Inspection and Monitoring of Structural Damage using Vibration Signatures and Smart Techniques

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Inspection and Monitoring of Structural Damage using Vibration Signatures and Smart Techniques

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This is to certify that the work presented in this dissertation entitled “*Inspection and Monitoring of Structural Damage using Vibration Signatures and Smart Techniques*” by “*Sasmita Sahu*”, Roll Number 512ME107, is a record of original research carried out by her under my supervision and guidance in partial fulfillment of the requirements of the degree of Doctor of Philosophy in Mechanical Engineering. Neither this dissertation nor any part of it has been submitted for any degree or diploma to any institute or university in India or abroad.

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Declaration of Originality

I, Sasmita Sahu, Roll Number 512ME107 hereby declare that this dissertation entitled “Inspection and Monitoring of Structural Damage using Vibration Signatures and Smart Techniques” represents my original work carried out as a doctoral student of NIT, Rourkela and, to the best of my knowledge, it contains no material previously published or written by another person, nor any material presented for the award of any other degree or diploma of NIT, Rourkela or any other institution. Any contribution made to this research by others, with whom I have worked at NIT, Rourkela or elsewhere, is explicitly acknowledged in the dissertation. Works of other authors cited in this dissertation have been duly acknowledged under the section "Bibliography". I have also submitted my original research records to the scrutiny committee for evaluation of my dissertation. I am fully aware that in case of any non-compliance detected in future, the Senate of NIT, Rourkela may withdraw the degree awarded to me on the basis of the present dissertation.

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Abstract

The structural damage detection plays an important role in the evaluation of structural systems and to ensure their safety. Structures like large bridges should be continuously monitored for detection of damage. The cracks usually change the physical parameters like stiffness and flexibility which in turn changes the dynamic properties such as natural frequencies and mode shapes. Crack detection of a beam element comprises of two aspects: the first one is the forward problem which is achieved from the Eigen parameters and the second one is the process to locate and quantify the effect of damage and is termed as ‘inverse process of damage detection’. In the present investigation the analytical and numerical methods are known as the forward problem includes determination of natural frequencies from the knowledge of beam geometry and crack dimension. The vibration signals are derived from the forward problem is exploited in the inverse problem.

The natural frequency changes occur due to the various reasons such as boundary condition changes, temperature variations etc. Among all the changes boundary condition changes are the most important factors in structural elements. Many major structures like bridges are made up of uniform beams of unknown boundary conditions. So in the present investigation two of the boundary conditions i.e. fixed -free and fixed- fixed are considered.

Using the forward solution method, the natural frequencies are determined. In the inverse solution method various Artificial Intelligence (AI) techniques with their hybrid methods are proposed and implemented. Damage detection problems using Artificial Intelligence techniques require a number of training data sets that represent the uncracked and cracked scenarios of practical structural elements. In the second part of the work different AI techniques like Fuzzy Logic, Genetic Algorithm, Clonal Selection Algorithm, Differential Evolution Algorithm and their hybrid methods are designed and developed. In summary this investigation is a step towards to forecast the position of the damage using the Artificial Intelligence techniques and compare their results. Finally the results from the Artificial Intelligence techniques and their hybridized algorithms are validated by doing experimental analysis.

Key words: Beam, Vibration, crack, Finite Element Analysis, Fuzzy Logic, Artificial Intelligence Techniques

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List of Symbols

a_1 = depth of crack

A = cross-sectional area of the beam

$A_i i = 1 \text{to } 12$ = 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

$\overline{K}_u$ $= \frac{\omega L}{C_u}$

$\overline{K}_y$ $= \left(\frac{\omega L^2}{C_y}\right)^{1/2}$

S_{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 = stiffness matrix for free vibration.

rcd = crack depth in dimensionless form (relative)

rcl = crack location in dimensionless form (relative)

fnf = first natural frequency in dimensionless form (relative)

snf = second natural frequency in dimensionless form (relative)

tnf = third natural frequency in dimensionless form (relative)

$U_i i=1,2$ = normal functions (longitudinal)

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)

W = depth of the beam

ω = natural circular frequency

β = relative crack location $\frac{L_1}{L}$

μ = $A\rho$

ρ = mass-density of the beam

ξ_1 = relative crack depth $\frac{a_1}{W}$

V = Aggregate (union)

Λ = Minimum (min) operation

$\forall$ = 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

η_{exp} =expansion factor added in the mutation operator

η_{cont} =contraction factor subtracted in the mutation operator

C = Total number of clones generated

n = Selected antibodies

β =Multiplying factor [Castro]

Q = Total number of antibodies (population size)

r = Rank of the selected antibodies

List of Acronyms

NDT = Nondestructive testing

CT = Computer Tomography

AI = Artificial Intelligence

FLS = Fuzzy Logic System

MF = Membership Function

GA = Genetic Algorithm

CSA = Clonal Selection Algorithm

DEA = Differential Evolution Algorithm

MAS = Mamdani-Adaptive Genetic-Sugeno model

ADFMF = Automatic design of Fuzzy Membership Function

ATFRBS = Automatic Tuning of Fuzzy Rules Base System

Chapter 1

Introduction

Structural applications are in use, all over the world for many decades and lots are built daily. The elements used in the structural applications are always in an overstressed phase due to the working and environmental load present. These loads may lead to crack initiation and formation. The cracks are the main source of hazardous catastrophic failure both in static and dynamic conditions. To avoid these tragic consequences structures need regular costly inspections. So during the last two decades researchers are getting attracted towards the cost effective non destructive methods. One such method is the vibration based damage detection method. Again in the modern world man wants everything should be done at the finger tip, so the vibration based damage detection method needs to be integrated with computational expert system to design robust tools for online fault diagnosis.

A brief portrayal about the systems that have been connected with damage detection in beam like elements has been given in this chapter. First part of the chapter illustrates the motivation behind the current work. The novelty in this research work is described in the second part of the chapter. The third portion of this chapter depicts the motivation of this exploration. Fourth segment narrates the aims and objectives of the research work. At last the details of contents of each chapter of the thesis for the current research work have been described in the third part of this chapter.

1.1 Purpose of this Research

Damage detection is very important in many fields such as civil, mechanical and aviation engineering. The presence of the cracks not only reduces the life span of the structure; it becomes the major source of potential economic and life threatening source. So the damage at the earliest site should be detected. Not only the damage detection but the location of the damage site is also very significant. Only the crack location can predict the severity of the damage. So the damage detection has gained a significant amount of attention and motivated many researchers for doing the same. There are different methods for the damage detection and localization in beam like structures. The damage detection methods can be divided into two methods i.e., local method and global method. Local methods are based on the NDT methods such as CT scanning, ultrasonic methods, acoustic emission, magnetic field, eddy current, radiographs and thermal fields. The methods usually do not need any data and theoretical models of the undamaged structures. But these methods cannot be applied to complex structures. These methods can only be applied for damage detection in some parts of the complex structures. For damage detection in such type of structures, we need a global method.

The global method is dependent on the alteration in the dynamic characteristics of the structural elements like stiffness, damping and mass. As we know due to the crack a change in the modal properties of the system occurs. So the deviations in the modal characteristics like natural frequencies can be used as the signal for the early damage occurrence within the structural system.

So the methods based on the vibration analysis can be used for damage detection in very large and complex structures. These types of vibration analysis methods are divided as conventional type and modern type. The methods using vibration analysis offer some advantages over conventional methods. The frequency measurement method is easier to obtain in real-time, it only requires a small number of sensors and the measurement is straightforward. With the advancement in the sensor designs, it could be easier to get “large data” for structural health analysis in near future.

As stated earlier it is very difficult to detect very small faults on large complex structures. So it is very much required by the researchers to extract more sensitive parameters of vibration analysis with the help of advanced methods. These methods make use of modern signal processing techniques and Artificial Intelligent (AI) techniques which together acts as a robust tool for damage detection. As these methods are least dependent on the structural size and shape, it can be called as an intelligent detection method. In this type of approach there is no need of using a validated reference model. AI is the branch of computer science widely used in many engineering and industrial applications. AI techniques are involved in the research, design and application fields. The conventional and traditional methods for modeling complex structure needs amounts of computing, numerical and mathematical resources. But AI based methods propose potential and efficient alternatives to solve different complex problems in engineering field. Briefly we can say Artificial Intelligent (AI) techniques are used to learn the dynamics of the cracked structures. This work is an inverse method to identify and locate crack in beam like structures. The changes in the Eigen frequencies are used as damage index to find the crack depth and crack location.

So motivated by the above reasons the proposed research work is carried out. This research work explores and exploits some of the logic based; nature inspired and immune system based Artificial Intelligent techniques such as Fuzzy logic System (Mamdani FIS and Sugeno FIS), Adaptive Genetic algorithm, Clonal Selection Algorithm and Differential Evolution Algorithm. Not only the stand alone AI techniques but the hybrid techniques using these AI techniques (Fuzzy Logic System, Genetic Algorithm (GA), Clonal Selection Algorithm (CSA), Differential Evolution Algorithm (DEA)) like 3-stage hybrid Mamdani-Adaptive Genetic-Sugeno model, Automatic Generation of Fuzzy Membership Functions, Automatic Tuning of Fuzzy Rules Base System using Genetic Algorithm, CSA-DEA method, CSA-GA method, CSA-FLS method and DEA-FLS method are also proposed in this work. The hybrid algorithms are designed and developed keeping in mind the problem variables for damage detection of structural elements.

1.2 Novelty and Originality of the Research Work

The present work describes the methods for damage detection using various direct and indirect methods. For modeling of the problem, Analytical and Finite Element methods have been used to get the problem variables. These are the direct methods to understand dynamic changes of the system. In this case two end-conditions for the structural element (beam) are considered and the loading conditions are described.

The conventional ways of designing intelligent systems never achieved the expected results. At that situation people started to think of using computers and soft computing methods. Use of Artificial Intelligence (AI) in environmental modeling has increased with recognition of its potential. Due to their vast field of application, in the course of the recent decades, AI-computing strategies for mechanized perception, learning, understanding, and reasoning-have taken commonplace in our lives. While applying various reverse methods for damage detection, some AI techniques are exploited in the current work.

