beam. Wavelet transform of dynamic response data, experimentally acquired using a piezoelectric sensor is used for this purpose. Gelman et al. [101] have employed a novel generic approach to fatigue crack diagnostics in machinery blades the approach consists of simultaneously using two new diagnostic features: the real and imaginary parts of the Fourier transform of vibro-acoustical signals generated from a blade. Kim et al. [102] have proposed the theory of wavelet analysis is presented including continuous and discrete wavelet transform followed by its application to structural health monitoring. Peng et al.[103] have presented a summary about the application of the wavelet in machine fault diagnostics, including the following main aspects: the time–

frequency analysis of signals, the fault feature extraction, the singularity detection for signals, the deionizing and extraction of the weak signals, the compression of vibration signals and the system identification. Douka et al. [104] have investigated both theoretically and experimentally the dynamic behavior of a cantilever beam with a breathing crack. Both simulated and experimental response data are analyzed by applying empirical mode decomposition and Hilbert transform. Taha et al. [105] have developed the wavelet transform (WT), a signal processing technique based on a windowing approach of dilated 'scaled' and shifted wavelets, is being applied to a broad range of engineering applications. Andreaus et al.[106] have presented the problem of a cantilever beam with an asymmetric edge crack subjected to a harmonic forcing at the tip is considered as a plane problem and is solved by using two-dimensional finite elements. Xiang et al. [107] have proposed a model-based crack identification method for estimating crack location and size, in shafts. The rotor system has been modeled using finite element method of B-spline wavelet on the interval (FEM BSWI), while the crack is considered through local stiffness change. Ackers et al. [108] have demonstrated a methodology for detecting cracks in a metal spindle, which is housed within a military vehicle wheel end assembly. A finite element model is used to estimate the undamped natural frequencies of the raw spindle. Additional mass and stiffness is then added to a simplified model of the spindle to simulate sources of variability within the assembly. Huang et al. [109] have developed a distributed two-dimensional (2D) Continuous Wavelet Transform (CWT) algorithm which can use data from discrete sets of nodes and provide spatially continuous variation in the structural response parameters to monitor structural degradation. Lonkar et al. [110] have proposed a method that uses finite element method to extract modal parameters of cracked and intact cantilever beam. Here the curvature response function, function of crack location and size, are approximated by means of polynomial surface fitting. The numerical data obtained is meshed using B-spline and Wavelet Transform and surface fitting technique is proposed for damage detection. Zhong et al. [111] have proposed a new approach using stationary wavelet transform (SWT). In this paper, the modal responses of damaged simply supported beams are computed using the finite element method in conjunction with some experimental tests.

Chapter 3

Analysis of Dynamic Characteristics of Beam with a Single Transverse Crack

Chapter 3

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.

3.1 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.

3.1.1 Theoretical Vibration Analysis

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 3.1.1, which gives coupling with the longitudinal and transverse motion.

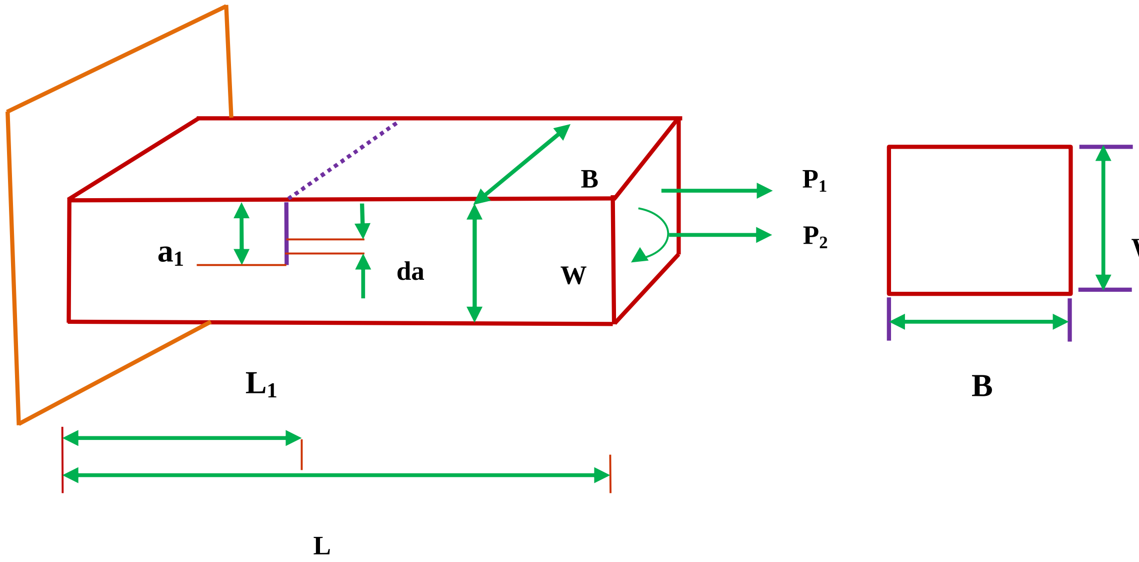

Figure 3.1.1 Geometry of the Cracked Cantilever Beam

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

$$J = \frac{1}{E'}(K_{11} + K_{12})^2 \text{ where } \frac{1}{E'} = \frac{1-\gamma^2}{E} \text{ (for plain strain condition)}$$

$$= \frac{1}{E} \quad \text{(for plain stress condition)} \qquad (3.1.1)$$

K_{11}, K_{12} are the stress intensity factors of mode I (opening of the crack) for load P_1 and P_2 respectively. The values of stress intensity factors from earlier studies as per Tada et al. are;

$$K_{11} = \frac{P_1}{BW}\sqrt{\pi a}\,(F_1(\frac{a}{W})) \qquad (3.1.2)$$

$$K_{12} = \frac{6P_2}{BW^2}\sqrt{\pi a}\,(F_2(\frac{a}{W})) \qquad (3.1.3)$$

Where expressions for F_1 and F_2 are as follows

$$F_1(\frac{a}{W}) = (\frac{2W}{\pi a}\tan(\frac{\pi a}{2W}))^{0.5}\left\{\frac{0.752 + 2.02(\frac{a}{W}) + 0.37(1-\sin(\frac{\pi a}{2W}))^3}{\cos(\frac{\pi a}{2W})}\right\} \qquad (3.1.4)$$

$$F_2\left(\frac{a}{W}\right) = \left(\frac{2W}{\pi a}\tan\left(\frac{\pi a}{2W}\right)\right)^{0.5}\left\{\frac{0.923 + 0.199\left(1-\sin\left(\frac{\pi a}{2W}\right)\right)^4}{\cos\left(\frac{\pi a}{2W}\right)}\right\} \quad (3.1.5)$$

Let Ut be the strain energy due to the crack. Then from Castiglione's theorem, the additional displacement along the force P_i is:

$$u_i = \frac{\partial U_t}{\partial P_i} \quad (3.1.6)$$

The strain energy will have the form $U_t = \int_0^{a_1} \frac{\partial U_t}{\partial P_i} da = \int_0^{a_1} J da$ (3.1.7)

Where, J is the strain energy density function.

From (3.1.6) and (3.1.7), we have

$$u_i = \frac{\partial}{\partial P_i}\left[\int_0^{a_1} J(a) da\right] \quad (3.1.8)$$

The flexibility influence co-efficient C_{ij} will be, by definition

$$C_{ij} = \frac{\partial u_i}{\partial P_j} = \frac{\partial^2}{\partial P_i \partial P_j}\int_0^{a_1} J(a) da \quad (3.1.9)$$

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

$$C_{ij} = \frac{\partial u_i}{\partial P_j} = \frac{\partial^2}{\partial P_i \partial P_j}\int_{-B/2}^{+B/2}\int_0^{a_1} J(a) da dz \quad (3.1.10)$$

Putting the value strain energy release rate in the above, equation (3.1.10) modifies as

$$C_{ij} = \frac{B}{E'}\frac{\partial^2}{\partial P_i \partial P_j}\int_0^{a_1} (K_{11} + K_{12})^2 da \quad (3.1.11)$$

Putting $\xi = \left(\frac{a}{W}\right), d\xi = \frac{da}{W}, da = W d\xi, a = 0, \xi = 0; a = a_1, \xi = \frac{a_1}{W} = \xi_1$

From above condition equation (3.1.11) converts to,

$$C_{ij} = \frac{BW}{E'}\frac{\partial^2}{\partial P_i \partial P_j}\int_0^{\xi_1}(K_{11}+K_{12})^2 d\xi \quad (3.1.12)$$

$$C_{11} = \frac{BW}{E'}\int_0^{\xi_1}\frac{\pi a}{B^2W^2}(F_1(\xi_1))^2 d\xi = \frac{2\pi}{E'}\int_0^{\xi_1}\xi(F_1(\xi))^2 d\xi \quad (3.1.13)$$

$$C_{12} = C_{21} = \frac{12\pi}{E'BW}\int_0^{\xi_1}\xi F_1(\xi)F_2(\xi)d\xi \quad (3.1.14)$$

$$C_{22} = \frac{72\pi}{E'BW}\int_0^{\xi_1}\xi F_1(\xi)F_2(\xi)d\xi \quad (3.1.15)$$

Converting the influence co-efficient into dimensionless form

$$\overline{C_{11}} = C_{11}\frac{E'B}{2\pi}, \overline{C_{12}} = C_{12}\frac{E'BW}{12\pi} = \overline{C_{21}}, \overline{C_{22}} = C_{22}\frac{E'BW^2}{72\pi} \quad (3.1.16)$$

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

$$K = \begin{bmatrix} K_{11} & K_{12} \\ K_{21} & K_{22} \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}^{-1} \quad (3.1.17)$$

Analysis of Vibration Characteristics of the Cracked Beam:

3.1.2 Beam Model

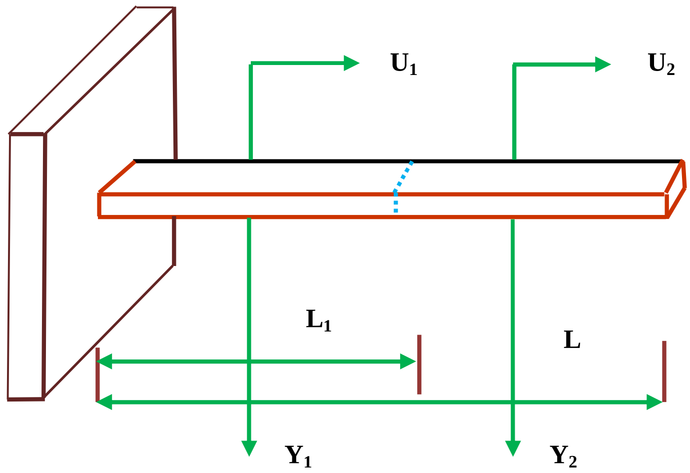

Figure 3.1.2 Amplitudes of Longitudinal and Bending vibration

A cantilever beam of length ‘L’ width ‘B’ and depth ‘W’, with a crack of depth ‘a_1’ at a distance ‘L_1’ from the fixed end is considered shown in Figure 3.1.1. 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 3.1.2.

From the governing equations of free vibration mode of the cracked beam

The normal function for the system can be defined as

$$\overline{U_1}(\overline{x}) = A_1 \cos(\overline{K_u}\,\overline{x}) + A_2 \sin(\overline{K_u}\,\overline{x}) \qquad (3.1.18)$$

$$\overline{U_2}(\overline{x}) = A_3 \cos(\overline{K_u}\,\overline{x}) + A_4 \sin(\overline{K_u}\,\overline{x}) \qquad (3.1.19)$$

$$\overline{Y_1}(\overline{x}) = A_5 \cosh(\overline{K_y}\,\overline{x}) + A_6 \sinh(\overline{K_y}\,\overline{x}) + A_7 \cos(\overline{K_y}\,\overline{x}) + A_8 \sin(\overline{K_y}\,\overline{x}) \qquad (3.1.20)$$

$$\overline{Y_2}(\overline{x}) = A_9 \cosh(\overline{K_y}\,\overline{x}) + A_{10} \sinh(\overline{K_y}\,\overline{x}) + A_{11} \cos(\overline{K_y}\,\overline{x}) + A_{12} \sin(\overline{K_y}\,\overline{x}) \qquad (3.1.21)$$

Where $\overline{x} = \frac{x}{L}, \overline{u} = \frac{u}{L}, \overline{y} = \frac{y}{L}, \beta = \frac{L_1}{L}$ (3.1.22)

$$\overline{K_u} = \frac{\omega L}{C_u}, C_u = (\frac{E}{\rho})^{1/2}, \overline{K_u} = (\frac{\omega L^2}{C_y})^{1/2}, C_y = (\frac{EI}{\mu})^{1/2}, \mu = A\rho \qquad (3.1.23)$$

A_i, (i=1, 12) Constants are to be determined, from boundary conditions. The boundary conditions of the cantilever beam in consideration are:

$$\overline{u_1}(0) = 0; \overline{Y_1}(0) = 0, \overline{Y_1}'(0) = 0; \overline{u_2}'(0) = (0); \overline{Y_2}''(1) = 0; \overline{Y_2}'''(1) = 0 \qquad (3.1.24)$$

At the cracked section:

$$\overline{u_1}(\beta) = \overline{u_2}(\beta); \overline{Y_1}(\beta) = \overline{Y_2}(\beta); \overline{Y_1}''(\beta) = \overline{Y_2}''(\beta); \overline{Y_1}'''(\beta) = \overline{Y_2}'''(\beta) \qquad (3.1.25)$$

Also at the cracked section, we have:

$$AE\frac{du_1(L_1)}{dx} = K_{11}(u_2(L_1) - u_1(L_1)) + K_{12}(\frac{dY_2(L_1)}{dx} - \frac{dY_1(L_1)}{dx}) \qquad (3.1.26)$$

Multiplying both sides of the above equation by $\frac{AE}{LK_{22}K_{21}}$ we get;

$$M_1M_2\overline{u}'(\beta) = M_2(\overline{u_2}(\beta) - \overline{u_1}(\beta)) + M_1(\overline{Y_2}'(\beta) - \overline{Y_1}'(\beta)) \qquad (3.1.27)$$

Similarly, $EI\frac{d^2Y_1(L_1)}{dx^2} = K_{21}(u_2(L_1) - u_1(L_1)) + K_{22}(\frac{dY_2(L_1)}{dx} - \frac{dY_1(L_1)}{dx})$ (3.1.28)

Multiplying both sides of the above equation by $\dfrac{EI}{LK_{22}K_{21}}$

$$M_3M_4\overline{Y_1}''(\beta) = M_3(\overline{u_2}(\beta) - \overline{u_1}(\beta)) + M_4(\overline{Y_2}'(\beta) - \overline{Y_1}'(\beta)) \qquad (3.1.29)$$

Where, $M_1 = \dfrac{AE}{LK_{11}}, M_2 = \dfrac{AE}{K_{12}}, M_3 = \dfrac{EI}{LK_{22}}, M_4 = \dfrac{EI}{L^2K_2}$ (3.1.30)

The normal functions, equation (3.1.11) along with the boundary conditions as mentioned above, yield the characteristic equation of the system as:

$$|Q| = 0 \qquad (3.1.31)$$

This determinant is a function of natural circular frequency (?), the relative location of the crack (ß) and the local stiffness matrix (K) which in turn is a function of the relative crack depth (a1/W).

Chapter 4

Analysis of Dynamic Characteristics of Beam using Finite Element Method

Chapter 4

ANALYSIS OF DYNAMIC CHARACTERISTICS OF BEAM USING FINITE ELEMENT METHOD

4.1 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.

4.2 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.

4.3 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.

4.3.1 Governing Equation of Free Vibration

The free bending vibration of an Euler-Bernoulli beam of a constant rectangular cross section is given by the following differential equation as given in:

$$EI\frac{d^4y}{dx^4} - m\omega_i^2 y = 0 \tag{4.3.1}$$

Where 'm' is the mass of the beam per unit length (kg/m), '? $_i$' is the natural frequency of the *i*th mode (rad/sec), E is the modulus of elasticity (N/m^2) and I the moment of inertia (m^4). By defining $\lambda^4 = \frac{m\omega_i^2}{EI}$ equation is rearranged as a fourth-order differential equation as follows:

$$\frac{d^4y}{dx^4} - \lambda^4 y = 0 \tag{4.3.2}$$

The general solution to equation is

$$y = A\cos\lambda_i x + B\sin\lambda_i x + C\cosh\lambda_i x + D\sinh\lambda_i x \tag{4.3.3}$$

Where A, B, C, D are constants and '?$_i$' is a frequency parameter. Adopting Hermitian shape functions, the stiffness matrix of the two-noded beam element without a crack is obtained using the standard integration based on the variation in flexural rigidity.