The originality of the work mainly depends on the expedition of the work present till now. Though the AI technique has been investigated, such as to detect the faults in the offshore plates, bearings, bridges, still it lacks major investigations. May be the main route in this area have been broadly explored, but it is the duty of a researcher to explore more and more from time to time to come across some unexpected and unexplored outcomes.

So in this research work an effort has been made to create some hybrid intelligent algorithms that can understand the dynamics of the deviations in the reactions of the faulty structure. In this effort some of the existing algorithms are studied, analyzed and then utilized to design the hybrid algorithm for damage detection.

The current research work has introduced novel adaptation mechanism for evolutionary algorithms like Clonal Selection Algorithm and Differential Evolution Algorithm to achieve proper balance between exploration and exploitation abilities of search spaces. The presented new versions of metaheuristic approaches have been successfully implemented for damage detection in beam like structural elements. A new hybrid learning approach has been proposed for training of the natural frequencies in the three stage hybridization method using Mamdani-Adaptive Genetic Algorithm-Sugeno model. Hybridizations of different evolutionary algorithms like CSA, DEA and GA with FLS have also been employed as damage detection strategy. These algorithms are also hybridized with each other for the same purpose. Damage detection performances of all proposed methods have been verified by comparing the outcomes with the test results.

1.3 Aims and Objectives

This section of the chapter narrates briefly the aims and objectives of the research work. Followings are the aims of the work;

- The main aim of the research work is to detect and localize surface cracks in beam like elements. For the localization of the cracks, the crack parameters like the crack depth and crack location should be predicted efficiently and effectively in real time. So different methodologies have been adopted to achieve the goal.

To achieve the above described goal, following objectives are used.

- To study the effect of crack location and crack depth on natural frequencies.
- To study the of end conditions on the changes in the natural frequencies.
- The objective of the research work is to find a suitable theoretical methodology to address the changes in the modal properties of the structural elements due to the formation of the crack.
- To study the effect of change in stiffness due to the initiation of the crack.
- To explore different AI techniques (FLS, GA, CSA and DEA) for detection of

cracks in structural elements.

- To design and develop various hybrid algorithms using the standalone AI techniques.
- To fabricate an experimental set-up for studying the vibration signatures of the cracked beam element.

1.4 Framework and Agenda

Cracks, faults or damages are serious threat to the current and future performance of the system. For decades research work is being carried out on the dynamic behavior of the structural elements for fault diagnosis. Cracks are initiated in structural elements due to numerous reasons. There are lots of reasons for which the damage occur like mechanical defects, lower fatigue strength etc. Different products may contain faults due to the human errors during the manufacturing processes. The presence of faults on structures and rotating machine elements in case of cyclic loading may cause severe catastrophic failure.

Beams are the fundamental and commonly used models of the structural elements which are studied extensively there are structures in engineering applications which can be modeled as beams like long span bridges, tall buildings and robot arms. So this work presents methods for damage detection in beam like structural elements for two end conditions.

As the stiffness and damping properties are affected due to the initiation of a crack, the natural frequencies and mode shapes are also changed. The natural frequencies and mode shapes contain information about the crack position. The changes in the vibration parameters must be closely monitored for the estimation of structural stability, performance and safety. The vibration behavior of cracked structures has been investigated by many researchers.

Modal parameters (notably frequencies, mode shapes, and modal damping) based damage discovery strategy has several preferences over other properties of the systems due to the fact that these parameters depend only on the mechanical properties (mass, damping, and stiffness) of the system and not on the external excitation. Since natural frequencies can be measured more effortlessly than mode shapes and are less influenced by experimental errors; it has been utilized as a likely damage index by numerous researchers. Due to the various encoding and decoding methods involved in this research work only the first three natural frequencies are used.

Taking into consideration the above discussed arguments in the field of vibration analysis of the cracked structures for damage detection and considering the benefits of AI techniques, the current research work is done. The framework of the procedures used for solving the problem narrated in the thesis is described in Figure 1.1.

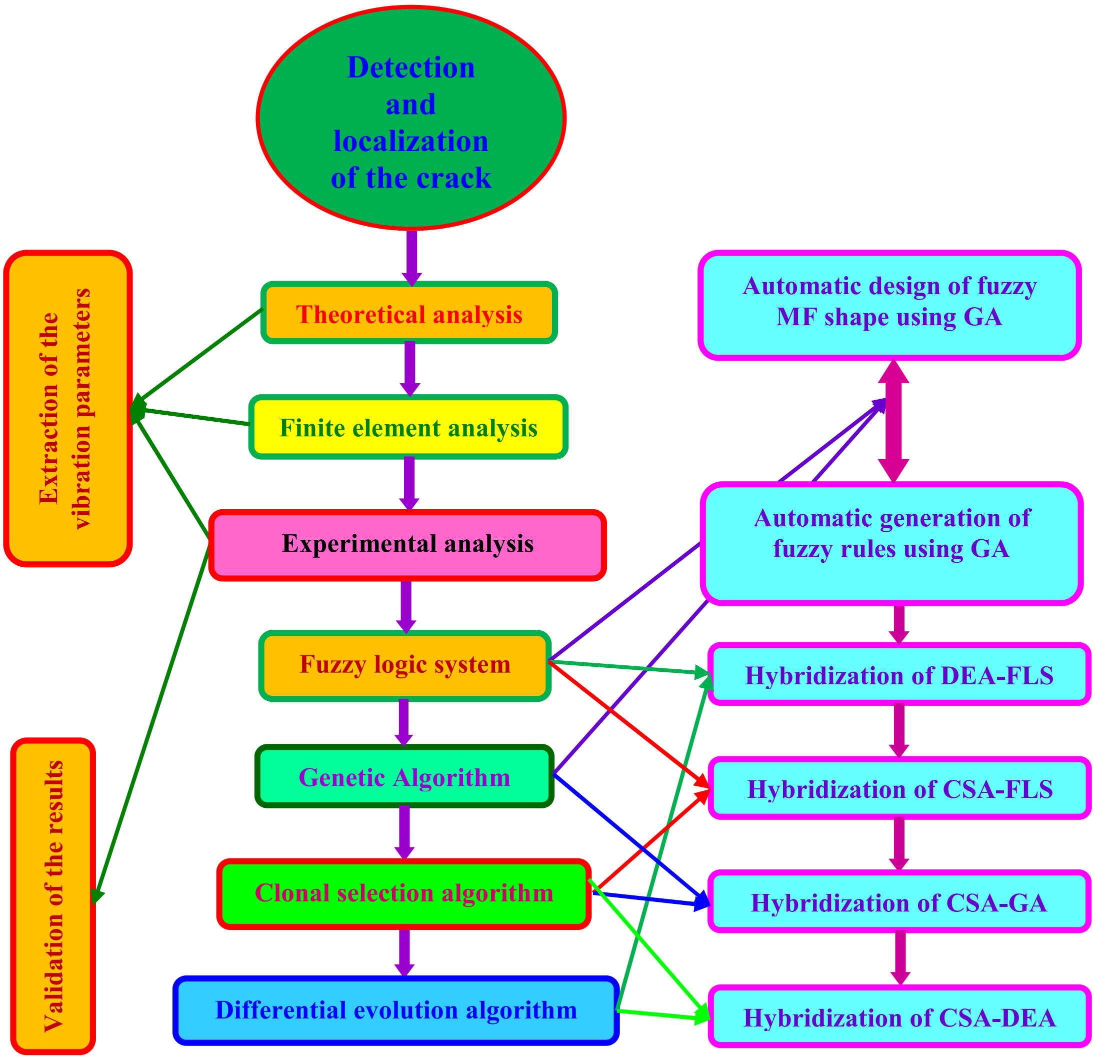


Figure 1.1: Framework of the problem solving process

In the effort to find a convenient solution to a problem using AI systems, several difficulties are faced by the designer. This clearly paves the way to find better AI systems in a hit and trial method. Due to the lack of a common framework it remains often difficult to compare the various AI systems conceptually and evaluate their performance comparatively. So in this work an attempt has been made to compare the performances of two evolutionary algorithms taking some similar parameters. The main aim of the work is to train the dynamic responses of the cracked beam in different AI techniques and hybrid techniques for damage detection and compare the performances of the techniques simultaneously.

Various strategies applied and analyzed for the crack detection and localization are described briefly in the following section;

- ♣ The problem domain has been divided into direct and inverse approach. The direct approach comprises of theoretical, finite element and experimental analyses.
- ♣ In the direct approach different crack configurations are analyzed to get the deviations in the first three natural frequencies. Then the values of the natural frequencies are converted into dimension less form (relative), by comparing them with the natural frequencies of the uncracked beam.
- ♣ Dimensionless form (relative) of the first three natural frequencies and the crack locations (depth and location) are used to train in the proposed AI based techniques.

  Dimensionless form of natural frequency (relative) = (natural frequency of damaged beam) / (natural frequency of undamaged beam) (1.1)

  Dimensionless form of crack depth (relative) = (depth of the crack on the test piece) / (beam width) (1.2)

  Dimensionless form of crack location (relative) = (location of the crack from the fixed end) / (length of the beam) (1.3)
- In the present work, the first three natural frequencies are extracted from the direct methods and converted into relative values. The yields from the system are the relative estimations of the crack depth (rcd) and crack location (rcl) which thus substance the data of damage seriousness. The reason behind the idea to take the relative values of the input and output variables is to lessen the coding error and running time of the algorithm when fed to it.
- ♣ In the inverse approach various Artificial intelligence techniques and their hybrid methods are used. The hybrid intelligent methods are designed and developed using the standalone methods. The different AI methods used are FLS, GA, CSA and DEA. Then the hybrid intelligent methods are outlined considering the pros and cons of the individual algorithms for crack detection.
- ♣ Finally the results from the AI techniques and the hybrid methods are compared with the experimental results for validation and the errors are found out. The errors are evaluated using the following formulae.