The element stiffness matrix of the uncracked beam is given as

$$\left[K^e\right] = \int \left[B(x)\right]^T EI \left[B(x)\right] dx \tag{4.3.4}$$

$$\left[B(x)\right] = \left\{H_1^{"}(x) H_2^{"}(x) H_3^{"}(x) H_4^{"}(x)\right\} \tag{4.3.5}$$

Where $H_1(x), H_2(x), H_3(x), H_4(x)$ is the Hermitian shape functions defined as follows

$$H_1(x) = 1 - \frac{3x^2}{l^2} + \frac{2x^3}{l^3} \tag{4.3.6}$$

$$H_2(x) = x - \frac{2x^2}{l} + \frac{x^3}{l^2} \tag{4.3.7}$$

$$H_3(x) = \frac{3x^2}{l^2} + \frac{2x^3}{l^3} \tag{4.3.8}$$

$$H_4(x) = -\frac{2x^2}{l} + \frac{2x^3}{l^2} \tag{4.3.9}$$

Assuming the beam rigidity EI is constant and is given by EI_0 within the element, and then the element stiffness is

$$\left[K^e\right] = \frac{EI_0}{l^3} \begin{bmatrix} 12 & 6l & -12 & 6l \\ 6l & 4l^2 & -6l & 2l^2 \\ -12 & -6l & 12 & -6l \\ 6l & 2l^2 & -6l & 4l^2 \end{bmatrix} \tag{4.3.10}$$

$$\left[K_c^e\right] = \left[K^e\right] - \left[K_c\right] \tag{4.3.11}$$

Here,

$\left[K_c^e\right]$=stiffness matrix of the cracked element

$\left[K_c\right]$=element stiffness matrix

$\left[K^e\right]$=reduction in stiffness matrix due to the crack

According to Peng et al. [10], the matrix is $\left[K_c\right]$

$$\left[K_c\right] = \begin{bmatrix} k_{11} & k_{12} & -k_{11} & k_{14} \\ k_{12} & k_{22} & -k_{12} & k_{24} \\ -k_{11} & -k_{12} & k_{11} & -k_{14} \\ k_{14} & k_{24} & -k_{14} & k_{44} \end{bmatrix} \tag{4.3.12}$$

Where,

$$k_{11}=\frac{12E(I_0-I_c)}{L^4}\left[\frac{2l_c^{\ 3}}{L^2}+3l_c(\frac{2L_1}{L^2}-1)^2\right] \tag{4.3.13}$$

$$k_{12}=\frac{12E(I_0-I_c)}{L^3}\left[\frac{l_c^{\ 3}}{L^2}+l_c(2-\frac{7L_1}{L}+\frac{6L_1^{\ 2}}{L^2})\right] \tag{4.3.14}$$

$$k_{14}=\frac{12E(I_0-I_c)}{L^3}\left[\frac{l_c^{\ 3}}{L^2}+l_c(2-\frac{5L_1}{L}+\frac{6L_1^{\ 2}}{L^2})\right] \tag{4.3.15}$$

$$k_{22}=\frac{12E(I_0-I_c)}{L^3}\left[\frac{3l_c^{\ 3}}{L^2}+2l_c(\frac{3L_1}{L}-2)^2\right] \tag{4.3.16}$$

$$k_{24}=\frac{12E(I_0-I_c)}{L^2}\left[\frac{3l_c^{\ 3}}{L^2}+2l_c(2-\frac{9L_1}{L}+\frac{9L_1^{\ 2}}{L^2})\right] \tag{4.3.17}$$

$$k_{44}=\frac{12E(I_0-I_c)}{L^2}\left[\frac{3l_c^{\ 3}}{L^2}+2l_c(\frac{3L_1}{L}-1)\right] \tag{4.3.18}$$

Here,

l_c=1.5W

L=total length of the beam

L_1=distance between the left node and crack

$I_0=\frac{BW^3}{12}$ =moment of inertia of the beam cross section

$I_c=\frac{B(W-a)^3}{12}$ = moment of inertia of the beam with crack

It is supposed that the crack does not affect the mass distribution of the beam. Therefore, the consistent mass matrix of the beam element can be formulated directly as

$$\left[M^e\right]=\int_0^1 \rho A\left[H(x)\right]^T\left[H(x)\right]dx \tag{4.3.19}$$

$$\left[M^e\right]=\frac{\rho AL}{420}\begin{bmatrix}156 & 22l & 54 & -13l\\ 22l & 4l^2 & 13l & -3l^2\\ 54 & 13l & 156 & -22l\\ -13l & -3l^2 & -22l & 4l^2\end{bmatrix} \tag{4.3.20}$$

The natural frequency then can be calculated from the relation.

$$\left[-\omega^2[M]+[K]\right]\{q\}=0 \qquad (4.3.21)$$

Where,

q=displacement vector of the beam

4.4 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.

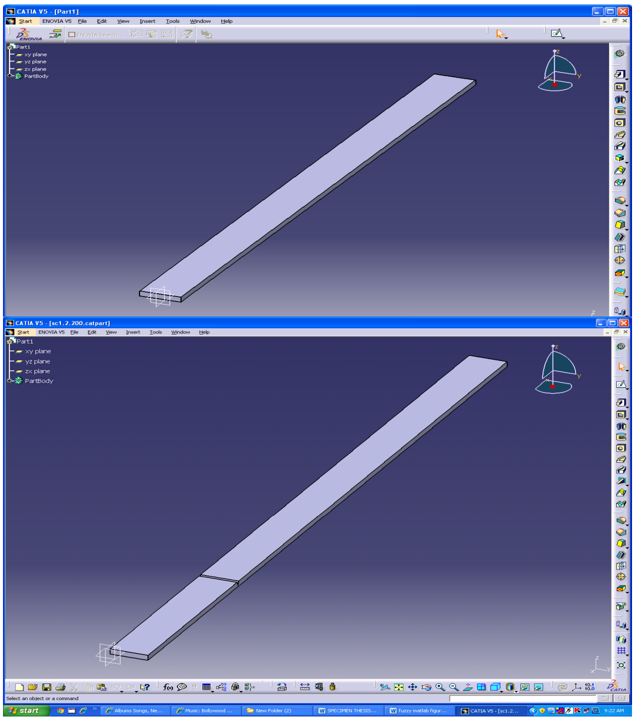

Figure 4.4.1 Model of the beam without crack and with crack

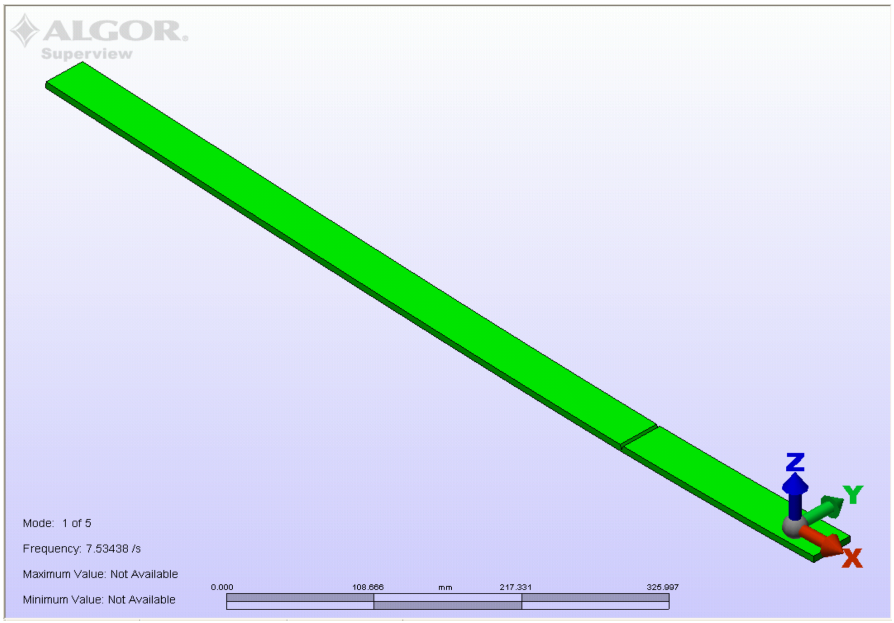

Figure 4.4.2 First Mode of Vibration of the Cracked Beam after Finite Element Analysis

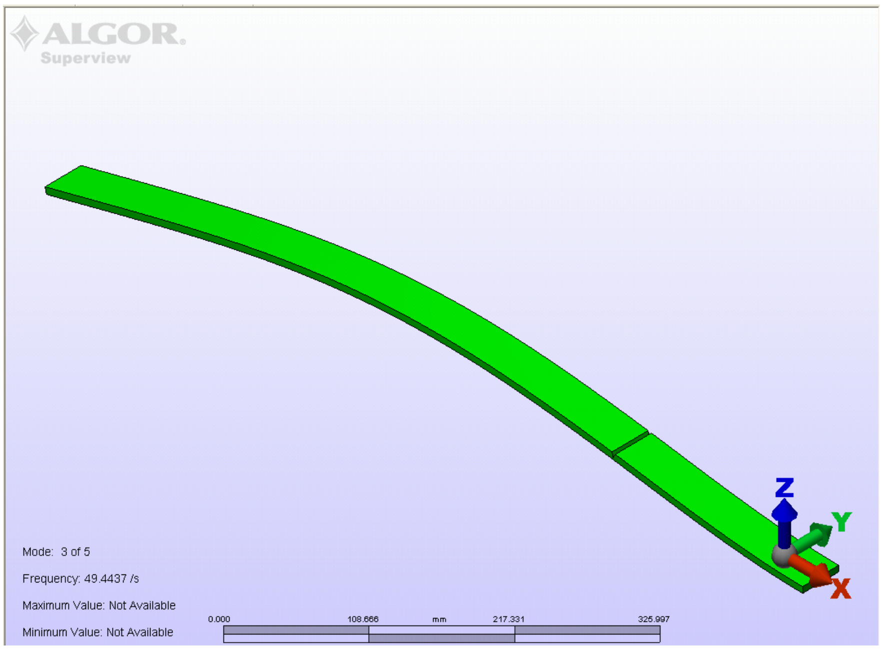

Figure 4.4.3 Second Mode of Vibration Cracked Beam after Finite Element Analysis

Chapter 5

Analysis of Fuzzy Logic Controller for Crack Detection

Chapter 5
ANALYSIS OF FUZZY LOGIC CONTROLLER FOR CRACK DETECTION

5.1 Introduction

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.

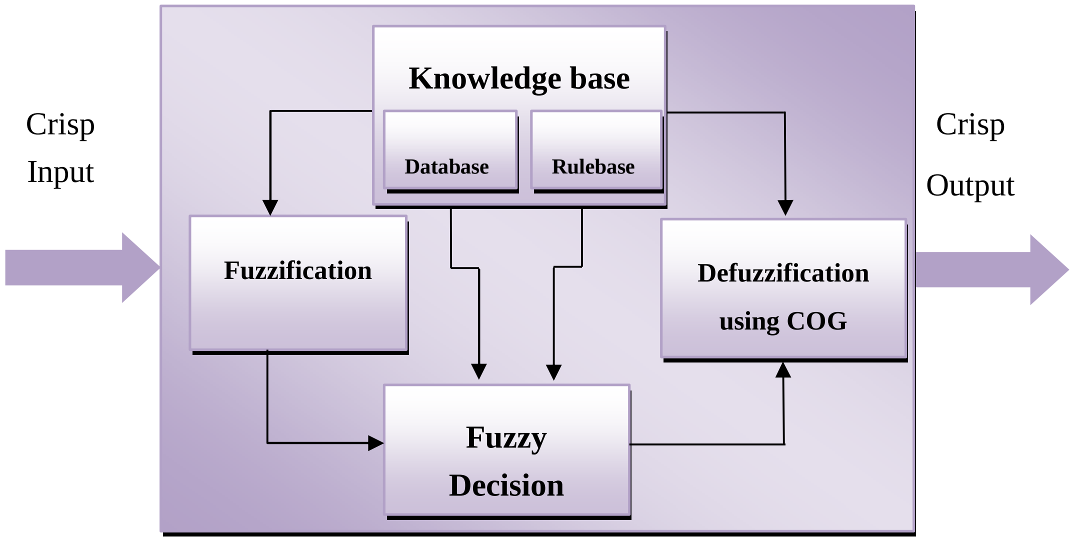

Figure 5.1.1 Flow Chart of Fuzzy Inference System

5.2 Analysis of Fuzzy Logic System for Crack Detection

Fuzzy logic is an extension of classical logic and uses fuzzy sets rather than classical sets. Zadeh says, “In its narrow sense, fuzzy logic is a logic approximate reasoning which may be viewed as a generalization and extension of multivalued logic”. As classical logic is based on classical set theory, fuzzy logic is based on fuzzy set theory. Different terms used in this system are provided below.

5.2.1 Fuzzy Set

A fuzzy set is a set that is defined by a membership function. A membership function assigns to each element in the set under consideration (the universal space) a membership grade, which is a value in the interval [0, 1]. In classical sets, objects either belong to a set or do not belong to a set; there is no other choice. By defining a set using a membership function, it is possible for an element to belong partially to a set.

5.2.2 Membership Function

The membership function $\mu_A(x)$ describes the membership of the elements x of the base set X in the fuzzy set A, whereby for $\mu_A(x)$ a large class of functions can be taken. Reasonable functions are often piecewise linear functions, such as triangular or trapezoidal functions. The grade of membership $\mu_A(x_0)$ of a membership function $\mu_A(x)$ describes for the special element $x = x_0$, to which grade it belongs to the fuzzy set A. This value is in the unit interval [0,1]. Of course, x_0 can simultaneously belong to another fuzzy set B, such that $\mu_B(x_0)$ characterizes the grade of membership of x_0 to B.There are different types of membership functions. Most commonly used membership functions are Triangular, Trapezoidal and Gaussian membership functions.

5.2.3 Fuzzy Operations

Now that we have an idea of what fuzzy sets are, we can introduce basic operations on fuzzy sets. Similar to the operations on crisp sets we also can intersect, unify and negate fuzzy sets. In his very first paper about fuzzy sets, L. A. Zadeh suggested the minimum operator for the intersection and the maximum operator for the union of two fuzzy sets. It is easy to see that these operators coincide with the crisp unification and intersection if we only consider the membership degrees 0 and 1.

5.2.4 Fuzzy Linguistic Variables

Linguistic variables are used every day to express what is important and its context. Linguistic variables are central to fuzzy logic manipulations and represent crisp information in a form and precision appropriate for the problem. The linguistic variables like “warm”, so common in everyday speech, convey information about our environment or an object under observation. Fuzzy set theory defines fuzzy operators on fuzzy sets. The problem in applying this is that the appropriate fuzzy operator may not be known. For this reason, fuzzy logic usually uses *If-Then* rules. Rules are usually expressed in the form;
if *variable* is *property* then *action*.

5.3 Steps used in Mamdani FIS

1. Determining a set of fuzzy rules
2. Fuzzifying the inputs using the input Membership Functions
3. Combining the fuzzified inputs according to the fuzzy rules to establish a rule strength
4. Finding the consequence of the rule by combining the rule strength and the output Membership Functions
5. Combining the consequences to get an output distribution
6. Defuzzifying the output distribution (this step is needed only if a crisp output is needed)

The following figure describes a two input, two rule Mamdani FIS.