  ((FEA result – result from the proposed technique) / (FEA result)) × 100 (1.4)

  ((Exp. result – result from the proposed technique) / (Exp. result)) × 100 (1.5)

Total error in %= (% error in rcd + % error in rcl)/2 (1.6)

Total average error in %= total error in %/5 (1.7)

1.5 Description of the Thesis

The present work as illustrated in this thesis is extensively arranged in ten noteworthy chapters with various systematic segments.

The first chapter of the dissertation gives an introductory idea about the knowledge gap, purpose and agenda of the research work. Subsequent to introduction, chapter two presents the literature survey of various research works on structural damage detection. The literature review section comprises of different analyses which considers the effect of damage on dynamic behavior of cracked structures, damage identification and detection by soft computing methods (Artificial Intelligence or soft computing techniques) such as Fuzzy logic System (Mamdani FIS and Sugeno FIS), Adaptive Genetic algorithm, Differential Evolution Algorithm, Clonal Selection Algorithm and their hybrid techniques.

Chapter three gives the Theoretical model of the analysis of the dynamic behavior of beam with a transverse crack, exploiting the expression of strain energy release rate and strain energy density function. The local flexibilities generated due to the commencement of crack have been utilized in these expressions. The free vibration analysis has been examined to enumerate the vibration attributes of the cracked beam segment.

Chapter four of the thesis provides the numerical analysis of the cracked beam using Finite Element model. This analysis is performed on the beam to evaluate the dynamic response from the cracked and uncracked beams. The dynamic characteristics of the beams are used for the identification of the cracks. The outcomes from the FEA are contrasted with the results of the test results for its validation.

Chapter five defines the concept of the 3-stage determination of damage location using Mamdani-Adaptive Genetic-Sugeno model. The chapter is divided into three major Sections; the first Section describes the fundamentals of Fuzzy Logic System which is used to design the 3-stage Mamdani-Adaptive Genetic-Sugeno model. The Fuzzy Logic System narrates types of Fuzzy Inference Engines (Mamdani FIS and Sugeno FIS). The second section defines the idea of Adaptive Genetic Algorithm which is designed using the Regression Analysis method alongside the fundamentals of the simple Genetic Algorithm. The third section describes the architecture of the 3-stage Mamdani-Adaptive Genetic-Sugeno model which is designed using Mamdani FIS, Sugeno FIS and Adaptive

Genetic Algorithm. The results from the proposed methods are compared with the results from the Finite Element and Experimental Analyses and the errors are also provided. The chapter also compares the performances of the individual methods with the proposed method.

Chapter six depicts an artificial immune based algorithm inspired from the clonal selection principle. This method proposes a robust and adaptive method for fault detection. Here the data available are represented as the antibodies and the modal frequencies from the sensors at the cracked section are designed as antigens. Then the fitness values are determined using the affinity measurement strategy. The antibodies then endure cloning/proliferation according to their affinity towards the antigens. After cloning, the antibodies undergo somatic hypermutation which produces more efficient antibodies (results). In subsequent chapters this algorithm is hybridized with Fuzzy Logic System (Mamdani FIS and Sugeno FIS), Genetic Algorithm and Differential Evolution Algorithm.

The next chapter (Chapter seven) portrays an evolutionary algorithm known as Differential Evolution Algorithm. Unlike other evolutionary algorithms, it does not require any representation scheme. The evolutionary algorithm depends on the initial definition of the upper and lower limitations of the parameter vectors presenting the individual solutions. The initial population of parameter vectors is so chosen that, the complete search could be covered during the iterations of the algorithm. The algorithm is successfully applied in the current problem.

In chapter eight, the combinations of the algorithms described above are analyzed. The hybrid intelligent systems are made to overcome the drawbacks of different AI techniques described in the initial chapters of the thesis. Sections 8.1 and 8.2 of Chapter 8 narrate the implementation of Genetic Algorithm for tuning of various parameters of the membership functions and the fuzzy rules. The next section (Section 8.3); the fuzzy logic parameters are optimized CSA. As the Clonal Selection Algorithm does not comprise recombination operation that can add improved genetic information to the already improved antibodies through the proliferation process. So in Sections 8.4 and 8.5 of Chapter 8, the Clonal Selection Algorithm has been integrated with GA and DEA which contain recombination operation. The hybridized methods where FLS is used are designed by using both the inference systems (Mamdani FIS and Sugeno FIS) and the respective results are provided.

Chapters 9 and 10 summarize the results and discussion and the conclusions drawn during the research work respectively. Chapter 10 also gives the idea about the scope for future research work in this field.

The experimental set-ups and procedure with the information about the instruments used are described in the Appendix 1. The results of the tests have been used to validate the results of the AI techniques. The outcomes of the Theoretical and Finite Element analyses are also compared with the results of the Experimental analysis and are found to be in close agreement with the test results.

Chapter 2

Literature Review

The problem addressed in the current research work describes a structural health monitoring method comprising of damage identification and localization. A good health monitoring method lowers the down time, maintenance cost and hazards. Before suggesting the solutions to the problem, the literature available must be studied thoroughly and understand the loopholes present in the existing methods. So this chapter presents the literature survey done during the research work.

2.1 Introduction

The problem under consideration is how to detect and locate damage in structural elements. Before addressing the problem, the knowledge gap must be analyzed. So for this analysis a thorough literature survey has been performed in the field related to the current problem and is depicted in this chapter. The problem domain covers non destructive testing, wellbeing check, discovery strategies and different fault inspection methodologies incorporating modal parameters. The non destructive techniques are mainly based on the deviation in the vibration signatures of the cracked structures. These methods offer some advantages over the traditional methods. To get the vibration parameters dynamic response from the cracked structural elements must be analyzed. Then coming to the modern methods or structural damage detection, many researchers have integrated artificial intelligence techniques to make the damage detection tool more powerful. The AI techniques depicted in this work are Fuzzy Logic, Genetic Algorithm, Clonal Selection Algorithm and Differential Evolution Algorithm. All the AI techniques have some of the drawbacks when implemented individually so to overcome individual's limitations, the AI techniques are integrated or hybridized. In the hybridization part of the work, the above described AI techniques are combined according to the feasibility to make more powerful and efficient damage detection device. From the vast literature available it can be observed that different researchers have used different methods for fault detection which vary from each other largely. The next section narrates different methods used for damage detection.

As it is not possible to cover the entire literature on damage detection, so the literatures considered for the current work are divided as follow:

a. Different methodologies for fault detection
b. Vibration based methods for damage detection
c. Finite element analysis for damage detection
d. Artificial intelligence technique applications for structural damage detection
    i. Fuzzy Logic
    ii. Genetic Algorithm
    iii. Clonal Selection Algorithm
    iv. Differential Evolution Algorithm
e. Hybrid intelligent techniques
    i. Automatic design of fuzzy MF using GA for damage detection
    ii. Genetic fuzzy rule based system for damage detection
    iii. Fuzzified DEA for damage detection
    iv. Hybridization of CSA-FLS for damage detection
    v. Hybridization of CSA-GA for damage detection
    vi. Hybridization of CSA-DEA for damage detection

2.2 Different methodologies for damage detection

This section describes different non destructive testing methods to check the structural integrity of various structures.

Jaiswal and Pande [1] have presented a fault detection method in structural elements using spatial wavelet transform. The mode shapes are then converted to mode shape curvatures. Then these mode shapes are submitted to wavelet transform for further training. From the results it could be concluded that the suggested method performs that many classical methods based only on modal data. Elshafey et al. [2] have discussed a crack prediction method using neural networks. The damage detection is used in an offshore jacket platforms applied to random loads to locate the damage. The outputs from the neural networks are used as the key to damage location. The decrease in the modal parameters is used as the inputs to the neural networks for training. Ramanamurthy and Chandrasekaran [3] have designed and developed a method for damage detection in composite structures using frequency-response function (FRF) curvature method. The dynamic analysis of the cracked structure has been performed and the results are compared with the results of the referred literature. Naik and Sonawane [4] have updated the various vibration based Crack/damage diagnosis techniques presented by various researchers for a cracked structure. The author has proposed various reliable analytical numerical and experimental methods which can be used as the cost effective non destructive testing methods for cracked beams. Heydari et al. [5] have studied forced flexural vibration of a cracked beam is by using a continuous bilinear model for the displacement field. The author has considered a prismatic beam and the crack are assumed to be an open edge U-shape notch. The displacements and stresses due to the loading conditions are supposed to be small and the crack is not in a growing stage and the material is assumed to be linear elastic. Younesian et al. [6] have investigated the frequency response of a cracked beam supported by a nonlinear visco elastic foundation. The crack is formulated using a set of nonlinear equations of motion. Different resonant conditions are assumed to derive the steady-state solutions. A sensitivity analysis is carried out and the effects of different modal parameters for different geometry and location of crack, loading position and the linear and nonlinear foundation parameters. Zhang et al. [7] have presented a strategic approach that combines ODS and weighted AWCD is proposed for crack location identification of the rotating rotor. To eliminate the false peaks of AWCD and obtain desirable results, a weight factor and ODS curvature data are introduced to the expression of the weighted AWCD. From the results the effectiveness of the approach can be visualized. Dubey et al. [8] have used a chaotic signal based method for the fault detection. The signal is used to excite the cracked beam. The wave form with the power spectrum in a time series is analyzed to detect and locate the crack. The author has considered three modes of excitation to get the waveforms for analysis. Pakrashi et al. [9] have presented the implementation of S transform for the successful detection of damage. The damage is measured in time and space domain. The performance of S transform is compared with the wavelet based simulations and validated using statistics based methods. From the results it could be analyzed that the S transform can successfully used as the very promising tool for fault detection. He et al. [10] have proposed a novel methodology for dynamic analysis of fatigue cracks in the structural elements. The methodology is based on the calculation of the fatigue crack growth for a particular material in a small time. The growth in the crack is calculated randomly at any time for a definite loading condition. Then the dynamics analysis and fatigue crack growth are modeled as a hierarchical model whose simultaneous solution gives dynamic response of the structure. The results from the proposed methods are then compared with the experimental results. Ratolikar and Reddy

[11] have addressed investigations on vibrations of cracked beam structures and methodology for crack identification. The crack is modeled as transverse crack and it is considered as a small element and is later assembled with the other discredited elements using FEM techniques. The simulation results of both the models are compared with the results of the experimental analysis and the HHT method is validated. Nandakumar et al. [12] have proposed an innovative method for detection of damage in the beam like structural elements. The method uses the transfer matrix for a lumped crack. The transfer matrix containing the crack geometry parameters is a square matrix. A heuristic method has been used to optimize the error between the derived and assumed responses. The main benefit of using transfer matrix method is that they are capable of identifying multiple cracks. Kral et al.[13] have presented a new technique using artificial neural networks simultaneously with acoustic emission sensors for health monitoring of structural elements. The structural elements mainly contain flat aluminum plates. The aluminum plates are made up of AL 2024-T3 and are subjected to gradually increasing tensile load. Acoustic emission sensors are used to measure strain wave signals were analyzed using ANN. From the results it could be proved that the neural network with acoustic emission sensors produces very impressive results. Grande et al. [14] have derived a simple procedure for estimating the damage in structures based on a data-driven subspace identification technique. The approach provides an iterative procedure devoted to determine damage coefficients varying from zero to one and defining the reduction of the stiffness—and/or the damping—matrix from the undamaged to the damaged state of the system. Lonkar and Srivastava [15] have described a system for crack discovery and area in a cracked bar component. The modular parameters are gathered from the limited component investigation of the cracked cantilever bar. The numerical information got is utilizing B-spline. Then Wavelet Transform and surface fitting procedure is actualized for damage location. Kajetan et al. [16] have displayed another harm recognition strategy in light of nonlinear crack wave connection. Low-frequency vibration excitation is acquainted with annoy crack, and high- frequency cross examining wave is utilized to distinguish crack related nonlinearities. The outcomes show that the proposed strategy can recognize and limit crack related and natural nonlinearities, taking into consideration dependable crack recognition. Dongming and Maria [17] have proposed fault discovery method for bridges using vehicle-prompted dislodging reaction without requiring earlier information about the movement excitation and street surface harshness. This study is inspired by the late advances in helpful estimation of basic removals empowered by video-

based sensors. Numerical simulations are done to explore the achievability and execution of the proposed crack identification technique utilizing three crack situations including crack at single, twofold, and numerous areas, each including a few degrees of crack characterized by the diminishment in component firmness. Sun et al. [18] have described a method for crack detection in bridge structures, which uses dynamic displacement of structures under moving vehicle. The issue is initially explained with closed-form arrangement of dynamic displacement, which is disintegrated into quasi static part furthermore, dynamic element. Parametric study on estimation noise level, crack area, crack degree, and different crack cases is performed, and the investigation comes about show both dependability and adequacy of this technique in crack location of extension structures.

2.3 Vibration based methods for damage detection

Most of the modern day damage detection methods make use of the fact that the crack has a remarkable effect on the dynamic response of the structural elements. Any sudden change in the structural integrity changes the stiffness matrix, which adds some amount of flexibility to the physical properties of the structure. The changes in the stiffness changes the modal characteristics like the natural frequencies and mode shapes of the structural elements. The modal parameters contain information about the crack geometry. So the researchers exploit modal parameters to find the crack location using various methods, some of which are described in this section of the work.

Waghulde and Kumar [19] have investigated the dynamics of the structures. The cracks can be predicted well before for preventing more damage to the system due to the high vibration excitation. The methods are proved to be promising and comprehensive. Fegade et al. [20] have studied the theoretical analysis of transverse vibration of a cantilever beam and fond out the dynamic responses of the cracked cantilever beam. The free vibration analysis used to find the parameters affecting the modal features of the beam element using ANSYS software and supplied various models of analysis. The author has also described various types of cracks in this study. Sayyad et al. [21] have addressed a method of the inverse problem for obtaining the crack location and crack size in various beam structure. The author has analyzed the axial natural frequencies of the cracked structural element using the theoretical method and predicted the connection between the crack location and the natural frequencies. The results from the analytical method are verified from the results of the experimental method. Wahalathantri et al. [22] have evaluated different configurations of SEDIs. The strain energy method has been used to find the fault in the reinforced concrete (RC) structures. The damage simulation has been done using a single crack and multiple crack conditions. The ranking is performed by ranking individual modal parameters based on the strain energy measurement. Shevtsov et al. [23] have presented the source of uncertainty as the human errors in the positioning of various accelerometers. The beam model is based on the Timoshenko beam theory. Finite element analysis has been performed to find the five mode shapes at the fixed points on the beam surface. The amplitudes of the vibration excitation are used for the derivation of the mode shapes. Khiem et al. [24] have derived the simplified terms for the multiple cracks present in structural elements from the vibration analysis. The author has formulated the cracked beam as the Eigen value problem. The efficiency of the method is verified using the results from the numerical simulation. Daneshmehr et al. [25] have presented a method describing the free vibration investigation. The free vibration analysis is applied to cracked composite beam which is subjected to coupled bending–torsion. The equations of motion are obtained using Hamilton theory, and then the boundary conditions are applied to find the solution. The results from the model are compared with other existing models. Behzad et al. [26] have developed the equations of motion and corresponding boundary conditions are applied for the derivation of the solution. For the analysis bending vibration of a beam is considered. The equations of motion are calculated using Hamilton principle. A disturbance function has been implemented for the formulation of the displacement field which is obtained by the Galerkin projection method. Yamuna and Sambasivarao [27] have studied the effect of presence of crack in a simply supported beam. The crack considered is a triangular crack. Then the results are validated by using numerical method. For the numerical analysis ANSYS software is used and the changes in the natural frequencies are studied for different crack configurations. Jagdale and Chakrabarti [28] have modeled an open edge crack using finite element analysis and the changes in the alteration of the modal parameters are studied in detail. Different boundary conditions have been considered during the analysis process. For the application of the numerical analysis the ABAQUS software has been considered. Isa and Rahman [29] have studied the change of dynamic responses of a free-free cracked beam using modal analysis. The crack considered here is a progressive crack. Then the results are well validated using the experimental analysis. For the experimental investigation an experimental arrangement is developed considering a free-free cracked beam. Israr [30] has derived the equation of motion of an isotropic plate with a randomly located part-through crack exactly at the centre of the plate. For the analysis the equations of motions are derived considering the nonlinear vibrations for a set of boundary conditions. The in-plane forces are modeled using Berger's formula. To find out the site of the crack only the half of the length of the crack is taken for the change in the Eigen frequencies. Majkut [31] has discussed the vibration analysis of the structural element which has an additional mass. The additional mass is considered to increase the elasticity. For this an inverse beam model has been proposed for analytical method and the additional mass has been considered as function of its localization. Chatterjee et al. [32] have simulated the dynamic response of a cantilever beam which is subjected to harmonic excitation. The crack under consideration is a type of breathing crack. The small displacement fields between the two moving surfaces are devoid of friction at the contact site. Then a finite element method is proposed for crack modeling. Orhan [33] has studied free and forced vibration analysis of a cracked beam. A single and two edge cracks were evaluated for modal parameters. From the analysis it is concluded that forced vibration is only able to detect the single crack condition. The forced vibration analysis better describes the effect of change in the crack configuration on the natural frequencies. Mao et al. [34] have addressed the free vibrations of the beams with multiple cracks assuming Euler-Bernoulli theory. For the analysis Adomian decomposition method is exploited. The mode shapes obtained from the adomian decomposition method are formulated as closed-form series solutions. Different numerical solutions are proposed to prove the feasibility of the proposed method. Candelieri et al. [35] have presented an application of a Support Vector Machines (SVM) classification framework. The diagnosis method is divided into two parts i.e., damage identification and detection. For this purpose the author has used ANN and numerical method. Kouchmeshky et al. [36] have addressed a novel method by performing physical tests at the damage site, and then the informations are treated in a co-evolutionary algorithm. The feasibility of the methods is verified using several numerical simulations. Bajaba et al. [37] have introduced a new procedure which can be used to integrate wavelet transforms and modal analysis for detection to make a vibration based methods. The structural damage reduces the stiffness and increases damping which can be used to find the modal parameters. The results were then compared with the numerical and experimental simulations. Wang and Qiao [38] have proposed a new fault detection method in a cantilever beam. Then a numerical filter has been used to draw the irregularity in the profile. The peak value of the irregularity in the profile is exploited to determine the crack size. For the validation of the suggested approach, it has been applied to cracked E-glass/epoxy laminated composite beam to locate the damage and it has given very efficient results.

2.4 Finite Element Analysis for damage detection

Finite element analysis is a sort of numerical examination strategy, which can be utilized to assess the natural frequencies and the mode shapes for 1D, 2D and 3D examination. In the current work finite element analysis has been used as a direct method to find the values of first three natural frequencies and to make a data base using different crack configurations. Then the natural frequencies are trained in inverse methods to evaluate the crack locations. Different researchers have used different strategies for finite element analysis and different software packages available, some of them are described in the following section.