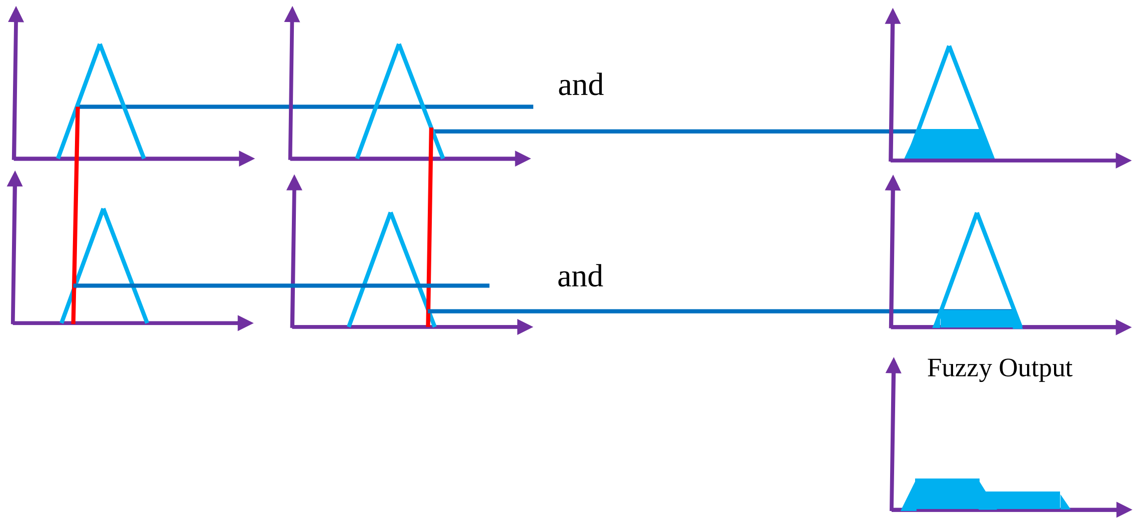

Figure 5.3.1 Two input, two rule Mamdani FIS

5.4 Fuzzy Mechanism used for Crack Detection

The fuzzy controller has been developed where there are 3 inputs and 2 outputs parameter. The natural linguistic representations for the input are as follows

Relative first natural frequency = "fnf"

Relative second natural frequency = "snf"

Relative third natural frequency = "tnf"

The natural linguistic term used for the outputs are

Relative crack depth = "rcd"

Relative crack length= "rcl"

Based on the fuzzy subset the fuzzy rules are defined in a general form as follows:

If (fnf is fnf_i and snf is snf_j and tnf is tnf_k) then (cd is cd_{ijk} and cl is cl_{ijk}) (5.4.1)

Where i= 1to 9, j=1 to 9, k=1 to 9

Because of "fnf", "snf", "tnf" have 9 membership functions each.

From the above expression (5.4.1), two set of rules can be written

$$\left.\begin{array}{l}\text{If (fnf is } fnf_i \text{ and snf is } snf_j \text{ and tnf is } tnf_k\text{) then cd is } cd_{ijk}\\ \text{If (fnf is } fnf_i \text{ and snf is } snf_j \text{ and tnf is } tnf_k\text{) then cl is } cl_{ijk}\end{array}\right\} \quad (5.4.2)$$

According to the usual Fuzzy logic control method (Parhi, 2005), a factor W_{ijk} is defined for the rules as follows:

$$w_{ijk} = \mu_{fnf_i}(freq_i) \wedge \mu_{snf_j}(freq_j) \wedge \mu_{tnf_k}(freq_k)$$

Where $freq_i$, $freq_j$ and $freq_k$ are the first, second and third natural frequency of the cantilever beam with crack respectively ; by Appling composition rule of interference (Parhi, 2005) the membership values of the relative crack location and relative crack depth (location) is given as

$$\left.\begin{array}{ll}\mu_{rcl_{ijk}}(location) = w_{ijk} \wedge \mu_{rcl_{ijk}}(location) & \forall_{length} \in rcl\\ \mu_{rcd_{ijk}}(depth) = w_{ijk} \wedge \mu_{rcd_{ijk}}(depth) & \forall_{depth} \in rcd\end{array}\right\} \quad (5.4.3)$$

The overall conclusion by combining the output of all the fuzzy can be written as follows:

$$\left.\begin{aligned}\mu_{rcl}(\text{location}) &= \mu_{rcl_{111}}(\text{location}) \vee .... \vee \mu_{rcl_{ijk}}(\text{location}) \vee .... \vee \mu_{rcl_{191919}}(\text{location})\\ \mu_{rcd}(\text{depth}) &= \mu_{rcd_{111}}(\text{depth}) \vee .... \vee \mu_{rcd_{ijk}}(\text{depth}) \vee .... \vee \mu_{rcd_{191919}}(\text{depth})\end{aligned}\right\} \quad (5.4.4)$$

The crisp values of relative crack location and relative crack depth are computed using the center of gravity method (Parhi, 2005) as:

$$\left.\begin{aligned}\text{Relative crack location} = rcl &= \frac{\int \text{location}.\mu_{rcl}(\text{location}).d(\text{location})}{\int \mu_{rcl}(\text{location}).d(\text{location})}\\ \text{Relative crack depth} = rcd &= \frac{\int \text{depth}.\mu_{rcd}(\text{depth}).d(\text{depth})}{\int \mu_{rcd}(\text{depth}).d(\text{depth})}\end{aligned}\right\} \quad (5.4.5)$$

5.5 Results and Discussions of Fuzzy Controller using Mamdani FIS

In this chapter a cantilever beam with a single crack has been taken into consideration. The change in local flexibility due to the presence of the crack is used to calculate the change in the natural frequencies of the cantilever beam. Here eight sets of data are utilized for training in the fuzzy controller and to predict the results from the fuzzy controller. A Fuzzy Controller has been designed using four types of membership functions i.e. Triangular (Figure 5.5.1), Gaussian (Figure 5.5.2), Trapezoidal (Figure 5.5.3) and Hybridized (Figure 5.5.4) membership functions. Figure 5.5.6, Figure 5.5.7, Figure 5.5.8, and Figure 5.5.9 describes the results of the fuzzy controller using different membership functions after the activation of rule 5 and 15 of the rule Table 5.5.2. Various linguistic terms used for different membership functions and for their ranges are given in the Table 5.5.1. Figure 5.5.10 shows the rule viewer of hybridized Mamdani FIS.

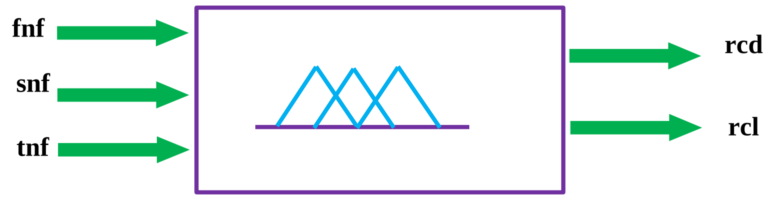

Figure 5.5.1(a) Fuzzy Controller using Triangular Membership Functions

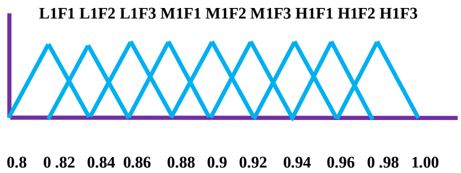

Figure 5.5.1(b) Triangular Membership Functions for First Natural Frequency

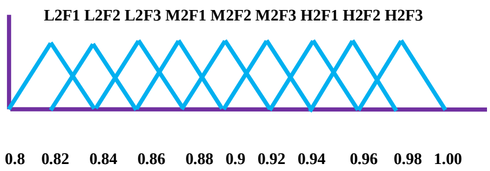

Figure 5.5.1(c) Triangular Membership Functions for Second Natural Frequency

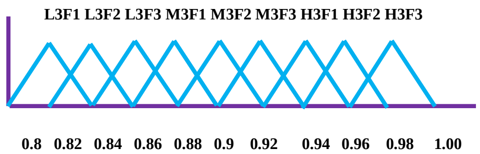

Figure 5.5.1(d) Triangular Membership Functions for Third Natural Frequency

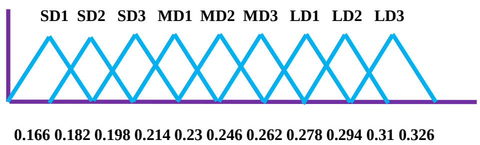

Figure 5.5.1(e) Triangular Membership Functions for Relative Crack Depth

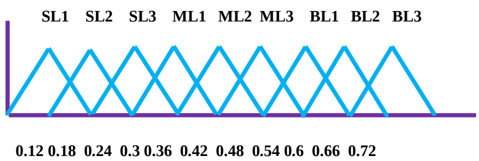

Figure 5.5.1(f) Triangular Membership Functions for Relative Crack Location

Figure 5.5.1 Fuzzy Controller using Triangular Membership function

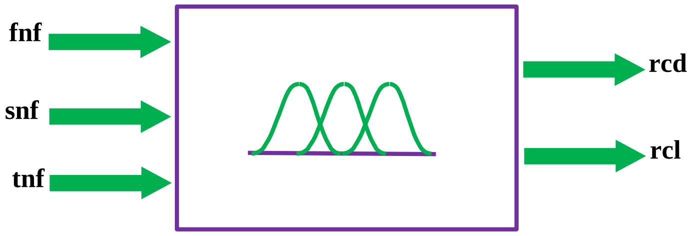

Figure 5.5.2(a) Fuzzy Controller using Gaussian Membership Functions

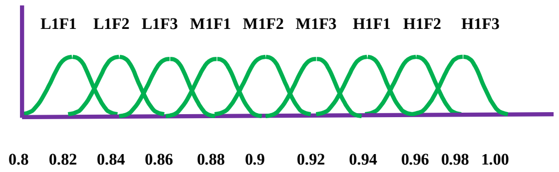

Figure 5.5.2(b) Gaussian Membership Functions for first Natural Frequency

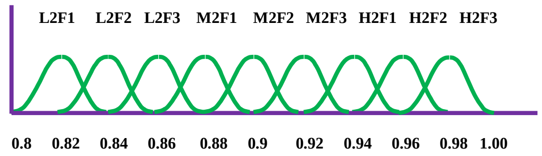

Figure 5.5.2(c) Gaussian Membership Functions for Second Natural Frequency

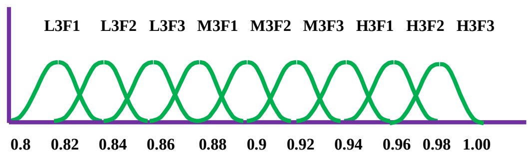

Figure 5.5.2(d) Gaussian Membership Functions for Third Natural Frequency

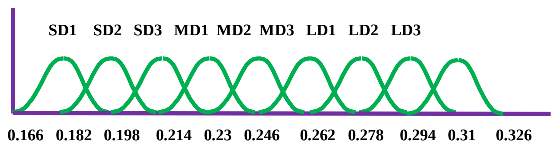

Figure 5.5.2(e) Gaussian Membership Functions for Relative Crack Depth

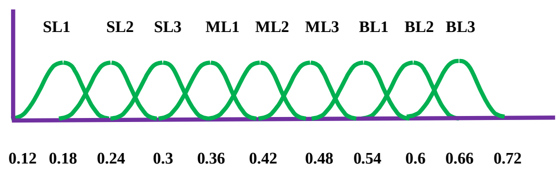

Figure 5.5.2(f) Gaussian Membership Functions for Relative Crack Location

Figure 5.5.2 Fuzzy Controller using Gaussian Membership function

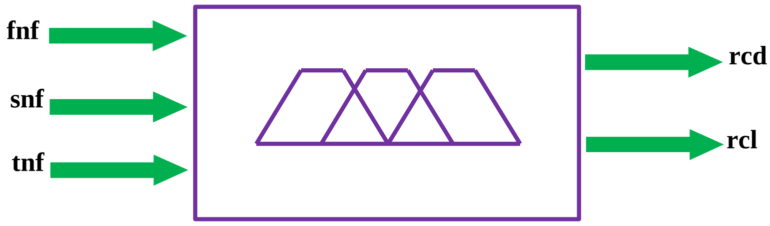

Figure 5.5.3(a) Fuzzy Controller using Trapezoidal Membership Functions

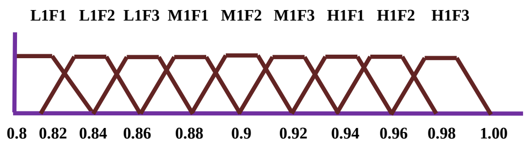

Figure 5.5.3(b) Trapezoidal Membership Functions for First Natural Frequency

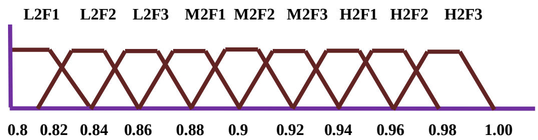

Figure 5.5.3(c) Trapezoidal Membership Functions for Second Natural Frequency

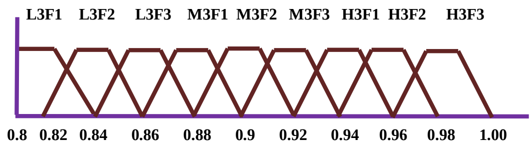

Figure 5.5.3(d) Trapezoidal Membership Functions for Third Natural Frequency

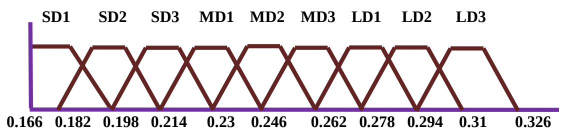

Figure 5.5.3(e) Trapezoidal Membership Functions for Relative Crack Depth

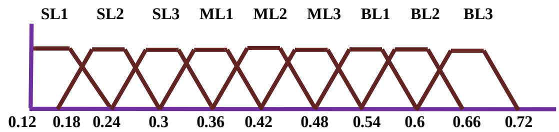

Figure 5.5.3(f) Trapezoidal Membership Functions for Relative Crack Location

Figure 5.5.3 Fuzzy Controller using Trapezoidal Membership function

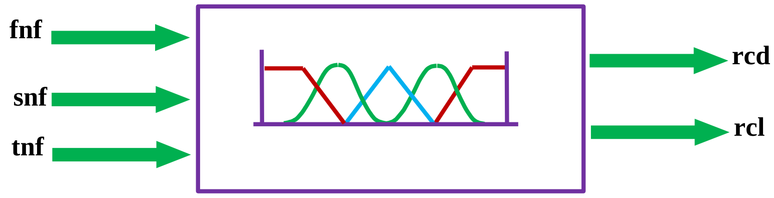

Figure 5.5.4(a) Fuzzy Controller using Hybridized Membership Functions

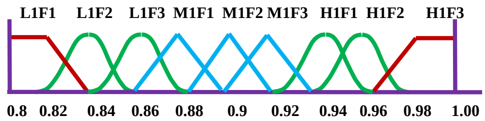

Figure 5.5.4(b) Hybridized Membership Functions for first Natural Frequency

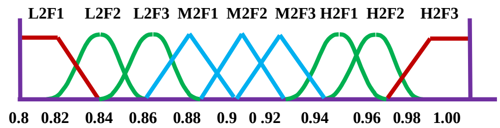

Figure 5.4.4(c) Hybridized Membership Functions for Second Natural Frequency

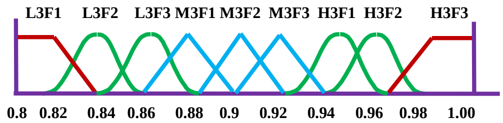

Figure 5.5.4(d) Hybridized Membership Functions for Third Natural Frequency

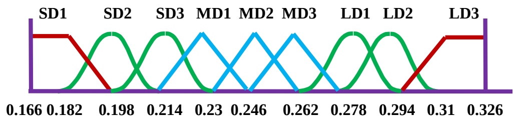

Figure 5.5.4(e) Hybridized Membership Functions for Relative Crack Depth

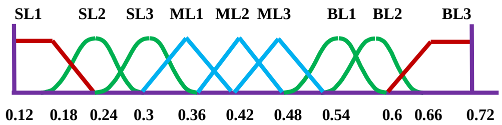

Figure 5.5.4(f) Hybridized Membership Functions for Relative Crack Location

Figure 5.5.4 Fuzzy Controller using Hybridized Membership function

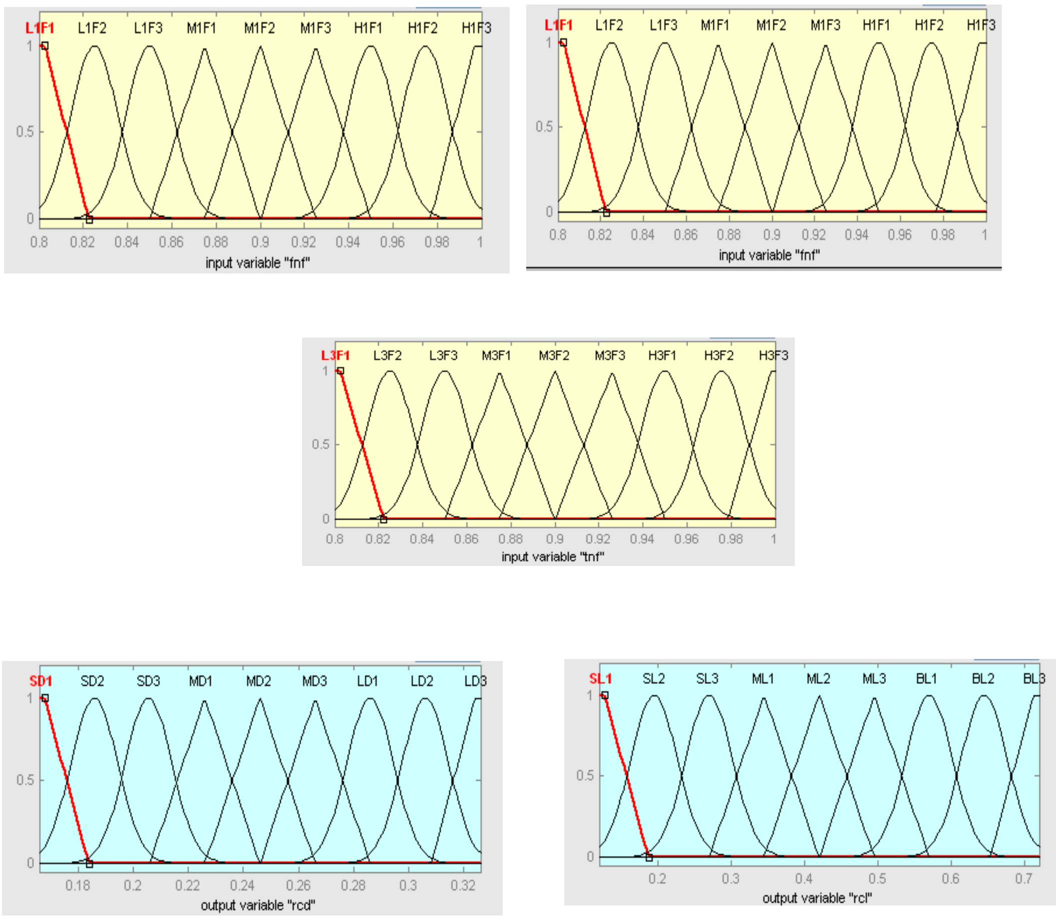

Figure 5.5.5 Input and output variables in a hybridized Mamdani FIS using MATLAB toolbox

Table .5.5.1Linguistic terms used for membership functions

Name of the Membership function	*Linguistic terms*	*Description and range of the linguistic terms*
L1F1,L1F2,L1F3	fnf_{1to3}	Low ranges of relative natural frequency for first mode of vibration in ascending order respectively.
M1F1,M1F2,M1F3	fnf_{4to6}	Medium ranges of relative natural frequency for first mode of vibration in ascending order respectively.