Nad et al. [39] have studied the effect of presence of damage on the modal properties of the structural element. Here the beam contains a single transverse open crack. The modal properties are found out by using finite element method. The crack under consideration is a single transverse open crack. Ranjbaran et al. [40] have presented a novel method of finite-element (FE) analysis for the buckling analysis of cracked columns. The change in the stiffness as the physical property of the cracked structure has been modeled using FEA. From the results of the method used it can be visualized that the technique is simpler, lowers the computational time and feasible. Yuan et al. [41] have narrated the safety monitoring methods of geotechnical structures. To describe the problem formulation the Radial Point Interpolation Method has been used to simulate the crack initiation which is tensile in nature. The goal of the problem is to study how the crack grows in earth structures. The FEM used in this problem are capable of automatically converting the crack model to RPIM nodes. Liang et al. [42] have analyzed the stress distribution of the multi-plate intersection shell structures. According to the analysis results, this paper describes the reasons for crack initiation and growth. The acoustic emission testing apparatus is used for the regular monitoring at the cracked site. Then the signals from the device are used to analyze the crack state. Finite element method has been adopted for analysis of the stress distribution at the damaged site. Musmar et al. [43] have investigated the physical response of shallow reinforced concrete beams when subjected to transverse loading. The distribution of stresses, cracks and load deflection relationship are evaluated using finite element analysis utilizing ANSYS software. To model the concrete Solid65 eight noded isoparametric elements are used. Pal and Rajagopal [44] have presented a Finite Element Method for the analysis of linear elasticity of cracked structures. For this displacement response at the crack tip is evaluated. Different simulation results using Finite Element Method has been supplied. Parandaman and Jayaraman [45] have presented the finite element analysis of beam made up with different fiber reinforced polymer (FRP) composites using ANSYS software. The models of three different RC beams with different FRP composites are designed using Pro-E software. The performances of the above described beams are compared with the simulated beams. Rajeshguna et al. [46] have presented a non linear finite element analysis. Which is carried out on a steel fiber reinforced concrete beams. The beams are strengthened by mixing glass fiber reinforced polymer (GFRP) laminates. The modelings of the fiber reinforced concrete beams are done using ABAQUS finite element software. Chopade and Barjibhe [47] have addressed the theoretical and numerical analyses of a cantilever beam. They have compared the results of the methods with each another. ANSYS program package is used for numerical analysis and the results are provided with percentage error between them. Meshram and Pawar [48] have described a finite element method for a cracked structural element. Here a single crack at different locations has been modeled. The analysis is done using ANSYS software. The beam element is taken as aluminum. Total 49 different crack configurations have been modeled and has been evaluated using ANSYS software. Baviskar and Tungikar [49] have formulated the cracked structural element with multiple cracks. Finite element method (FEM) is applied to obtain the natural frequency of beam. The data pool is generated by FEM. For validation of the addressed method some of the results obtained from the Finite Element Method are compared with the results from the Artificial Neural Network (ANN). Alipourbenam et al. [50] have studied the vibration analysis of the Micro-Electro mechanical systems using the finite element method. The Micro-Electro mechanical system consists of four cantilever beams connected to a central mass. For finite element analysis ANSYS software has been implemented and the vibrational behavior of structures has been examined. Ahn et al. [51] have proposed an extension finite element model has been tested for free vibration analysis of composite laminated systems. Higher-order shape functions are evaluated using higher-order Lobatto shape functions. The described model can be used to relieve complexity of determining the aspect ratios in modeling very thin bonding layer. Quila et al. [52] have described transverse vibration of a fixed beam. Finite element analysis has been used for the calculation of the modal parameters. All the analytical values are analyzed with the numerical method. The numerical analysis is done using ANSYS software. The percentage error is evaluated between the calculated theoretical values and the numerical values from ANSYS software. Zargar [53] has analyzed the nonlinearity present in crack tip at different locations. The theoretical analysis is performed on different types of materials. An experimental set-up is used for the validation of the results. The experimental results are treated in fast Fourier transform. For the evaluation and modeling purpose the author has used ANSYS software. Chen and Tsai [54] have applied the finite element method to model the crack on a turbine blade and calculate the modal parameters. The blades with and without cracks are analyzed using FEA and the details of the blade configurations is supplied. During research work it has been observed that the blades show higher frequency at the blade root in no crack condition and show lower frequency at the blade root in cracked condition. Mudigoudar et al. [55] have assessed the dynamic reaction of crack initiation and spread in brittle material. The brittle material used in this problem is Gray cast iron. During the analysis remeshing method has been applied to model the crack site and derive the dynamic responses. The fracture dynamics narrated in the problem considers the inertia forces. Camellia et al. [56] have modeled planar structures containing stationary cracks submitted to dynamic loads of seismic nature. This modeling aims to evaluate the stress intensity factor in dynamic condition, characterizing the resistance to brutal fracture of cracked structures, using two analysis strategies. Jiang et al. [57] have presented the method for deriving the intensity factors at dynamic state of structures containing multiple structural discontinuities. The extended finite element method is implemented to model the structural discontinuity. The boundary of the void is not included in the damage site. Al-Waily [58] has calculated the natural frequency of a cracked beam with different support conditions. Both analytical and numerical methods are used for the analysis purpose. For the finite element analysis of various crack locations ANSYS software package is used. Then the effects of change in crack location are studied.

2.5 Applications artificial intelligence techniques for structural damage detection

Artificial Intelligence (AI) techniques are an attempt to develop computer based methods that could act like humans. They have the ability to execute tasks, learn languages and imitate human expertise and decision making. The main objective of AI techniques is to achieve maximum intelligence by creating computer programs that demonstrate the activities. Artificial Intelligence has been made in the area of problem solving methods for making a program to trace the reason about problems rather to calculate a solution. AI techniques can provide human like expertise for uncertain reasoning, noisy and time varying environment and handling practical computing problems. Due to the similarities between the two methods AI techniques can be treated as expert systems. For the above stated reasons AI techniques are used increasingly as alternatives to more classical or traditional method to model different complex engineering problems. There are different types of AI techniques that are picking up consideration in the field of controls like mechanical autonomy, commercial enterprises and plants. In the current scenario of ESs, a wide range of AI techniques has emerged and included such as frames, Bayesian updating, fuzzy logic, swarm intelligence, neural network, genetic algorithm etc. though a number of metaheuristic optimization algorithms with numerous mathematical benchmark test functions have been invented by numerous researchers but the performance of such algorithms have rarely been addressed for application in real world problems.

In the process of damage identification and detection, traditional mathematical techniques are rather insufficient due to difficulty in modeling of highly nonlinear components. New methods of modeling based on AI techniques have shown promising results for modeling nonlinearities. So the inverse problem of damage detection of any material of any section can be solved using computational intelligent techniques. The following section gives some of the literature based on the AI techniques for damage detection.

Moradi et al. [59] have examined a multiple crack detection technique. A fitness based function has been outlined in light of the adjustment in the modular parameters. Several optimization techniques are used to evaluate the performance of the fitness function. Several experiments are conducted on cracked cantilever beams for the verification of the results from the evolutionary algorithm. Bhuyar et al. [60] have proposed method for the quantification of a fatigue crack in a structural element. The crack is an open type of crack present on a cantilever beam. The crack parameters are calculated using the experimental analysis and then treated in an evolutionary algorithm, so this method gives the efficiency of the technique and does not need any validation and comparison. Haryanto et al. [61] have narrated a computational procedure for investigating the structural stability. For this purpose an artificial neural networks has been exploited. Damage indices are predicted by the stiffness reduction in structure which is a function of changes of the structural static parameters such as deflection and strain. This method has been proved more efficient than identification of damage than the displacement. Malekzehtab and Golafshani [62] have applied finite element model to detect damage an offshore jacket platform. To measure the modal data numerical analysis is done. To learn the dynamics of the crack, genetic algorithm is utilized as a robust global searching tool. To deal with errors present in the modal data a penalty term is added to the fitness function. Nasiri et al. [63] have used vibration parameters to detect and localize the damage. The structural element considered is a composite plate. Then the extracted using modal signals are trained in an artificial intelligence method to identify the severity of the damages. Experiments are then carried out to verify the developed model. Nazarko and Ziemianski [64] have obtained the dynamic responses of the cracked structures and are then treated in artificial neural network. The vibration indices are extracted using digital filters in wavelets decomposition and Principal Components Analysis. Finally all the data obtained are trained the results in artificial neural network. Hakim and Razak [65] have presented the application of Artificial neural networks (ANNs) and adaptive neuro-fuzzy inference system (ANFIS) as two different artificial intelligence technique for damage detection. They have also compared the results of the two techniques produced the results from the two techniques. From the results it is observed that the ANFIS produces better result as compared to ANNs. Yaya et al. [66] have described the health monitoring of immersed structures. They have proposed a new method based on artificial intelligence. Gaussian neural networks are exploited for signal processing with wavelets transformation and principal component analysis. The results are verified using experimental measurements obtained from immersed plates including surface cracks with different configurations. Zhang et al. [67] have described a damage assessment method in this work. A neural system based back engendering rules has been planned and produced for fault evaluation. The aftereffects of the neural system technique is compared with the other three robust back propagation algorithms namely Levenberg-Marquart algorithm, adaptive variable step-size algorithm and homogeneous algorithm which are addressed for localization the crack. Tabrizian et al. [68] have presented a damage assessment methodology based on the changes in dynamic parameters. Here the finite element modeling has been used to model the cracked structure. Then a newly developed AI technique has been used for detecting and locating the damaged structure. The metaheuristic optimization algorithm known as the charged system search (CSS) is utilized and the results are compared with the results of the particle swarm optimization.

2.5.1 Fuzzy Logic for damage detection (Mamdani FIS and Sugeno FIS)

The fuzzy logic system is based on the fuzzy set theory. Fuzzy sets are invented by L.A. Zadeh to deal with the uncertainties or noise present in the data derived from any nonlinear system. Fuzzy Logic system has been successfully implemented and executed for a wide variety of problems: robot, heat exchange, traffic junction power system and nuclear reactor, on-line shopping, washing machines, etc. It has also been applied in the field of damage detection but less work has been done in this field. Some of the literatures on fuzzy logic formulation in different fields of engineering and research are depicted in this section.

Dash [69] has described a method based on fuzzy Gaussian technique for multi crack detection of structural elements. For training the vibration responses derived from the numerical methods of the cracked cantilever beam. Then the results are compared with the results of the experimental method, and are found to be in good agreement. Dixit and Singh [70] have proposed structural health monitoring method. The technique uses impact source identification for fault detection. The crack detection method has been designed and developed using fuzzy inference engine and MATLAB's fuzzy logic toolbox. Zhu and Singh [71] have proposed another sort of structural fault identification technique utilizing ANFIS. They have implemented the adaptive nature of the neuro-fuzzy inference system (ANFIS). This method uses exploits the best approximation theory of ANFIS for system identification and response prediction. Chandrashekhar and Ganguli [72] have proposed a fuzzy logic system for structural damage detection. For the design of the fuzzy logic system modal curvatures are used as the input variables. For fuzzification of the modal curvatures Gaussian fuzzy sets are used. To obtain the modal parameters Finite element analysis has been implemented. Verma et al. [73] have presented an approach to design the fuzzy logic controller for identification of cracks a cantilever beam. Different (Gaussian, triangular, trapezoidal) fuzzy membership functions are utilized to develop the variables of the fuzzy controller. A number of fuzzy rules are generated from vibration parameters which are finally used for prediction of crack location. Liu et al. [74] have presented a methodology for the fault identification of bridge. The damage assessment method is based on the ratios of modal shape components. For developing the fuzzy method fuzzy nearness-based method is executed in the design work. The results are verified with the results of the numerical analysis method. Chang and Lan [75] have developed a technique for health monitoring of structures like part of aircraft. The aerodynamic models are generated by using flight data. Then the varying parameters of the data are obtained by numerical model. These data are then fuzzified in the fuzzy logic model. Here the structural flexibility matrix is used as the damage index. Escamilla et al. [76] have presented wavelet transform theory and fuzzy logic technology for damage diagnosis. Wavelet Packet Transform is used for extraction for the vibration parameters. Then this fuzzy logic set are used to model ambiguity and vulnerability present in the extracted data. The vibration response data are obtained from six accelerometers. Sazonov et al. [77] have presented a damage assessment method using strain energy or curvature mode shapes. Finite element model is used to calculate strain energy mode shapes and calculation of curvature as well. Then the data are used in fuzzy logic system to get the required damage location. Ettefagh et al. [78] have designed a novel strategy for fault identification using fuzzy classification technique. The fuzzy classification technique uses the Autoregressive Moving Average for parametric modeling of the damaged system. A numerical simulation method is used for the frame structure under consideration. Then the results from the numerical simulations are applied in the proposed method for damage detection. Hamid and Dzati [79] have proposed a fuzzy inference engine for ingle biometric speaker verification systems. This study verifies the use of Fuzzy Inference System for weight inference. Tarighat [80] has presented an Adaptive Neuro-Fuzzy Inference System for detection of possible damage. In the design of the Adaptive Neuro-Fuzzy Inference System, a Sugeno Fuzzy Inference System is used. Hakim and Razak [81] have proposed an Adaptive Neuro-Fuzzy Inference engine. Here the natural frequencies are treated in the ANFIS model. The execution of the ANFIS model is enhanced by the Mean Square Error and coefficient of determination. The author has used here the Sugeno Fuzzy Inference System for developing the ANFIS model.

2.5.2 Adaptive Genetic Algorithm for damage detection

Genetic algorithm is the most popularized and successfully used optimization method. This optimization method works on the principle of survival of the fittest. During the advancement through the algorithm, the evolution of the population (candidate solutions) occurs which leads to the enhancement of results. Genetic algorithm proceeds through the genetic operators: representation, initialization of population, selection, crossover, mutation and again selection. A lot of publications are present on application and formulation of genetic algorithm in different field of research but it is impossible to describe all these research work, so some of them are depicted in the following section.

Karimi et al. [82] have presented a different strategy for crack identification in circular cross section beams using an evolutionary algorithm. Genetic algorithm was used to train the results from the neural network. The normalized figures of the input data were treated in the neural network. The results obtained were in good approximation which proved the robustness of the method. Goldfeld et al. have [83] proposed an identification technique for a damaged plane frame element. The damage assessment strategy is based on the optimization method using Genetic Algorithm. Using the dynamic stiffness method, the natural frequencies were calculated. These modal variables are then treated in Genetic Algorithm to get damage location and the damage severity. Karimi et al. have [84] presented a procedure for fault detection in blades. The method is described in four stages. First the crack is analyzed using Finite Element Method to obtain the natural frequencies then two Multi Layer Feed Forward neural networks were generated. The outputs from the neural networks were fed to the genetic algorithm then the results were again treated in the neural network to get the final filtered result. The results show they are in good agreement with actual assumption. Khaji and Mehrjoo [85] have outlined crack detection in beam-like structures. The stiffness matrix of the cracked beam elements are evaluated using the conjugate beam concept based on Betti's concept. After obtaining the natural frequencies and mode shapes, an inverse approach is established. The inverse method is designed and developed using genetic algorithm. The proposed method is able to identify various crack geometries in a cracked beam. Zheng et al. [86] have used hierarchical genetic algorithms for detecting multiple cracks in beams. The research work is done for the identification of the multiple cracks in beam like elements. During the running of the algorithm, it has been observed that the hierarchical genetic algorithm needs lesser number of iterations than the traditional genetic algorithm and still produces makeable result as compared to the later one. Chou et al. [87] have proposed the damage recognition issue as a backwards problem. The problem addressed as an optimization technique using genetic algorithm. Using the Genetic Algorithm the author tries to evaluate existence, location and severity of damage. The fitness function is designed to take care of the displacements at unmeasured degree of freedoms. The described method is able to approximate the crack location. Srinivas and Ramanjaneyulu [88] have formulated an objective function in Genetic Algorithm for the damage detection of the structure. The alteration of the stiffness, frequency and MAC values are used as the damage index. Laier and Morales [89] have employed an improved meta-heuristic evolutionary algorithm for diagnosis of damage. The structural element assumed in this problem is a truss type structure. For the detection of the damage finite element simulation has been proposed. Xia and Hao [90] have implemented genetic algorithm for crack identification in structures by exploiting the vibration parameters. The fitness function is a minimization type. The fitness function is used to minimize the parameter values before and after the damage initiation. An experiment is carried out on a frame and a cantilever beam is used to demonstrate the changes in the physical property due to the presence of the damage. Wang et al. [91] have proposed optimization based genetic algorithm for structural damage detection. The author has described a multi-layer genetic algorithm to overcome the short comings of the problem. In this methodology the initial population into groups containing less numbers of candidate solution to the problem. Then each population is evolved while passing through each layer of Genetic Algorithm. The experiments were also conducted for both single- and multiple-damage scenarios. Liu et al. [92] have proposed a novel technique for damage diagnosis by addressing an improved genetic algorithm. The problem has been modeled as a multi-objective function using the genetic algorithm. The optimization based on the minimization of the weight coefficient value choice. Ebrahimi et al. [93] have presented a fault detection method for MF285 Tractor gearbox. In this problem the data is passed to a neural network through a Fourier transform. Then the output parameters from the neural network is selected and trained in genetic algorithm. For the calculation of the parameters the three different shaft speeds are taken.

Dervilis et al. [94] have detailed a regression analysis method for data analysis. The absence of data from damaged structures in many cases forces a dependence on novelty detection as a means of diagnosis. Lazarevic et al. [95] have described a novel data mining method for the efficient damage detection within the large-scale complex mechanical structures. They have made a localized clustering-regression model for each structural element, so that regression analysis model gives better result than any other traditional technique. Ismail et al. [96] have depicted a technique to reduce the field data. The author has used residuals from the regression of the mode shapes. For the regression analysis Chebyshev rational series have been used. Shahidi et al. [97] have detailed a model free, fault detection method using single- and multivariate regression models. Two sample tests are also done using the t-test methods. From the analysis of the results, the authors have found that multiple statistical models improve the detection of the change in the damage sensitive parameters.

2.5.3 Clonal Selection Algorithm for damage detection

Clonal selection algorithm is based on the immune system of the human being. This method works on the theory that the cells which are able to recognize the pathogens undergo proliferation and produce respective antibodies for the protection of the system. Then these cloned antibodies endure somatic hypermutation for the addition of information and improvement of the affinity of the cloned antibodies. Lot of literature is available for the application of Clonal selection algorithm in different field of research but less work has been done using Clonal selection algorithm for damage localization in beam like elements. Some of the literatures available in different fields of research and for fault detection are produced in the following section.

Xie et al. [98] have put forward a kind of artificial immune system evolution process which works on clonal selection algorithm. The parameters of the Vibration analysis are treated in the clonal selection algorithm of a rotating lathe shaft. Tamandani et al. [99] presented a Clonal Selection algorithm to an optimization method for sitting and sizing of distributed generation in IEEE 33 bus test system. For the formulation of the objective function voltage profile for different nominal load of system and power losses in the system are considered. The performance efficiency of the proposed algorithm is verified from the results of the simulations in MATLAB. Strackeljan and Leiviska [100] have developed an Artificial Immune System inspired by the human immune system for damage diagnosis. Here the AbNET method is used to identify the normal and damaged performance of the system by modeling the unexpected anomaly situations. The results from the Artificial Immune System are compared with the outcomes of the experimental tests. Gao et al. [101] have employed the clonal optimization method to tune the detectors to get the best anomaly detection performance. The Artificial Immune System applied for the fault detection in the motor bearings is known as Negative Selection Algorithm. Simulations are made using both negative selection algorithm and clonal selection algorithm and the results from both the methods are compared with each other and with the experimental analysis. Anaya et al. [102] have proposed a structural health monitoring method for damage detection of an aircraft skin panel. The method uses the bio-inspired theory for the fault detection of structural changes using an artificial immune system. The damage features are extracted from the data of various sensors. Then the damage indices are evaluated using principal component analysis, and then the filtered parameters are treated in the artificial immune system. Li et al. [103] have presented an immune algorithm based hybrid system for structural health monitoring. The artificial immune system is integrated with symbolic time series analysis method. The artificial immune system is a combined method of Real-Valued Negative Selection and Adaptive Immune Clonal Selection Algorithm. For the validation of the results experimental analysis on a five-story shear frame structure is performed. Wang and Wang [104] have presented a simulation model to optimize the best ignition advanced angle of hydrogen-fueled engine. The simulation model is made using Clonal Selection Algorithm. The results from the Clonal Selection Algorithm are compared with the results of the BP neural network describing the shortcomings of it.