H1F1,H1F2,H1F3	$fnf_{7\ to\ 9}$	Higher ranges of relative natural frequency for first mode of vibration in ascending order respectively
L2F1,L2F2,L2F3	snf_{1to3}	Low ranges of relative natural frequency for second mode of vibration in ascending order respectively.
M2F1,M2F2,M2F3	$snf_{4\ to\ 6}$	Medium ranges of relative natural frequency for second mode of vibration in ascending order respectively.
H2F1,H2F2,H2F3	snf_{7to9}	Higher ranges of relative natural frequency for first mode of vibration in ascending order respectively
L3F1,L3F2,L3F3	tnf_{1to3}	Low ranges of relative natural frequency for second mode of vibration in ascending order respectively.
M3F1,M3F2,M3F3	$tnf_{4\ to\ 6}$	Medium ranges of relative natural frequency for second mode of vibration in ascending order respectively.
H3F1,H3F2,H3F3	tnf_{7to9}	Higher ranges of relative natural frequency for first mode of vibration in ascending order respectively.
SD1,SD2,SD3	rcd_{1to3}	Small ranges of relative crack depth in ascending order respectively.
MD1,MD2,MD3	rcd_{4to6}	Medium ranges of relative crack depth in ascending order respectively.
LD1,LD2,LD3	rcd_{7to9}	Larger ranges of relative crack depth in ascending order respectively.
SL1,SL2,SL3	rcl_{1to3}	Small ranges of relative crack location in ascending order respectively.
ML1,ML2,ML3	rcl_{4to6}	Medium ranges of relative crack location in

		ascending order respectively.
BL1,BL2,BL3	rcl_{7to9}	Bigger ranges of relative crack location in ascending order.

Table.5.5.2 Rules for the Fuzzy Controllers

Sl.no	*Some Examples of Fuzzy rule used in the Fuzzy Controller*
1	If fnf is L1F1, snf is L2F1, tnf is L3F1 then rcd is LD3 and rcl is SL1
2	If fnf is L1F1, snf is L2F1, tnf is L3F2 then rcd is LD3 and rcl is SL2
3	If fnf is L1F1, snf is L2F2, tnf is L3F3 then rcd is LD3 and rcl is SL3
4	If fnf is L1F1, snf is M2F1, tnf is M3F1 then rcd is LD3 and rcl is ML1
5	If fnf is L1F1, snf is M2F2, tnf is M3F2 then rcd is LD3 and rcl is ML2
6	If fnf is L1F1, snf is M2F3, tnf is M3F3 then rcd is LD3 and rcl is ML3
7	If fnf is L1F1, snf is H2F1, tnf is H3F2 then rcd is LD3 and rcl is BL1
8	If fnf is L1F1, snf is H2F2, tnf is H3F3 then rcd is LD3 and rcl is BL2
9	If fnf is L1F1, snf is H2F3, tnf is H3F3 then rcd is LD3 and rcl is BL3
10	If fnf is L1F2, snf is L2F1, tnf is L3F1 then rcd is LD2 and rcl is SL1
11	If fnf is L1F2, snf is L2F1, tnf is L3F2 then rcd is LD2 and rcl is SL2
12	If fnf is L1F2, snf is L2F2, tnf is L3F3 then rcd is LD2 and rcl is SL3
13	If fnf is L1F2, snf is M2F1, tnf is M3F1 then rcd is LD2 and rcl is ML1
14	If fnf is L1F2, snf is M2F2, tnf is M3F2 then rcd is LD2 and rcl is ML2
15	If fnf is L1F2, snf is M2F3, tnf is M3F3 then rcd is LD2 and rcl is ML3
16	If fnf is L1F2, snf is H2F1, tnf is H3F2 then rcd is LD2 and rcl is BL1
17	If fnf is L1F2, snf is H2F2, tnf is H3F3 then rcd is LD2 and rcl is BL2
18	If fnf is L1F2, snf is H2F3, tnf is H3F3 then rcd is LD2 and rcl is BL3
19	If fnf is L1F3, snf is L2F1, tnf is L3F1 then rcd is LD1 and rcl is SL1
20	If fnf is L1F3, snf is L2F1, tnf is L3F2 then rcd is LD1 and rcl is SL2

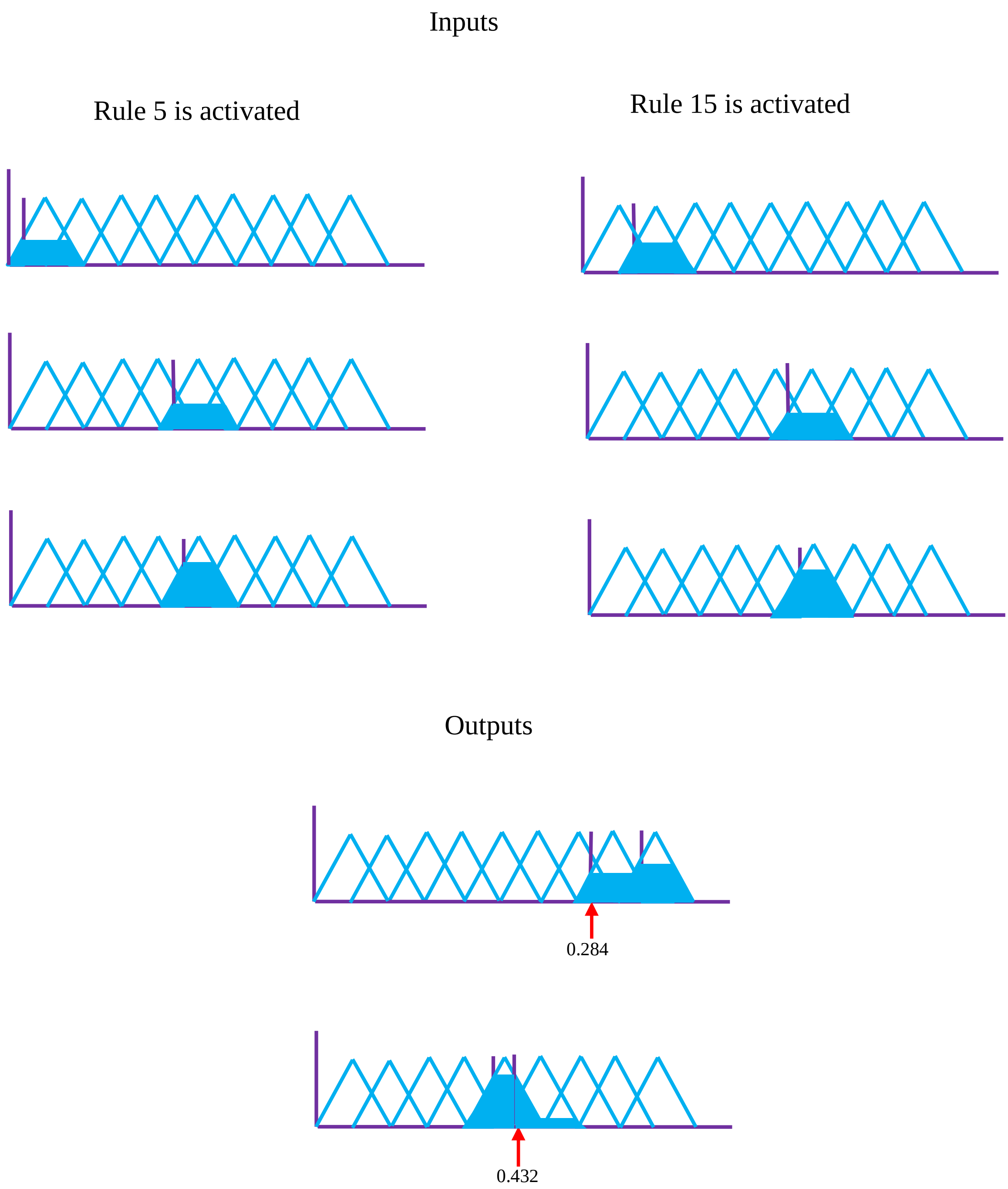

Figure .5.5.6 Resultant values of ‘rcd’ and ‘rcl’ when rules 5 and 15 of Rule table 5.5.2 is activated using Triangular membership function

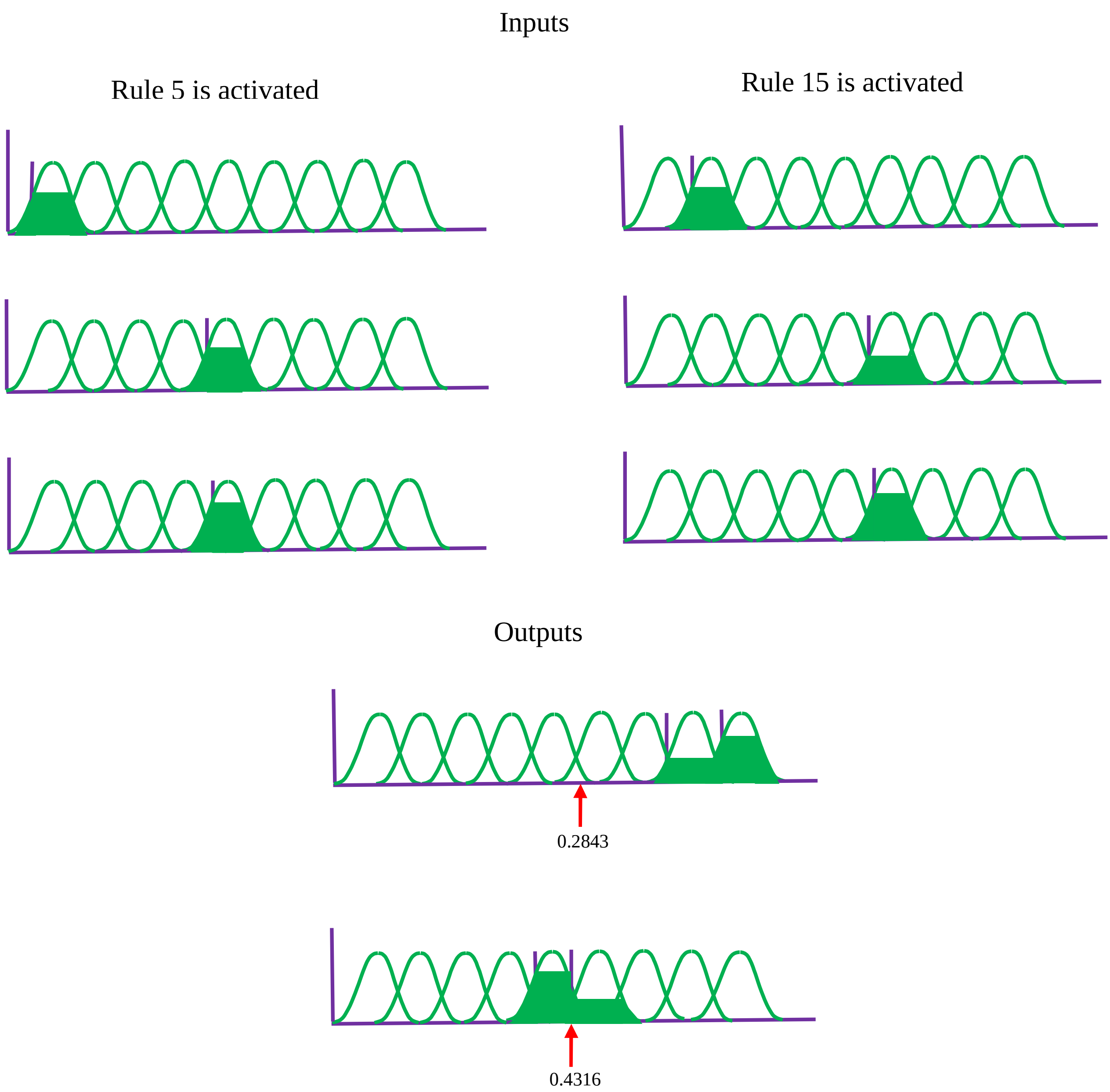

Figure .5.5.7 Resultant values of ‘rcd’ and ‘rcl’ when rules 5 and 15 of Rule table 2 is activated using Gaussian membership function

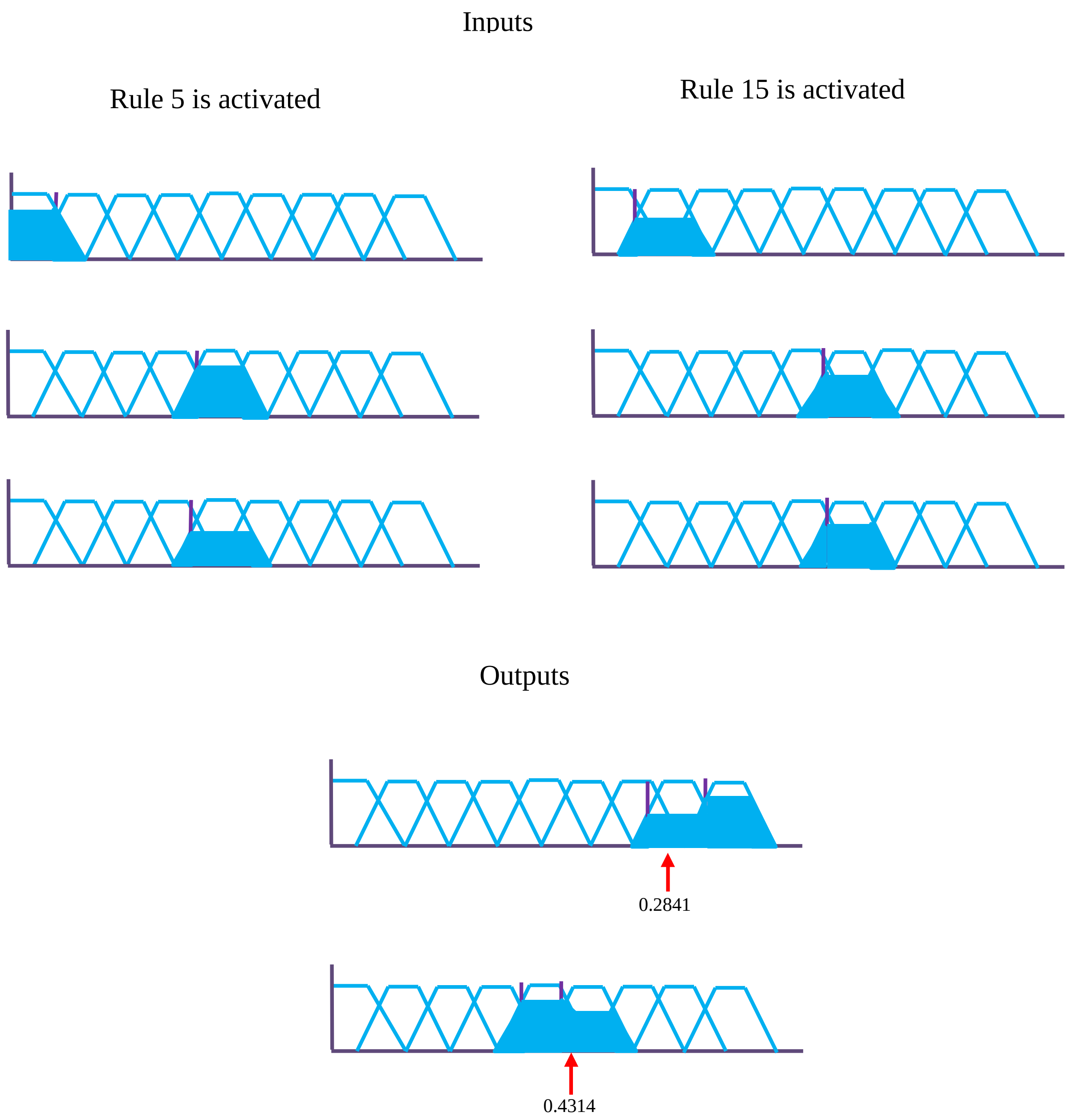

Figure .5.5.8 Resultant values of ‘rcd’ and ‘rcl’ when rules 5 and 15 of Rule table 2 is activated using Trapezoidal membership function

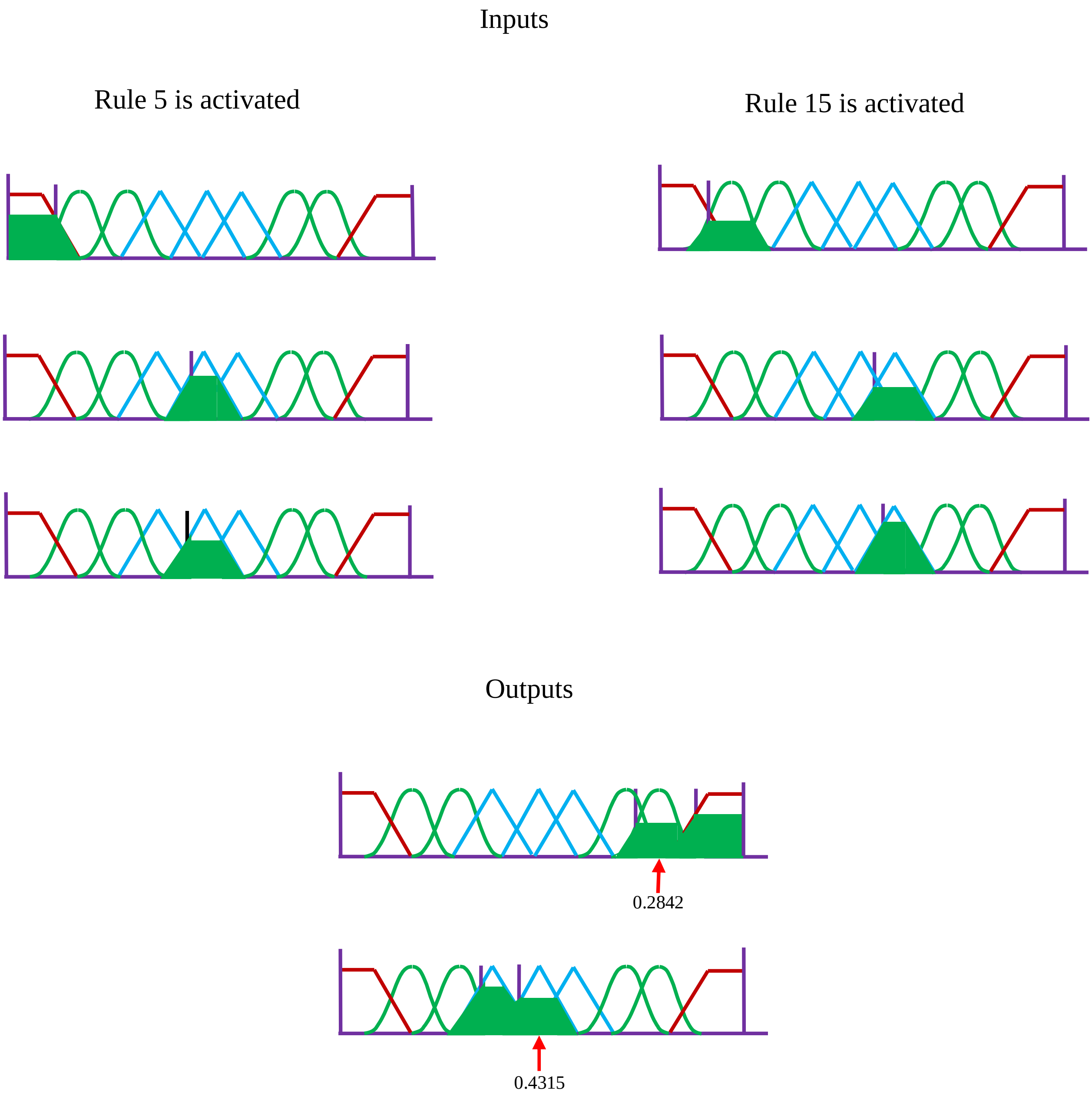

Figure .5.5.9 Resultant values of 'rcd' and 'rcl' when rules 5 and 15 of Rule table 2 is activated using Hybridized membership function

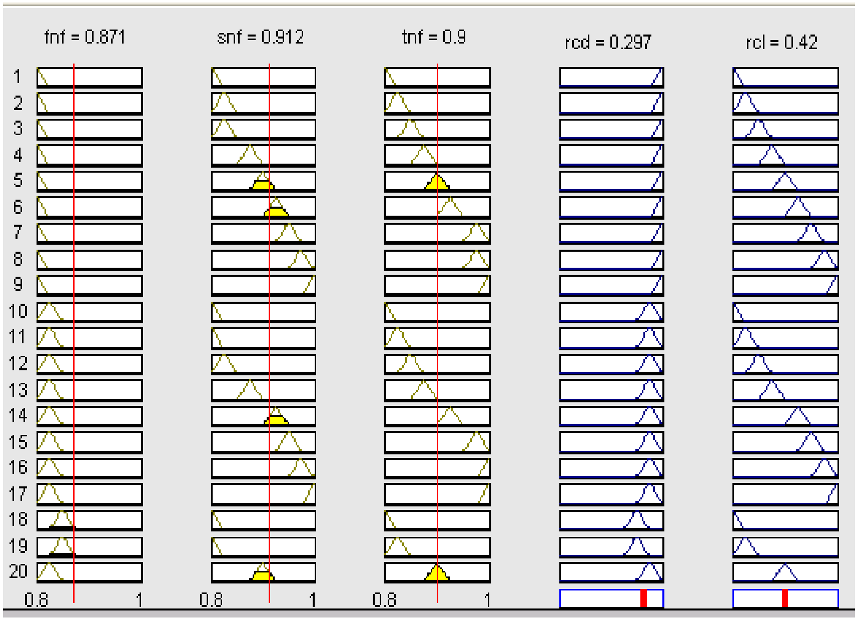

Figure 5.5.10 Rule viewer for hybridized Mamdani FIS

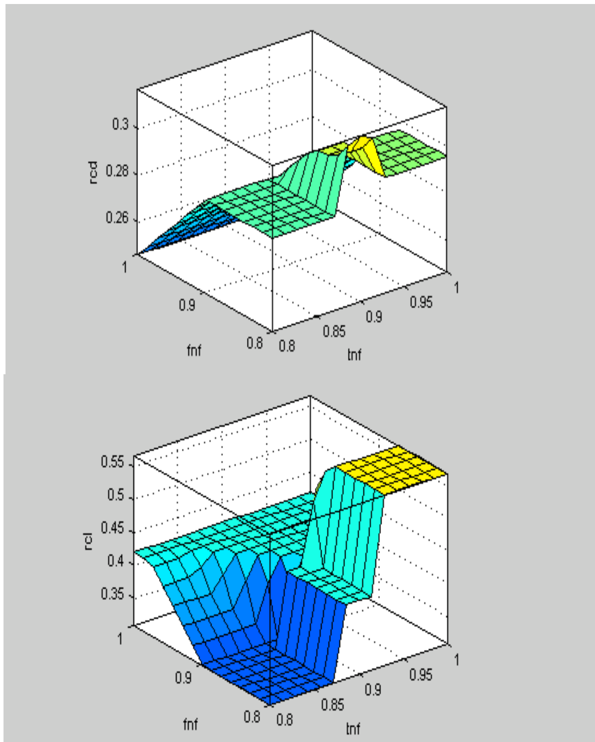

Figure 5.5.11 Surface viewer for hybridized Mamdani FIS

Table 5.5.3 Comparison of the results of Fuzzy Controller using Triangular Membership Function and Gaussian Membership Function

Sl. No	*Relative fnf*	*Relative snf*	*Relative tnf*	*Relative crack depth*	*Relative crack location*	*rcd using triangular MSF*	*rcl using triangular MSF*	*rcd using gaussian MSF*	*rcl using gaussian MSF*
1	0.8141	0.8140	0.8136	0.3167	0.125	0.3160	0.1243	0.3164	0.1245
2	0.8635	0.8634	0.8626	0.3	0.1875	0.2991	0.1865	0.2995	0.1870
3	0.9012	0.9011	0.9005	0.2833	0.25	0.2826	0.2491	0.2830	0.2494
4	0.9314	0.9312	0.9272	0.2667	0.3125	0.2660	0.3117	0.2664	0.3121
5	0.9544	0.9543	0.9308	0.25	0.375	0.2491	0.3741	0.2494	0.3745
6	0.9692	0.9690	0.9685	0.2333	0.4375	0.2324	0.4365	0.2329	0.4373
7	0.9839	0.9836	0.9832	0.2167	0.5	0.2158	0.4992	0.2163	0.4995
8	0.9907	0.9894	0.9900	0.2	0.5625	0.1991	0.5616	0.1994	0.5621

Table 5.5.4 Comparison of the results of Fuzzy Controller using Trapezoidal Membership Function and Hybridized Membership Function

Sl No	*Relative fnf*	*Relative snf*	*Relative tnf*	*Relative crack depth*	*Relative crack location*	*rcd using trapezoidal MSF*	*rcl using trapezoidal MSF*	*rcd using hybridized MSF*	*rcl using hybridized MSF*
1	0.8141	0.8140	0.8136	0.3167	0.125	0.3162	0.1244	0.3162	0.1245
2	0.8635	0.8634	0.8626	0.3	0.1875	0.2992	0.1866	0.2994	0.1868
3	0.9012	0.9011	0.9005	0.2833	0.25	0.2829	0.2493	0.2828	0.2493
4	0.9314	0.9312	0.9272	0.2667	0.3125	0.2663	0.31121	0.2661	0.3119
5	0.9544	0.9543	0.9308	0.25	0.375	0.2492	0.3744	0.2493	0.3744
6	0.9692	0.9690	0.9685	0.2333	0.4375	0.2325	0.4369	0.2326	0.4369
7	0.9839	0.9836	0.9832	0.2167	0.5	0.2159	0.4991	0.2161	0.4994
8	0.9907	0.9894	0.9900	0.2	0.5625	0.1991	0.5618	0.1993	0.5619

Table 5.5.5 Comparison of the results of Fuzzy Controller using Gaussian Membership Function and Hybridized Membership Function

Sl. No	*Relative fnf*	*Relative snf*	*Relative tnf*	*Relative crack depth*	*Relative crack location*	*rcd using gaussian MSF*	*rcl using gaussian MSF*	*rcd using hybridized MSF*	*rcl using hybridized MSF*
1	0.8141	0.8140	0.8136	0.3167	0.125	0.3164	0.1245	0.3162	0.1245
2	0.8635	0.8634	0.8626	0.3	0.1875	0.2995	0.1870	0.2994	0.1868
3	0.9012	0.9011	0.9005	0.2833	0.25	0.2830	0.2494	0.2828	0.2493
4	0.9314	0.9312	0.9272	0.2667	0.3125	0.2664	0.3121	0.2661	0.3119
5	0.9544	0.9543	0.9308	0.25	0.375	0.2494	0.3745	0.2493	0.3744
6	0.9692	0.9690	0.9685	0.2333	0.4375	0.2329	0.4373	0.2326	0.4369
7	0.9839	0.9836	0.9832	0.2167	0.5	0.2163	0.4995	0.2161	0.4994
8	0.9907	0.9894	0.9900	0.2	0.5625	0.1994	0.5621	0.1993	0.5619

5.6 Takagi-Sugeno Fuzzy Model

The Sugeno fuzzy model (also known as the TSK fuzzy model) was proposed by Takagi, Sugeno, and Kang [40, 41] in an effort to develop a systematic approach to generate fuzzy rules from a given input-output data set. A typical fuzzy rule in a Sugeno fuzzy model has the form

If x_1 *is* X_1 *and* x_2 *is* X_2 *then* $y = f(x_1, x_2)$, (5.6.1)

Where $X_1$and X_2 are fuzzy sets in the antecedent, while $y = f(x_1, x_2)$ is a crisp function in the consequent. Usually $f(x_1, x_2)$ is a polynomial in the input variables x_1 and x_2, but it can be any function as long as it can appropriately describe the output of the model within the fuzzy region specified by the antecedent of the rule. When $f(x_1, x_2)$ is a first-order polynomial, the resulting fuzzy inference system is called a first-order Sugeno fuzzy model. When ‘f’ is a constant, we then have a zero-order Sugeno fuzzy model, which can be viewed either as a special case of the Mamdani fuzzy inference system, in which each rule's consequent is specified by a fuzzy singleton (or a pre-defuzzified consequent).

Figure5.6.1 shows the fuzzy reasoning procedure for a first-order Sugeno fuzzy model. Since each rule has a crisp output, the overall output is obtained via weighted average, thus avoiding the time-consuming process of defuzzification required in a Mamdani model. In practice, the weighted average operator is sometimes replaced with the weighted sum (that is, $y = w_1x_1 + w_2x_2 + ...$ operator to reduce computation further, especially in the training of a fuzzy inference system. Since the only fuzzy part of a Sugeno model is in its antecedent, it is easy to demonstrate the distinction between a set of fuzzy rules and non fuzzy ones.

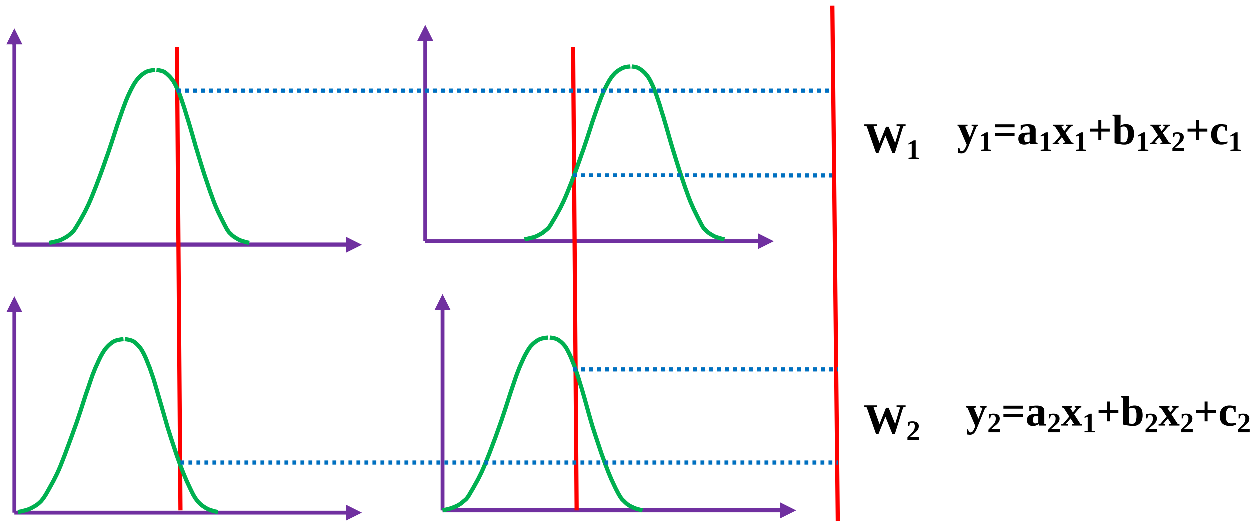

Figure 5.6.1 Takagi-Sugeno Fuzzy inference System

5.7 Steps for Diagnosing Crack using Takagi-Sugeno FIS

General structure of FIS contains a fuzzification process of input variables by membership functions μ, the design of the base of if-then rules or automatic if-then rules extraction from input data, operators (AND,OR,NOT) application in if-then rules, implication and aggregation within these rules, and the process of defuzzification of gained values to crisp values.