2.5.4 Differential Evolution Algorithm for damage detection

Different metaheuristic are described in this work, one of them is the differential evolution algorithm. This evolutionary algorithm operates on real-value optimization problems by evolving a population of possible solutions. It has been emerging as a powerful population-based stochastic search technique for various types of problems. This method does not require any encoding scheme but its success largely depends on the appropriately choosing trial vector from the initial population of vectors. Lot of publications is present on the implementation and formulation of differential evolution algorithm, but a few damage detection methodologies using differential evolution algorithm till date. Some of them are described in the following section.

Kumar et.al [105] has designed a GUI for optimization of scheduling jobs. For this purpose MATLAB simulations are developed. Both conventional and evolutionary approaches are used for job scheduling. The results from the automated Differential evolution algorithm tool are validated using experimental analysis. Reed [106] et al. have a proposed modified version of the differential evolution algorithm for the prediction of structural damage parameters. The proposed algorithm tries to manipulate both mutation and cross-over rates during the implementation of the algorithm such that convergence rate to the global solution will be attained. The modified and improved differential evolution algorithm is applied to the fault detection of submerged shell structures.. Vincenzi [107] et al. have proposed a different type of problem formulation where finite element model updating is done by using two methods. The proposed method also gives the comparison between the differential evolution algorithms and coupled local minimizers. The methods are proposed for both single and multiple crack detection. A pseudo-experimental method is considered for the verification of the results.

Georgioudakis [108] et al. has addressed a non-destructive testing and assessment method for auxiliary damage identification. The modal parameters for training in the single-objective optimization problem using differential evolution algorithm is obtained from the simulated experimental data simultaneously with the finite element analysis. For the detection and localization of the damage the objective function formulated is minimized. Seyedpoor and Yazdanpanah [109] have narrated a damage assessment problem using differential evolution algorithm. The damage indices are derived which approximates the crack location by proposing the problem as an optimization problem. Numerical simulations are designed for the comparison of the performance of the particle swarm optimization algorithm and differential evolution algorithm. Wang [110] et al. have proposed an optimization problem to solve damage detection problem. In the current three methods are described and compared using multi-objective differential evolution optimization, non-dominated sorting genetic algorithm and accumulative modal assurance criterion. Mahdad and Srairi [111] have presented the implementation of simple differential evolution algorithm for decision making of the multi objective optimal power flow in the power system with shunt FACTS devices. For the verification of the results different case studies are considered and from the comparison it has been concluded that the differential evolution algorithm is very efficient in getting the global solution from the vast search space. Rout et.al [112] have designed proportional-integral controller based on differential evolution algorithm. This method proposes automatic generation control of an interconnected power system. The results are compared with the results of the bacteria foraging optimization algorithm and genetic algorithm based PI controller and from the results the superiority of the results are proved. Wang and Zhao [113] proposed a modified and improved differential evolution algorithm known as self-adaptive population resizing mechanism. The performance of differential evolution algorithm is effectively enhanced by choosing one of two mutation strategies and by adjusting the control parameters in such a way that it can adjust to the changing issue techniques. Asafuddoula et al. [114] have proposed a metaheuristic optimization for solving the real world problems. The author has proposed a hybridization of differential exponential crossover with search method of the algorithm for the enhancement of the performance efficiency. Then the results of other algorithms while solving for the same test functions are compared and it is found that performs better than the addressed other methods. Regulwar [115] et al. have proposed an application of differential evolution for the optimal operation of multipurpose reservoir. The objective of the study is to maximize the hydropower production. Before solving for the objective function the constraints for the algorithm are defined and they are irrigation supply demand constraints, turbine release capacity constraints, reservoir capacity and storage continuity. The control parameters are defined as crossover constant, population size, and the weight. The problem is also formulated using genetic algorithm and the results are compared.

2.6 Hybrid Intelligent Techniques for damage detection

In the effort to find a convenient solution to a problem using AI systems, several difficulties are faced by the designer. It is not an easy task to find out the problems while running an algorithm. This clearly paves the way to find better AI systems in a hit and trial method. It has also been found that sometimes the direct applications of the AI techniques could not obtain a fair solution, so hybridization of AI techniques are used.

Hybridized intelligent systems (HIS) are combined AI systems or expert systems used for further optimization of the problem solving capabilities. The integration or fusion of different learning techniques is developed in the field of computation to overcome individual limitations. Due to the competition of developing more efficient performance and better result, the combinations of various techniques are now designed. This process has contributed a lot in developing a large number of new intelligent system designs. These ideas have invented several different kinds of intelligent system architectures.

To solve real world complex problems a diversity of intelligent systems are required. These techniques include traditional computing techniques and soft computing techniques. These intelligent techniques are complementary rather than competitive so they are combined and not used exclusively for getting better results of the defined problems. As the main aim of the current problem is to detect the damage with less time consumption, some of the proposed AI techniques are hybridized. But the hybridization must be done in a judicious mode so that the resulting algorithm contains the positive features of both the algorithms and can overcome each other’s limitations. Most of the approaches follow a special design methodology, which is justified by success in certain application domains. Due to the lack of a common framework it remains often difficult to compare the various AI systems conceptually and evaluate their performance comparatively.

Following sections describe some of the works on the hybrid intelligent systems. The later part of the chapter describes research work done on the hybrid intelligent methods described in the former part of the chapter.

Grosan et al. [116] have emphasized the need for hybrid evolutionary algorithms and then we illustrate the various possibilities for hybridization of an evolutionary algorithm and also present some of the generic hybrid evolutionary architectures that has evolved during the last couple of decades. Ajith [117] has presented some of the facts on hybridization of different intelligent systems. In this paper a discussion on these architectures with an emphasis is also presented. Latif [118] has discussed about different artificial intelligence techniques and their hybrid methods. For the above analysis some landmark problems are solved using the hybrid methods. Namdev et al. [119] have presented the comprehensive discussion on the design and developments of hybrid artificial intelligence techniques. Rajeswari and Prasad [120] have presented the combinations of the knowledge based systems. They also described the merits and demerits of hybridizing two intelligent methods. Amelia et al. [121] have proposed the hybrid methods using two AI methods for solving the production of crude palm oil problem and discussed the merits and demerits of it. Chen et al. [122] have discussed several Knowledge-based techniques and their hybrid methods in their work.

2.6.1 Automatic design of fuzzy MF using GA for damage detection

Srinivasan et al. [123] have proposed the development of an intelligent technique based on fusion of two expert intelligence techniques. The combination is designed by the combination of fuzzy logic and genetic algorithms. The hybrid method is so designed that it helps exploiting the strength of each method. This method is then applied for the detection of faults in power distribution networks. Aydin et al. [124] have developed an artificial immune inspired algorithm in combination with fuzzy clustering. The artificial immune algorithm used here is the negative selection algorithm. The inputs for the negative selection algorithm are generated by genetic algorithm. The proposed method is applied for fault detection in rotor bar and connectors in induction motors. Kavitha and Kumari [125] have modelled a fuzzy rule based system. The method described in this problem emphasizes on the optimization of the fuzzy membership functions using particle swarm optimization algorithm. The algorithm is designed to be applied for intrusion detection in the networks. Abadeh et al. [126] have developed a novel method for detecting intrusion in a computer network. The hybrid method proposes the combination of genetic fuzzy techniques for the optimisation of the fuzzy parameters. The outcomes from the genetic fuzzy system are compared with the results from neural fuzzy systems. Mohammadian et al. [127] have developed a fuzzy logic controller where the membership function is tuned and optimized using genetic algorithm. The proposed method is used for solving truck back-upper Problem. Konak et al. [128] have proposed a tutorial and overview on genetic algorithms. The proposed method differs largely from the conventional genetic algorithms. This improved method can be applied for solving many complex engineering optimization problems. Pawar and Ganguli [129] have designed an inverse method for damage detection. The inputs to the genetic- fuzzy systems are the natural frequencies which are extracted from the finite element method. The genetic-fuzzy systems are used for the automatic generation of the rules and are proved as a robust tool for online fault detection. Shu and Ding [130] have described a hybrid method for deriving the fuzzy sets. In this work the immune based clonal selection algorithm and genetic algorithm has been combined for a given transactions. This combination is performed to get a balanced result between the global search and local search. This method is applied to solve data mining problems. Shankar et al. [131] have presented a novel method where a fitness function is used to optimize the nonlinear fuzzy constraints and fuzzy coefficients applying genetic algorithm. The optimization process does not need any mathematical modelling of the fuzzy nonlinear programming. The hybridized algorithm emerged as a global tool for solving any type of real world problems. Ansari and Alam [132] have used fuzzy logic due to the fact that it behaves like human decision making system but sometimes this fact generates errors in calculations. So for the design of the optimal fuzzy knowledge based system distribution of the membership functions are required. In this work the optimization method is done by the genetic algorithm. This method is applied to guidance and control law for four stage launch vehicle. Deshkar et al. [133] have proposed a method for the for fuzzy membership function shape optimization using genetic algorithm. Different special type of special mutation operation and the fitness function for genetic algorithm design. The proposed algorithm is used to optimize the missile acceleration and proportional navigation guidance law.