In the process of defuzzification, standardization of inputs and their transformation to the domain of the values of membership functions μ takes place. There is no general method for designing shape, number and parameters of input and output membership functions μ.

The input to fuzzification process is a crisp value given by the universum (Reference Set). The output of fuzzification process is the membership function μ value. The design of the base of if-then rules can be realized by extraction of if-then rules from historical data, provided that they are available. The best results are obtained by the method based on the optimization of the form of output membership functions μ based on input data.

The base of rules consists of if-then rules. These rules are used for creating predicate clauses representing the base of FIS.

Let x_1, x_2, x_3 be input variables defined on reference sets X_1, X_2, X_3 and let y_1 and y_2 are output variable defined on reference sets Y_1 and Y_2. Then FIS has three input variables and two output variables. Further each set $X_j, j = 1, 2, 3.$ can be divided into $i = 1, 2, ..., n$ fuzzy sets.

$$\mu_{j,1}(x), \mu_{j,2}(x), ..., \mu_{j,i}(x), ..., \mu_{j,n}(x) \qquad (5.7.1)$$

Individual fuzzy sets represent assignment of linguistic variable values, which are related to sets X_j. Then the kth if-then rule R_k in FIS Takagi-Sugeno type can be written down in the following form

$$R_k : \text{If } x_1 \text{ is } A_{1,i(1,k)} \text{ AND } x_2 \text{ is } A_{2,i(2,k)} \text{ AND } x_3 \text{ is } A_{3,i(3,k)} \text{ then } y_1 = h_1 \text{ and } y_2 = h_2 \qquad (5.7.2)$$

Where $A_{1,i(1,k)}, A_{2,i(2,k)}, A_{3,i(3,k)}$, represent the values of linguistic variable and h_1, h_2 are constants. Fuzzy inference system composed of if-then rules defined by relation (5.7.2) is called a zero order Takagi-Sugeno type FIS. If the kth if-then rule R_k in Takagi-Sugeno type FIS is in form.

$$R_k : \text{If } x_1 \text{ is } A_{1,i(1,k)} \text{ AND } x_2 \text{ is } A_{2,i(2,k)} \text{ AND } x_3 \text{ is } A_{3,i(3,k)} \text{ then } y_1 = f_1(x_1, x_2, x_3) \text{ and } y_2 = f_2(x_1, x_2, x_3) \qquad (5.7.3)$$

Where $f_1(x_1, x_2, x_3)$ and $f_2(x_1, x_2, x_3)$ are linear functions, then the FIS consisting of if-then rules R_k, k=1,2, … ,N, defined by relation (5.7.3) is called a first order Takagi-Sugeno type FIS.

The Takagi-Sugeno type FIS was designed in order to achieve higher computational effectiveness. This is possible as the defuzzification of outputs is not necessary. Its advantage lies also in involving the functional dependencies of output variable on input variables. The output level y_k of each the k-th if-then rule R_k is weighted by the $w_k = \mu(x_1)$ AND $\mu(x_2)$ AND $\mu(x_3)$. The final output y of the Takagi-Sugeno type FIS is the weighted average of all N if-then rule R_k outputs y_k, k=1, 2… N, computed as follows:

$$y = \frac{\sum_{k=1}^{N} y_k \times w_k}{\sum_{k=1}^{N} w_k} \tag{5.7.4}$$

5.8 Difference between Mamdani and Sugeno Fuzzy Inference System

Mamdani type Inference, expects the output Membership Functions to be Fuzzy sets. After the aggregation process, there is a Fuzzy set for each output variable that needs defuzzification. It is possible, and in many cases much more efficient, to use a single spike as the output Membership Function rather than a distributed Fuzzy set. This is sometimes known as a Singleton Output Membership Function, and it can be thought of as a pre defuzzified Fuzzy set. It enhances the efficiency of the defuzzification process because greatly simplifies the computation required by the more general Mamdani Method, which finds the centroid of Two Dimensional function.

The first two parts of the fuzzy inference process, fuzzifying the inputs and applying the fuzzy operator, are exactly the same. The main difference between the Mamdani and Sugeno is that, the Sugeno output membership functions are either linear or constant.

In terms of use, the Mamdani FIS is more widely used mostly because it provides reasonable results with a relatively simple structure and also due to the intuitive and interpretable nature of the rule base. Since the consequents of the rules in a TSK FIS are not fuzzy this interpretability is lost; however the TSK FIS'S rules consequents can have as many parameters per rule as input values, this translates into more degrees of freedom in the design than a Mamdani FIS thus providing the system's designer with more flexibility in the design of the system.

5.9 Results and Discussions of Fuzzy Controller using Takagi-Sugeno FIS

In this portion of the chapter, the results for the relative crack depth and relative crack location has been derived from the Takagi-Sugeno FIS using MATLAB toolbox [42]. The results are provided in Table5.9.1, and Input and Output variables of Takagi-Sugeno FIS and Rule viewer of Takagi-Sugeno FIS is given in Figures 5.9.1and 5.9.2. The difference between the Mamdani FIS and Takagi-Sugeno FIS is that, in the former type, we get the output in the form of membership functions as that of the input but in case of Takagi-Sugeno FIS, the output is either linear or constant.

Summarizing the main motivations of finding the relative crack depth and relative crack location, developed with Mamdani FIS and with a TSK FIS and to compare the results are:

- Ø The TSK FIS is more flexible because it allows more parameters in the output as a function of the inputs, it expresses a more explicit relation among them;
- Ø In computational terms the TSK FIS is more effective because the complex defuzzification process of the Mamdani FIS is replaced with a weighted average.

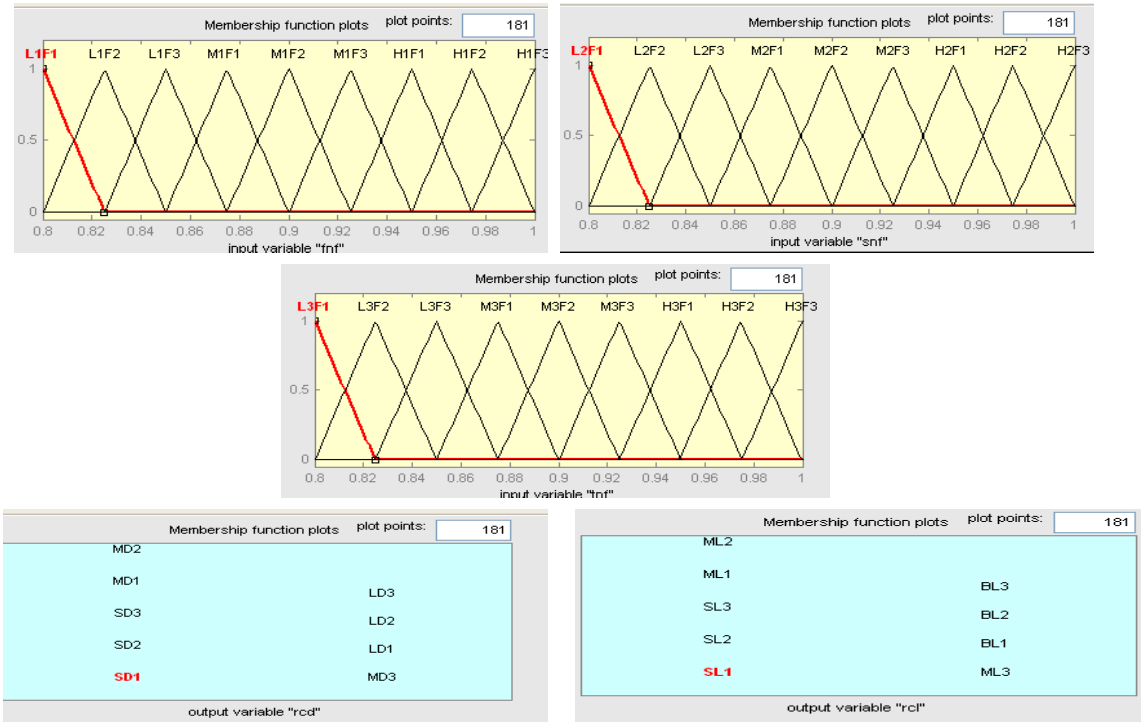

Fig.5.9.1 Input and Output variables of Takagi-Sugeno FIS

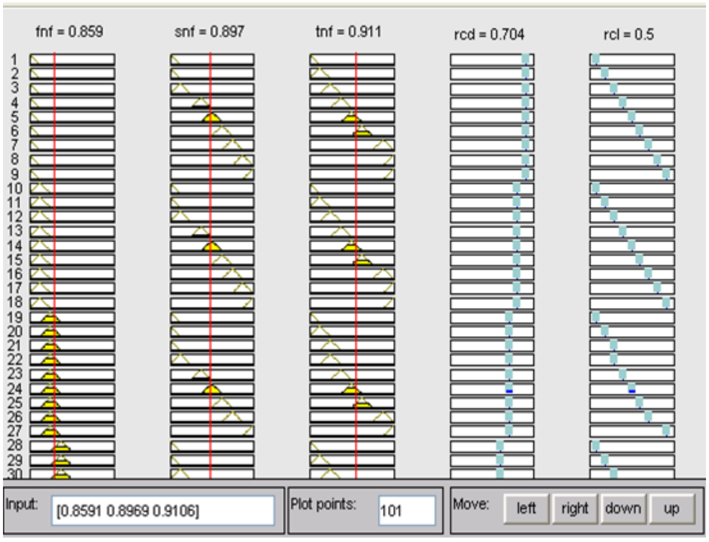

Fig.5.9.2 Rule viewer of Takagi-Sugeno FIS

Table 5.9.1Comparison of the results of Mamdani FIS using Hybridized Membership Function and Takagi-Sugeno FIS

Sl. No	*Relative fnf*	*Relative snf*	*Relative tnf*	*Relative crack depth*	*Relative crack location*	*rcd using gaussian MSF*	*rcl using gaussian MSF*	*rcd using T-S method*	*rcl using T-S method*
1	0.8141	0.8140	0.8136	0.3167	0.125	0.3164	0.1245	0.3164	0.1246
2	0.8635	0.8634	0.8626	0.3	0.1875	0.2995	0.1870	0.2994	0.1872
3	0.9012	0.9011	0.9005	0.2833	0.25	0.2830	0.2494	0.2831	0.2493
4	0.9314	0.9312	0.9272	0.2667	0.3125	0.2664	0.3121	0.2664	0.3122
5	0.9544	0.9543	0.9308	0.25	0.375	0.2494	0.3745	0.2495	0.3745
6	0.9692	0.9690	0.9685	0.2333	0.4375	0.2329	0.4373	0.2331	0.4371
7	0.9839	0.9836	0.9832	0.2167	0.5	0.2163	0.4995	0.2163	0.4995
8	0.9907	0.9894	0.9900	0.2	0.5625	0.1994	0.5621	0.1995	0.5622

5.10 Summary

From the above analysis and discussions, the summaries drawn are depicted as follows.
Crack depth and crack location have got effect on natural frequencies of the vibrating structures. The fuzzy controllers developed here take natural frequencies for prediction of crack depth and crack location. The predicted results from fuzzy controllers for crack depth and crack location are compared with the Theoretical analysis, Finite element analysis and they show a very good agreement. The result of Gaussian and Hybridized membership function fuzzy controller is more accurate in comparison to other two controllers. It has also been found that the Takagi-Sugeno FIS provides better result with less time consumption because the complex defuzzification process is not considered. So from this chapter it can be presumed that the developed fuzzy controller along with the technique can be used as a robust tool for fault detection in cracked structural elements and machine members.

Chapter 6

Analysis of Genetic Algorithm Controller for Crack Detection

Chapter 6

ANALYSIS OF GENETIC ALGORITHM CONTROLLER FOR CRACK DETECTION

6.1 Introduction

Fault detection is one of the key aspects in structural engineering both for safety reasons and because of economic benefits that can result. Many non destructive methods are generally used to investigate the critical changes in the structural parameters, so that an unexpected failure can be prevented. This chapter proposes evolution based methodology for damage detection in a cantilever beam with a single crack. In this approach, a Genetic Controller is designed and is used to detect the relative crack depth and relative crack location. The designed controller uses three inputs and two outputs. The inputs to the Genetic Controller are the relative values of the first three natural frequencies and the outputs are the relative crack depth and relative crack location.

6.2 Methodology used in Genetic Algorithm

First an initial population of n strings (for n parameters) is created. The strings are created in a random fashion, i.e., the values of the parameters that it represents. The set of parameters is passed through a numerical model of the problem space. The numerical model gives out a solution based on the input set of parameters. On the basis of the quality of this solution, the string is assigned a fitness value. The fitness values are determined for each string in the entire population of strings. With these fitness values, the three genetic operators are used to create a new generation of strings, which is expected to perform better than the previous generation (better fitness values). The new set of strings is again decoded and evaluated, and a new generation is created using the three basic operators. This process is continued until convergence is achieved within a population.

Among the three genetic operators, selection is the process by which strings with better fitness values receive correspondingly better copies in the new generation, i.e. we try to ensure that better solutions persist and contribute to better offspring (new strings) during successive generation and strings with lower fitness values are eliminated.

Crossover is the process in which the strings are able to mix and match their desirable qualities in a random fashion. Crossover proceeds in three simple steps. First, two new strings are selected whose fitness value is close to that of the field variables (natural frequency). Second, a random location in both strings is selected. Third, the portions of the strings to the left and right of the randomly selected location in the two strings are exchanged. In this way information is exchanged between strings, and portions of high quality solutions are exchanged and combined. Crossover gives genetic algorithm most of its searching power. The next genetic operator, mutation, helps to increase the searching capability. In order to understand the need for mutation, let us consider the case where crossover may not be able to find an optimum solution. During the creation of a generation it is possible that the entire population of strings is missing a vital bit of information that is important for determining the correct or the most nearly optimum solution. Future generations that would be created using selection and crossover would not be able to alleviate this problem. Here mutation becomes important. Occasionally, the value at a certain string location is changed to a zero and vice versa. Mutation thus ensures that the vital bit of information is introduced into the generation. At the end, GA proposes the fittest individual as the solution to the problem.

6.3 Genetic Algorithm Terms

Some of the essential terms of genetic algorithm which is used in this research work are given below.

6.3.1 Encoding of Chromosome

The chromosome should in some way contain information about the solution which it represents. The most used way of encoding is a binary string. Each chromosome has one binary string. Each bit in this string can represent some characteristic of the solution. Or the whole string can represent a number.

After converting to binary string the chromosome could look like this:

fnf1	1	0	0	1	1	0	0	1	0	1
fnf4	1	0	0	0	1	1	0	0	1	1

Figure 6.3.1 Encoding the chromosomes into bit strings

6.3.2 Initial Population

After obtaining the input natural frequencies, a population of individuals, is generated at random. A population of individuals represents a candidate solution to the problem. The initial population is then submitted to generic operators, resulting in the evolution of populations through generations (iteration cycles).

6.3.3 Selection

Selection is a genetic operator where the best chromosomes are selected to continue, and the rest are discarded. Individual solutions are selected through a *fitness-based* process, where fitter solutions (as measured by a fitness function) are typically more likely to be selected.

6.3.4 Reproduction

Reproduction is the genetic operator used to produce the second generation of populations from those selected through selection using crossover and mutation. To this end, two chromosomes are selected by random as parents and by applying crossover operator two new offspring are created.

6.3.5 Crossover

After we have decided what encoding we will use, we can make a step to crossover. Crossover selects genes from parent chromosomes and creates a new offspring. The simplest way to do this is to choose randomly some crossover point and everything after and before the point is crossed between the parents and copied. There are different types of crossover. In this study single point crossover is used in the design of genetic algorithm controller.

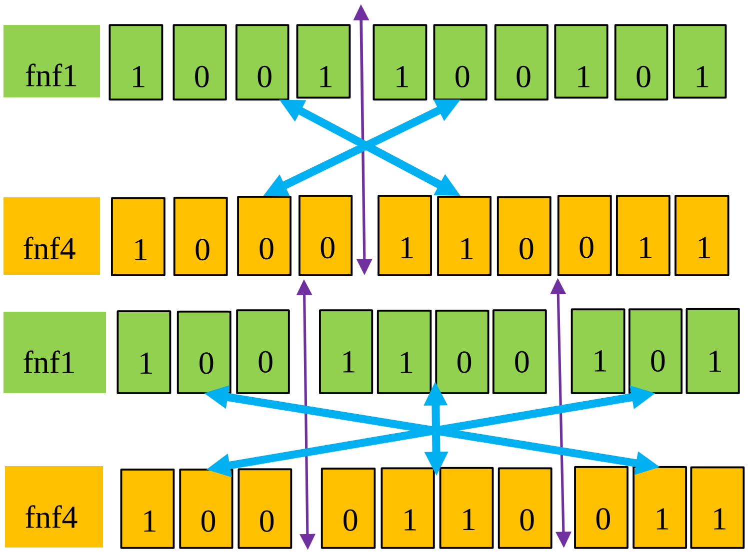

Figure 6.3.2 Single point and Two point crossover

6.3.6 Mutation

After crossover the mutation operator is applied on all the chromosomes except the best chromosome, which is called *the elite*. It can introduce traits not available in the original population and keeps the GA from converging too fast, i.e. before sampling the entire population. In the mutation operator the whole chromosome is changed or each bit can be inverted.

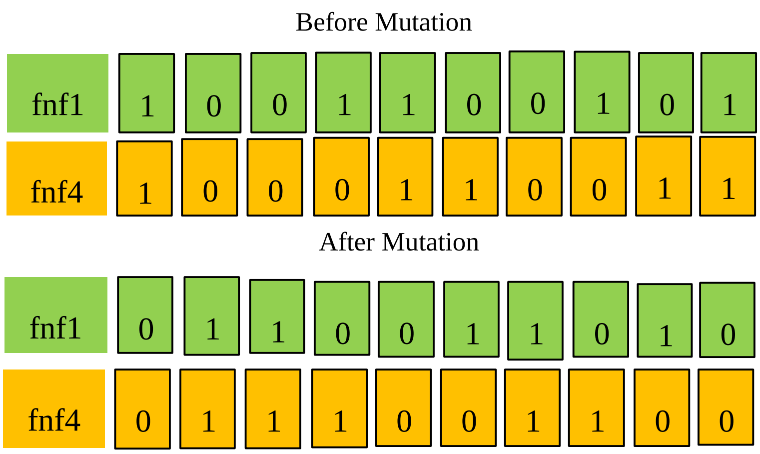

Figure 6.3.3 Chromosomes before and after Mutation

6.3.7 Iterating the Algorithm and Stopping Criterion

After mutation one generation is completed and in the next generation the mutated natural frequencies is used for calculating relative crack depth and relative crack location. The best fitness value is checked in every generation and if the fitness reaches a certain level, or if the maximum number of iterations is achieved, the algorithm is stopped.

6.4 Crack Identification with Genetic Algorithm Deployment

This section depicts the steps used for the deployment of the Genetic Algorithm in the research work. For the determination of these steps, several genetic algorithm runs were considered with the criteria of efficiency and computational cost (time). The GA initialized with three inputs, which corresponds to the characteristic of the crack for prediction of relative crack depth and relative crack location.

6.4.1 Procedure of Genetic Algorithm Analysis

1) First of all the variables and fitness function are selected

The GA begins by defining input variables whose values are to be optimized using fitness function and output variables whose values are to be anticipated using genetic operators.

The fitness function to be minimized is defined as

Fitness function=

$$\sqrt{(fnf_{fld} - fnf_{x_{1,i}})^2 + (snf_{fld} - snf_{x_{1,i}})^2 + (tnf_{fld} - tnf_{x_{1,i}})^2} \qquad (6.4.1)$$

fnf_{fld} = First natural frequency of the field

fnf_{x} = Relative first natural frequency

snf_{fld} =Second natural frequency of the field

snf_{x} = Relative second natural frequency

tnf_{fld} =Third natural frequency of the field

tnf_{x} = Relative third natural frequency i =number of iterations

2) A data pool (initial population) of containing twenty numbers of data sets (individuals) is created.

fnf,	**snf,**	**tnf,**	**rcd,**	**rcl**
0.9318	0.9741	0.9784	0.1667	0.125

3) These data pool is acquired from F.E.A and Theoretical analysis.

4) Two parents (i.e., two data set) from data pool (i.e., from twenty data sets) using fitness function are selected.

5) Then the chosen parents are converted to binary string from decimal values

fnf	**Snf**	**tnf**	**rcd**	**rcl**
0.9318	0.9741	0.9784	0.1667	0.125
1110111001	1111100100	1111101001	0110010110	0010010001

6) The binary string is randomly cut at any point for doing crossover.

7) The children (two numbers) from the parents are found out

8) Then the fitness values of the parents and children are compared, to find out the best fit member.

9) If the child comes as a best fit then it is added to the data pool, and a new set of data pool is created.

10) After generating a new population, the process of selection and crossover is repeated, if needed mutation is done after twenty to thirty crossovers, till we get the best fit for the given set of natural frequencies or the stopping criteria is not met.

11) If a parent comes as the best fit, then the desired output (rcd, rcl), is the output of that set**.**

6.5 Results and Discussions

Early detection of damage in beam type structural elements is very essential to avoid a major failure or accident. For non-destructive testing of cracked cantilever beam, vibration based methods make a good approach. In this chapter a Genetic Algorithm based method has been used to find out the relative crack depth and relative crack location. The variable parameters of the problem, which are codified into individuals and the population size, are deliberately defined and depend on the problem under consideration. Further choices and adjustments are made in the context of a GA search (selection strategy, crossover points, mutation rate etc.), which strongly influence both efficiency of the results and the computational time required. These selections are usually problem oriented and several GA runs are required to achieve an optimal setting. After finding the results after several runs of the GA, it has been ruled out that GA can be used to get precised results for damage detection in a structure and which can be observed from the Table 6.5.1.

Table .6.5.1 Output relative crack depth and crack location using genetic algorithm

Sl .No	*Relative fnf*	*Relative snf*	*Relative tnf*	*Relative crack depth*	*Relative crack location*	*rcd using GA controller*	*rcl using GA controller*
1	0.8141	0.8140	0.8136	0.3167	0.125	0.3163	0.1245
2	0.8635	0.8634	0.8626	0.3	0.1875	0.2993	0.1867
3	0.9012	0.9011	0.9005	0.2833	0.25	0.2829	0.2491
4	0.9314	0.9312	0.9272	0.2667	0.3125	0.2663	0.3120
5	0.9544	0.9543	0.9308	0.25	0.375	0.2494	0.3746
6	0.9692	0.9690	0.9685	0.2333	0.4375	0.2327	0.4371
7	0.9839	0.9836	0.9832	0.2167	0.5	0.2163	0.4994
8	0.9907	0.9894	0.9900	0.2	0.5625	0.1995	0.5620

6.6 Pattern Search Algorithm for Crack Detection

The exhaustive search in the GA provides results with the highest possible accuracy, but the time required makes this approach inappropriate for real time crack identification problems. Here in this section, Pattern Search (PS) algorithm is taken as the searching tool that results in a comparatively fast and repeatable performance in the identification of crack characteristics. Moreover, to initialize PS a seeding process is employed using genetic algorithm with its random parameters to have relatively faster convergence rate.

Pattern Search is a direct method for searching minima of a function which is not necessarily differentiable, stochastic, or even continuous. A PS algorithm searches a set of points around the current point, looking for one where the value of the fitness function is lower than the value at the current point. It computes a sequence of points that gets closer and closer to the optimal point. At each step, the algorithm searches a set of points, called a mesh, around the current point-until finding a point in the mesh where value of the fitness function decreases compared to the value at the current point. This new point becomes the current point at the next step of the algorithm. The mesh is formed by adding a scalar multiple of a fixed set of vectors called ‘‘Pattern Vector” to the current point.

Following flow chart explains the pattern search algorithm briefly.

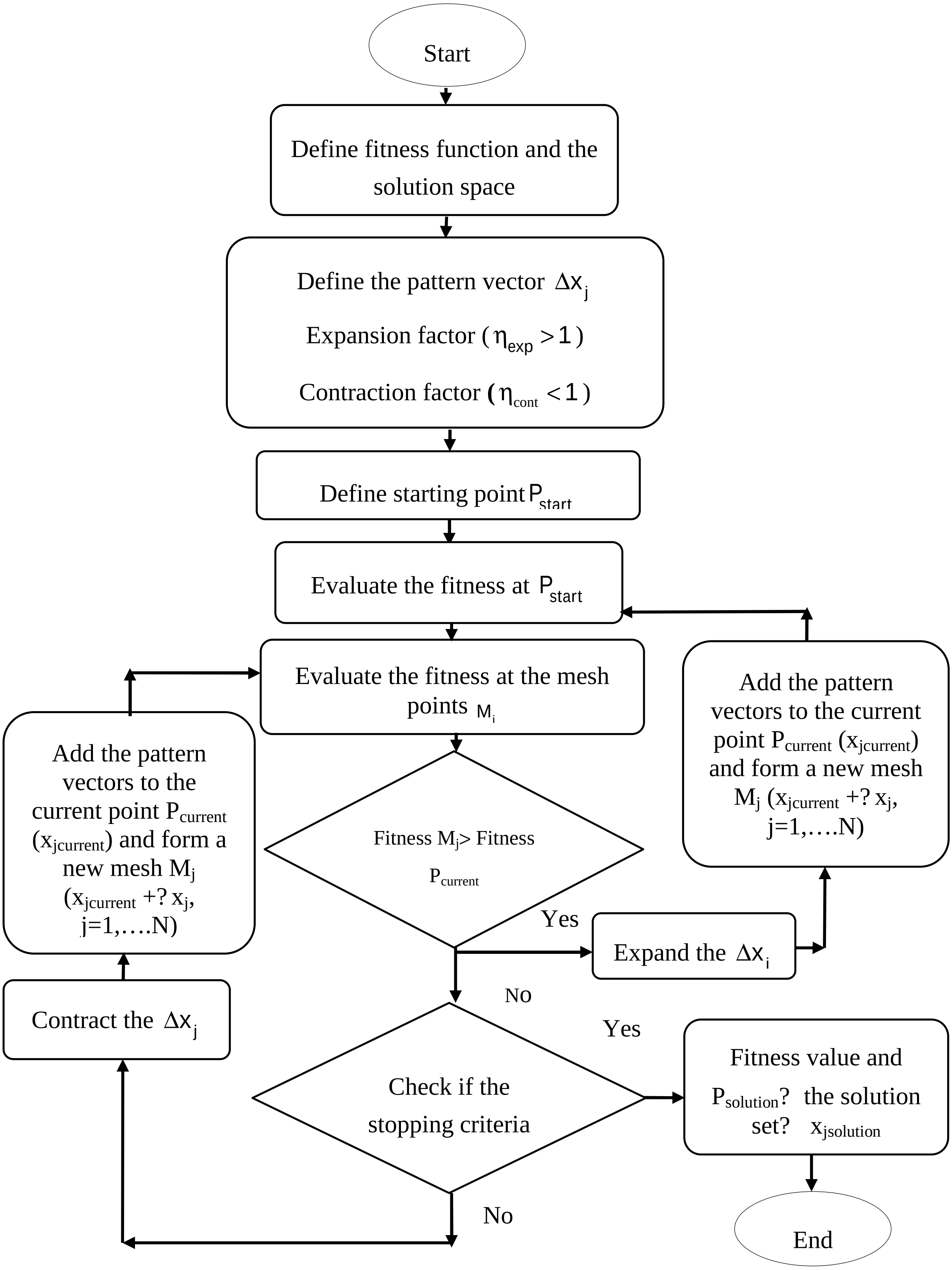

Figure 6.6.1 flow chart describing pattern search algorithm

6.7 Terminologies used in Pattern Search Algorithm

Some of the Pattern Search terms which are used further in this section are given below.

6.7.1 Patterns

A *pattern* is a set of vectors that the pattern search algorithm uses to determine which points to search, at each iteration. The set is defined by the number of independent variables in the objective function, N. With GPS, the collections of vectors that form the pattern are fixed-direction vectors.

6.7.2 Meshes

At each step, pattern search searches a set of points, called a *mesh*, for a point that improves the objective function.

6.7.3 Polling

At each step, the algorithm polls the points in the current mesh by computing their objective function values. The algorithm stops polling the mesh points as soon as it finds a point whose objective function value is less than that of the current point. If this occurs, the poll is called *successful* and the point it finds becomes the current point at the next iteration.

The algorithm only computes the mesh points and their objective function values up to the point at which it stops the poll. If the algorithm fails to find a point that improves the objective function, the poll is called *unsuccessful* and the current point stays the same at the next iteration.

6.7.4 Expanding and Contracting

After polling, the algorithm changes the value of the mesh size. The default is to multiply by expansion factor after a successful poll and by contraction factor after an unsuccessful poll.

6.8 Methods used in Pattern Search Algorithm

1. Definitions: This step consists of the following sub steps:

Step 1.1. Definition of the solution space consisting of variables x_j ; $j = 1,....,N$ and fitness function. The variables and the fitness function are same as that of the GA. Here N is three as the input variables are the first three natural frequencies.

Step 1.2. Definition of the working parameters: Δx_j (pattern vector), expansion factor, η_{exp} and contraction factor, η_{cont}

In this sub step six number of pattern vectors are defined as the number of input variables are three.

Step1.3. Definition of the starting point P_{start} $j = 1,....,N$

A starting point in the solution space should be defined for the algorithm to start. The starting point is taken from the GA after twenty crossovers. After defining the starting point, the mesh points are calculated by adding the pattern vectors to the starting point.

2. Poll process: In this second main step, the following processes are performed:

Step 2.1. Evaluate the fitness at the mesh points M_j $j = 1,....,N$

Step 2.2. Compare the finesses at the current $P_{current}$ and the mesh points M_j $j = 1,....,N$

Step 2.3. If one of the M_j $j = 1,....,N$ is fitter than the current point $P_{current}$, then in the next iteration firstly expand the pattern vector by multiplying the expansion factor and add it to the current point, $P_{current}(x_{jcurrent}, j = 1...N)$ to update the current point and finally build a new mesh on this current point .

$M_j \Leftrightarrow x_{jcurrent} + \Delta x_j, j = 1.....N$ And go to Step 2.1;

The mesh point of the previous iteration becomes the current point in the current iteration after each successful poll.

Step 2.4. If the $P_{current}$ is fitter than the M_j $j = 1,....,N$

Check if the stopping criteria are met. If it is satisfied, then $P_{solution}$ and its fitness value are outputted. Otherwise, follow the next step;

Step 2.5. In this step, firstly multiply the current mesh size by η_{exp} then multiply to the pattern vector and add it to the current point; to update the current point and finally build a new mesh on this current point $M_j \Leftrightarrow x_{jcurrent} + \Delta x_j, j = 1.....N$ and go to Step 2.1. In this case the algorithm does not change the current point.

The total procedure is repeated till the algorithm arrives at a converging result or the stopping criteria are met.

Step 3. The following criteria can be used to stop the algorithm:

(i) maximum iteration which is the maximum number of iterations the algorithm performs; (ii) maximum function Evaluations which is the maximum number of evaluations of the objective and constraint functions; (iii) time limit which is the maximum time in seconds the Pattern Search algorithm runs before stopping; and finally (iv) function tolerance which is the termination tolerance for the objective function value.

6.9 Results and Discussions

The total procedure for finding the crack depth and crack location using the pattern search algorithm is described in this section. Figure 6.8.1 describes the flow chart of the pattern search algorithm. Starting point in the solution space is determined by a seeding process which consists of running “genetic algorithm” and the starting point is taken from the genetic algorithm after twenty crossovers. Here the same fitness function as that of the Genetic Algorithm is used. The expansion factor is always greater than one and the contraction factor is always less than one. Due to the use of genetic algorithm for finding the start point the pattern search can give more approaching result towards the data sets taken in the data table and this is shown in the Table 6.10.1.

Table .6.9.1 Comparisons of results of the Genetic algorithm and pattern search algorithms

Sl. No	*Relative fnf*	*Relative snf*	*Relative tnf*	*Relative crack depth*	*Relative crack location*	*rcd using GA controller*	*rcl using GA controller*	*rcd using PS Algorithm*	*rcl using PS Algorithm*
1	0.8141	0.8140	0.8136	0.3167	0.125	0.3163	0.1245	0.3166	0.1248
2	0.8635	0.8634	0.8626	0.3	0.1875	0.2993	0.1867	0.2997	0.1874
3	0.9012	0.9011	0.9005	0.2833	0.25	0.2829	0.2491	0.2832	0.2496
4	0.9314	0.9312	0.9272	0.2667	0.3125	0.2663	0.3120	0.2667	0.3124
5	0.9544	0.9543	0.9308	0.25	0.375	0.2494	0.3746	0.2497	0.3749
6	0.9692	0.9690	0.9685	0.2333	0.4375	0.2327	0.4371	0.2333	0.4374
7	0.9839	0.9836	0.9832	0.2167	0.5	0.2163	0.4994	0.2165	0.4998
8	0.9907	0.9894	0.9900	0.2	0.5625	0.1995	0.5620	0.1998	0.5624

6.10 Summary

Summarizing the main motivations of finding the relative crack depth and relative crack location, using the Genetic Algorithm and pattern search algorithm the results are:

GAs outperforms the efficiency of conventional techniques in searching non-linear and non continuous spaces. The exhaustive search in the GA provides results with the highest possible accuracy, but the time required makes this approach sometimes inappropriate for real time crack identification problems. Here Pattern Search (PS) algorithm is taken as the searching tool that results in a comparatively fast and repeatable performance in the identification of crack characteristics with less computational time involved. Moreover, to initialize PS a seeding process is employed using Genetic Algorithm with its random parameters to have relatively faster convergence rate.

Chapter 7

Description of Experimental Set-Up

Chapter 7

DESCRIPTION OF EXPERIMENTAL SETUP

In order to support the validation of the results from the theoretical analysis and finite element analysis discussed in chapter-3 and chapter-4, which are used in different artificial intelligence controller proposed to forecast crack location and crack depth discussed in chapter-5 to chapter-6, Experimental analysis is carried out. For the experimental investigations an experimental set-up has been developed in order to measure the dynamic response of the cantilever beam with a transverse crack. The details of the instruments used in the experimental set-up, test specimens and experimental procedure are presented in the subsequent sections.

7.1 Description of Instruments used in the Experimental Analysis

A (800mm x 38mm x 6mm) aluminum beam specimen is selected for the experimental investigations. The diagram of the whole experimental setup is shown in Fig. 7.2.1. The detailed specifications of the instruments used in this investigation are given below.

Specimen	-	cantilever type cracked aluminum beam specimen of dimension (800mm x 38mm x 6mm)		
Vibration pick-up (Accelerometer)	-	Delta Tron Accelerometer		
		Type	:	4513-001
		Make	:	Bruel & Kjaer
		Sensitivity	:	10mv/g-500mv/g
		Frequency		

		Range	:	1Hz-10KHz
		Supply voltage	:	24volts
		Operating temperature Range	:	-50^0C to $+100^0$c
Vibration Analyzer	-	Type	:	3560L
		Product Name	:	Pocket front end
		Make	:	Bruel & Kjaer
		Frequency Range	:	7 Hz to 20 Khz
		ADC Bits	:	16
		Simultaneous Channels	:	2 Inputs, 2 Tachometer
		Input Type	:	Direct/CCLD
Vibration indicator	-	PULSE LabShop Software Version 12		
		Make	:	Bruel & Kjaer

7.2 Experimental Set-Up

A racked cantilever beam has been rigidly clamped to the concrete foundation base as shown in the Fig.7.2.1. The amplitude of vibration of the uncracked and cracked cantilever beam is taken by the accelerometer (vibration pick-up) and is fed to the vibration analyzer, which is connected to the vibration indicator. The vibration indicator is a laptop which is loaded with a PULSE LabShop Software Version 12 for vibration analysis. The vibration signatures are analyzed graphically by PULSE LabShop Software loaded in the laptop. Figure 7.2.2 shows the picture of the Vibration Analyzer which is connected to the vibration pick-up and vibration indicator. Figure 7.2.3 shows the picture of the Vibration Pick-up or Accelerometer.

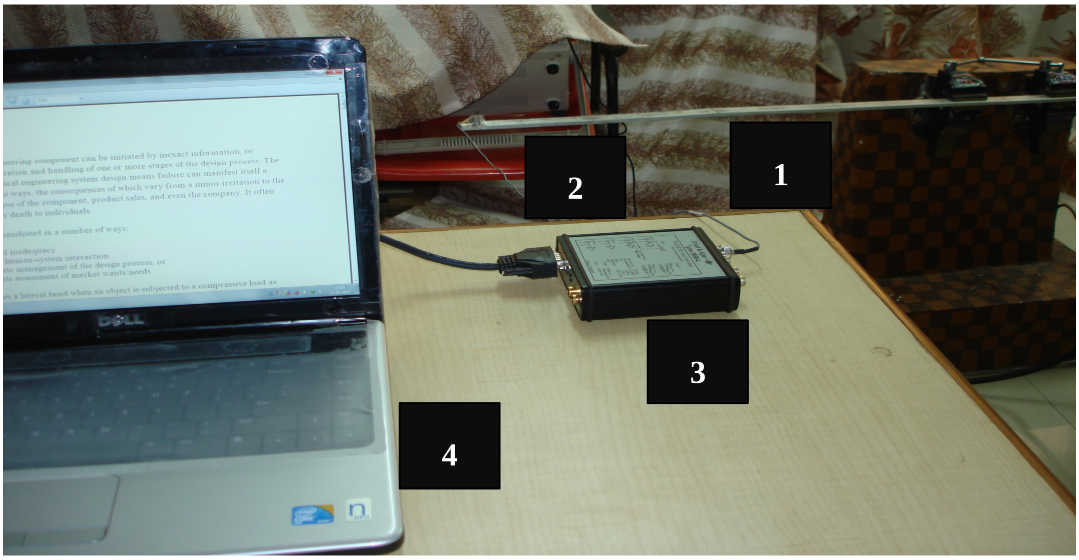

Figure 7.2.1 Experimental Set-up

1-Cracked cantilever beam with a single crack

2-Vibration pick-up

3-Vibration analyzer

4-Vibration indicator

Figure 7.2.2 Vibration Analyzer

Figure 7.2.3 Vibration Pick-up or Accelerometer

7.3 Experimental Procedure

Several tests are conducted using the experimental setup (Figure 7.2.1) on Aluminum beam specimens (800mm x 38mm x 6mm) with a transverse crack for determining the natural frequencies and mode shapes for different crack locations and crack depths. These specimens are set to vibrate under 1st, 2nd and 3rd mode of vibrations and the corresponding amplitudes are recorded in the vibration indicator. Experimental results for amplitude of transverse vibration at various locations along the length of the beam are recorded.

7.4 Experimental Results and Discussions

The experimental results of relative amplitude for different relative crack locations and different crack depths for 1st, 2nd and 3rd modes of vibration are taken and used to validate the results from the fuzzy logic controller and genetic algorithm controller. The experimental results for relative crack location and relative crack depth are compared with the corresponding results from the fuzzy logic controller and the genetic algorithm controller, and it is found that they are in good agreement with each other.

Table .7.4.1 validation of the results by comparing with experimental results

Sl. No	*Relative fnf*	*Relative snf*	*Relative tnf*	*rcd using gaussian MSF*	*rcl using gaussian MSF*	*rcd using GA controller*	*rcl using GA controller*	*rcd taken in experiment*	*rcl taken in experiment*
1	0.8141	0.8140	0.8136	0.3164	0.1245	0.3163	0.1245	0.3165	0.1246
2	0.8635	0.8634	0.8626	0.2995	0.1870	0.2993	0.1867	0.2996	0.1869
3	0.9012	0.9011	0.9005	0.2830	0.2494	0.2829	0.2491	0.2830	0.2492
4	0.9314	0.9312	0.9272	0.2664	0.3121	0.2663	0.3120	0.2665	0.3122
5	0.9544	0.9543	0.9308	0.2494	0.3745	0.2494	0.3746	0.2495	0.3747
6	0.9692	0.9690	0.9685	0.2329	0.4371	0.2327	0.4371	0.2330	0.4373
7	0.9839	0.9836	0.9832	0.2163	0.4995	0.2163	0.4994	0.2165	0.4996
8	0.9907	0.9894	0.9900	0.1994	0.5621	0.1995	0.5620	0.1996	0.5623

Chapter 8

Results and Discussions

Chapter 8

RESULTS AND DISCUSSIONS

8.1 Introduction

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

8.2 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. The stiffness matrix is the inverse of the flexibility matrix or compliance matrix. From the normal functions and boundary conditions the characteristic equation is found out, which is a function of natural frequency, the relative location of crack and the local stiffness matrix which in turn is a function of the relative crack depth. In the analysis Figure 3.1.1 shows the geometry of the cracked cantilever beam.

In the finite element analysis chapter, the effects of the single crack on the vibration signature of the cantilever beam have been elucidated. The Euler-Bernoulli beam model is assumed for the finite element formulation. The crack in this case is assumed to be an open crack and the damping is not being considered in this theory. Both crack locations and crack depth are varied, and the variations in the first three natural frequencies were noted down. These data are further used for training in different controllers.

Chapter four portrays analysis and design of fuzzy controller to give the relative crack depth and crack location. Different types of membership functions are used to define different fuzzy controller. Different linguistic terms (Table 5.5.1) are used to give an idea for various ranges of the membership functions. Then fuzzy rules are constructed to be applied in the fuzzy controller design is provided in Table 5.5.2. In this chapter mainly triangular, Gaussian, trapezoidal and hybridized membership functions are used for input and output variables of the controller. These are described in the Figure 5.5.1 to Figure 5.5.4. The outputs of the fuzzy controller after the applications of rule 5 and 15 from the Table 5.5.2 are explicated in Figure 5.5.6 to Figure 5.5.9. All these calculations have been done using Mamdani FIS. Figure 5.5.10 and Figure 5.5.11 shows the rule viewer and surface viewer for the hybridized Mamdani FIS.
Further in this chapter, Takagi-Sugeno type of FIS is analyzed using Matlab toolbox. In this analysis the first two steps (fuzzification and rule formulation) are same as that of the Mamdani FIS, but the defuzzification process is different. The output is taken as either linear or constant. There is no need to assign any membership functions to the output variables. By taking the weight of the rules we can get the output. The final output of the system is the weighted average of all rule outputs.

In the fifth chapter, Genetic algorithm and Pattern search algorithm have been elucidated. Genetic algorithms are an evolutionary search approach which is an alternative to traditional methods. Genetic algorithm follows the concept of solution evolution by stochastically developing generations of solution populations using a given fitness statistic. Genetic algorithms are likely to be close to the global optimum because it uses to search the entire solution space.

Here Genetic algorithm has been used for detecting the crack characteristics. The search process proposed in this research utilizes binary algorithm and single point crossover to find the crack location and depth whose natural frequencies have maximum similarity with the input field natural frequencies.

The stochastic nature of the GA may be considered a weakness, since it may lead to non optimal solution. This may be diminished if a combination of pattern search algorithm is deployed. So further in this chapter Pattern search algorithm has been used for predicting the output values. Same objective function, solution space, input and output variables are used to run the algorithm. In the pattern search algorithm the starting point is taken from the Genetic Algorithm after twenty crossovers. It is found that the results (Table .6.9.1**)** of the Pattern search algorithm more approaching towards the data taken and requires less computational time.

Experimental analysis is carried out to validate the results from the Fuzzy controller, Genetic Algorithm controller and they are found to be in good agreement with each other. The experimental set-up and the experimental procedures are described in chapter seven. The comparison of the results from the Fuzzy controller and Genetic Algorithm controller is given in the Table .7.4.1. Figure 7.2.1describes the experimental Set-up and the different instruments used are given in Figure 7.2.2 and Figure 7.2.3.

Chapter 9

Conclusions and Scope for Future Work

Chapter 9

CONCLUSIONS AND SCOPE FOR FUTURE WORK

9.1 Contributions

Theoretical analysis of the cracked beam on the basis of strain energy release rate has been carried out to find out the effect of crack depth and crack location on vibration signatures of the beam.

Finite element analysis has been carried out on the basis of above theoretical analysis for studying the influence of crack depth and crack location on the dynamic response of the cracked beam. Four techniques comprising of artificial intelligence techniques such as fuzzy logic using Mamdani FIS, fuzzy logic using Takagi –Sugeno FIS, Genetic Algorithm and Pattern search have been developed for diagnosis of crack depth and crack location. Finally Experimental analysis has been done for validating the results obtained fro above techniques.

9.2 Conclusions

- A deviation in the natural frequencies at the surroundings of crack location has been observed from the comparison of uncracked and cracked beam during the vibration analysis.
- Due to the changes in the crack depth and crack location there is always a significant change in the natural frequencies. It is also observed that theoretical, finite element and experimental analysis are in good agreement.
- In the analysis of fuzzy controller four types of membership functions (triangular, Gaussian, trapezoidal and hybridized) have been designed for the prediction of relative values of crack depth and crack location. Many rules are formed and used for these fuzzy controllers.

- It has been observed Mamdani FIS provides reasonable results (with less error involved) with a relatively simple structure, and also due to the intuitive and interpretable nature of the rule base. The Gaussian Mamdani FIS derives the result more correctly than others which can be observed from the Table 5.5.3.
- The results obtained from Takagi-Sugeno FIS are more precised and needs less designer intervention. The first two steps i.e., fuzzification and rule formulation are same as that of the Mamdani FIS. The only difference is in the process of defuzzification process which produces the results directly without going through the lengthier defuzzification process. As there are different defuzzification processes, the results may also differ. But in case of Takagi-Sugeno FIS we can get directly the crisp values of the outputs.
- The obtained results show that the T-S FIS presented provides a suitable functional approximation with a low computational load.
- Comparisons of the results from the Fuzzy Controller with the Theoretical, Finite element and Experimental results show the effectiveness of the proposed method for the identification of location and the extent of damage. It is found that fuzzy controller with Gaussian membership functions (Mamdani FIS) and Takagi-Sugeno FIS are more suitable in detecting a fault in a cantilever beam.
- In Genetic Algorithm the variable parameters of the problem which are codified into individuals and the population size are deliberately defined and depend on the problem under consideration. Further choices and adjustments are made in the context of a Genetic Algorithm search (selection, crossover points, mutation rate etc.), which strongly influence both efficiency of the results and the computational time required.
- GA produces results which are in good agreement with that of the data table. This can be observed from the Table 6.7.1. The exhaustive search in the GA provides results with the highest possible accuracy, but the time required makes this approach sometimes inappropriate for real time crack identification problems.
- GA embedded 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.

9.3 Applications

- The techniques used and the controller designed using Artificial Intelligence techniques can be used for prediction of damage in turbo machinery, nuclear plants, ship structures.
- As this technique does not involve any removal of parts from work can be used as a non destructive technique for condition monitoring of structural members.
- This work which uses optimization and Artificial Intelligence technique can be used for handling inverse engineering applications/problems.
- The designed controllers can also be used as effective tools for online condition monitoring of engineering system.

9.4 Scope for future work

- The problem can be extended for to treat multiple cracks in shafts and cantilever beams.
- GA and fuzzy logic can be hybridized with each other and with other Artificial Intelligence techniques (which can be used for this type of problem) to design other controllers. So that the online condition monitoring will be done with less time consumption.
- Other complicated structures having damage can be diagnosed using current proposed technique.

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Appendix-A

The ALGOR V 19.3 SP 2 Finite Element Program [109] was used for vibration analysis of the uncracked and cracked cantilever beam. For this purpose the beam element with different single crack was plotted using CATIA V5R15 software. For this analysis different crack depths and crack locations were taken. The uncracked and cracked beam model was then analyzed in ALGOR environment. First of all the mesh generation was performed. The mesh size was around 1.4529mm and approximately 33369 elements were created. Then from the tool command FEA model was created by using the FEA editor. Then the parameters such as element type, material name were defined in the ALGOR environment. Then cantilever boundary conditions were modeled by constraining all degrees of freedom of the nodes located on the left end of the beam. The model unit was then changed to S.I. standards. Then in the analysis window the particular analysis type was selected (natural frequency i.e. modal analysis). Then the analysis was performed and the three modes of natural frequencies at different crack locations and crack depths of the cantilever beam were noted down. Figure 4.4.1 shows the CATIA model of the uncracked and cracked cantilever beam which is used in the ALGOR environment for finite element analysis. Figure 4.4.2 shows first mode of vibration of the Cracked beam after finite element analysis and Figure 4.4.3 shows second mode of vibration Cracked beam after finite element analysis.

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1. Parhi D.R., Sahu S., Review of methodologies used for fault detection using smart techniques, *International Journal of Applied Artificial Intelligence in Engineering System*, 2(2), 2010, pp.161-166.

2. Parhi D.R., Sahu S., Fault Detection of a cracked Structural element using Fuzzy Inference Tool, *International Journal of Applied Artificial Intelligence in Engineering System*, 2(2), 2010, pp.123-132.

3. Parhi D.R., Sahu S., Vibration Analysis of Cracked beam using Genetic Controller, *Emerging Technologies in Mechanical Engineering*, 2011, pp.212-221.

Papers Communicated

1. Damage detection in a cantilever beam using Finite Element Method and Genetic Controller.

   (Has been considered for review in Engineering Computations of Emerald Journal)

2. Damage detection of a cracked structural element using Fuzzy Logic with Gaussian Membership function

   (Has been considered for review in Inderscience Journal)