2.6.2 Automatic Tuning of Fuzzy Rules Base System using Genetic Algorithm

Al-Shammaa and Abbod [134] have proposed automatic generation for fuzzy classification. The fuzzy rules of the FIS structure are generated using genetic algorithm. The objective function searches for the fittest fuzzy rule. The fuzzy classification is done by fuzzy c-means clustering with various cluster numbers. From the results it is observed better accuracy and a well compromised sensitivity and specificity. Kilic and Casillas

[135] have discussed the design of the three staged hybrid genetic-fuzzy method to find out the hidden fuzzy if-then rules. The work also tries to cover up the knowledge gap present in the literature using the genetic-fuzzy methods. Rabelo et al. [136] have proposed a Mamdani fuzzy inference system whose parameters are optimized by using genetic algorithm then it is implemented for solving hydrothermal systems. Different simulation results are provided to validate the results. Mankad and Sajja [137] have discussed the different aspects of hybridization of fuzzy logic system which deals with the uncertainty and the genetic algorithm based on the natural evolution to make a robust search method. Aydogan et al. [138] have designed a hybrid genetic algorithm using integer-programming formulation. The hybrid algorithm is used to solve classification problems and to produce number of rules for the fuzzy classification methods. Leal and Rabelo [139] have proposed a genetic –fuzzy method for the improvement of the performance of the Mamdani’s fuzzy inference system. This method is applied to determine the sink node and number of hops in a wireless sensor networks problem. Celikyilmaz and Turksen [140] have proposed a hybrid method using fuzzy clustering and evolutionary methods. In the improved fuzzy clustering method the membership values are improved using the evolutionary algorithm operators. Chen et al. [141] have designed a hybrid system using genetic fuzzy system. The hybrid system is applied in receiver operating characteristic curve and the area under the ROC curve for machine learning algorithms. Zhang and Wang [142] have addressed a hybrid method for automatic generation of the fuzzy rules using genetic algorithm. The algorithm exploits the population of fuzzy rules and the crossover and mutation rate to automatically adjust the fuzzy rule parameters for self generation of the new set of fuzzy rules. Ting et al. [143] have proposed a hybrid intelligent method using Fuzzy Reasoning and Petri nets technique. The performance of the inference system has been increased by using a two-level fuzzy rule decision tree integrated with Petri nets technique. The justification of the design of the proposed technique has been proved from the results. Jalali et al. [144] have addressed a fuzzy genetic algorithm to solve combinatorial optimization problem. The fuzzy inference system approached here the performance of the selection of the crossover operator and its probability value is controlled by the set of fuzzy rules determined from the Fuzzy Logic System.

2.6.3 Fuzzified DEA for damage detection

Seyedpoor and Yazdanpanah [145] have described a structural health monitoring method for the damage assessment. First of all the damage detection is converted to an optimization problem using the inverse method and then the architecture of the differential evolution algorithm is designed. From the results it could be observed that the differential evolution algorithm is more efficient in obtaining the global optimization. Villalba-Morales and Laier [146] have proposed a damage detection method using a metaheuristic method applying adaptive differential evolution algorithm. The fitness function for the evolutionary algorithm has been designed considering the dynamic responses from the cracked structural element. Li and Yin [147] have addressed a population based differential evolution algorithm for solving multidimensional global optimization problems. The proposed algorithm is used to find parameters like the polarization angle, the electrical dipole moment, the regional coefficients, the distance from the origin and depth of the source from quantitative interpretation of self-potential data in geophysics. Yu et al. [148] have proposed a hybrid differential evolution algorithm for fault detection. The damage indices are extracted using augmented analytical redundancy relations and to identify the damage. Once the dynamic parameters are obtained an empirical method applying multiple hybrid differential evolution algorithms is designed for the treatment of the dynamic parameters. The results are then compared with the simulation results. Cuevas et al. [149] have introduced a method for circle diagnosis in computer vision algorithms. In this work the objective function tries to find out the individuals with circles. Then the results are contrasted with the outcomes of the tests and are promising. Parvaresh et al. [150] have designed and developed a new fault detection method to solve the HVAC system (Heating, Ventilating, and Air Conditioning system) with refrigerant leakage for detection of fault. First a fuzzy classifier of Takagi-Sugeno type is used to extract the fault indices then they are treated in the optimization problem using differential evolution algorithm. The simulations are made using MATLAB-Simulink for the validation of the results.

2.6.4 Hybrid CSA-FLS for damage detection

Following are some of the literatures on hybrid methods of hybridization of clonal selection algorithm and fuzzy logic system. Almost no publication on application of CSA-FLS till date is present.

Kamalloo and Abadeh [151] proposed a fuzzy classification method combined with artificial immune system and the new combination is named as fuzzy artificial immune system. The authors have designed two types of memory cell: k-layer memory and simple memory. From the results it is observed that with the definition of new memory cells the rule extraction from the fuzzy classifiers become easier and simpler. This method has been successfully applied banks and financial institutes for the evaluation of credit risks. Jiao et al. [152] have approached a damage identification method in bridges. A polynomial fitting method is applied to evaluate the modal curvature of the damaged and undamaged structure. Then the difference between the undamaged and damaged modal curvature is trained in the fuzzy logic system for localization of the damage. Andhale and Wankhade [153] have presented a non destructive testing method for fault detection. The damage indices are extracted using curve fitting in Matlab which are then treated in the fuzzy logic for crack localization. For this the Euler's beam is taken. Wang et al. [154] have hybrid optimisation algorithm for Fisher Iris data classification. The hybrid technique is designed by the fusion of clonal selection algorithm and harmony search technique. The results from the optimisation algorithm are further trained in the Sugeno fuzzy classification systems which show the effectiveness of the proposed method. Chan et al. [155] have described an Artificial Immune System based classification method. Here Clonal Selection Algorithm has been approached for the classification method. This technique is then applied to network intrusion detection system. The results from the hybrid method applied for solving the same problem like Random Tree, Support Vector Machine and Naive Bayes methods. Chernov et al. [156] have presented artificial intelligence model for fault monitoring. The fuzzy dynamical systems consisting of fuzzy classifiers are combined with the artificial immune system for automatic generation of rules. The mathematical model with the details of process of formulation is described in this paper. Zhao et al. [157] have suggested a combinatorial method for web services according to their Quality of Service. The method is proposed using fusion of a population based artificial immune system with elitist learning mechanism of particle swarm optimization algorithm. From the results it could be visualized that the proposed method outperforms the second hybrid method. Zhang et al. [158] have proposed the concept of hesitant fuzzy sets and its mathematical description is supplied in the paper. The hesitant fuzzy sets are the extension of the fuzzy sets. This method is applied to the decision making problem.

2.6.5 Hybrid CSA-GA for damage detection

Liu et al. [159] have presented a multi agent immune clonal selection algorithm applied in the field of multicast routing to avoid the premature convergence of clonal selection algorithm and the results are compared with that of the traditional genetic algorithm. Chittineni [160] has developed a clonal selection algorithm to improve the innate and adaptive properties by combining it with shuffle frog leaping algorithm to make it fast and improved method and has shown some of the experimental results. Murugesan and Sivasakthi [161] have developed an improved and modified clonal selection algorithm. The algorithm is then applied in the field of job scheduling to get better results. For the enhancement of the performance of the clonal selection algorithm the initialization process of the algorithm is improved by using positive selection method. The results exhibit superiority and the flexibility of application of the new improved clonal selection algorithm. Kumar and Jyotishree [162] have introduced an improved genetic algorithm for solving any type of real world optimization problem. The authors have proposed a new representative scheme for genetic algorithm. Marinakis et al. [163] have used nature inspired algorithm for successfully solving the Vehicle Routing Problem with Stochastic Demands. The hybrid method is designed by incorporating variable neighborhood search and iterated local search algorithm. The results from the proposed algorithm are compared with several evolutionary algorithms like a differential evolution algorithm, two versions of the particle swarm optimization algorithm and a genetic algorithm. Lin et al. [164] have proposed a strategy where different modifications are done to ant colony optimization algorithm and cloud computing which is then combined with clonal selection algorithm to reach at the global optimum solution. For this to achieve the convergence speed of the clonal selection algorithm a different strategy is introduced to iterations of ant colony and the use of reverse mutation strategy in ant colony optimization is exploited. Nguyen et al. [165] have suggested a new structure for artificial neural network using Clonal Selection Algorithm. The authors introduced some special concepts, which are available in biology to make the model understandable. The detectors are derived from the artificial neural network and then clonal selection algorithm is used for finding the best artificial neural network's structure and weights. Guan et al. [166] have recommended an improved clonal selection algorithm to overcome the short comings of the standard clonal selection algorithm. For this purpose first the crossover and mutation is performed with the antibodies then hyper mutation is performed to increase the diversity in the population of the antibodies. This algorithm is applied to entropy image segmentation problem and the results are validated using images of Lena and Camera from the image library.

2.6.6 Hybrid CSA-DEA for damage detection

Xu and Zhang [167] have studied in detail various self adaptive methods present for solving the real world problems. The narration contains self-adaptive learning based particle swarm optimization; self-adaptive learning based immune algorithm and self-adaptive differential evolution algorithm. In this paper a self-adaptive evolutionary algorithm has been proposed. Chen et al. [168] have proposed a different coding method for differential evolution algorithm due to the difficulty faced during the design of the real-coded differential evolution algorithms. The global convergence of the new differential evolution algorithm is theoretically developed and is compared the results with the existing evolutionary algorithms using binary encoding. Ali [169] has proposed a hybrid evolutionary algorithm for a constrained real world problem. The frame work of the hybrid evolutionary algorithm has been designed using differential evolution algorithm and genetic algorithm. The global search capacity of differential evolution algorithm is enhanced by the integration of linear crossover of genetics with differential evolution algorithm which can increase the searching capacity of the hybrid algorithm. Wang et al. [170] have introduced a new hybrid differential evolution algorithm for grinding-classification problem. The hybrid differential evolution algorithm based on multi-population algorithm. The addressed algorithm is applied to solve a multi objective optimization problem. Yu et al. [171] have proposed a hybrid differential evolution algorithm for identification of the fault pattern vector. The proposed hybrid method is capable of identification and localization of the multiple damages. Several experimental and simulation results are presented for the validation of the proposed method. Cisar et al. [172] have recommended an artificial immune based algorithm for solving the travel-salesman problem using the presented algorithm. To improve the performance of the algorithm several strategies are applied which are different from standard artificial immune based algorithm. Zeng et al. [173] have presented an approach to handle the drawbacks of one of the artificial immune based algorithm known as negative selection algorithm. The improved algorithm is used to solve anomaly detection problems.

2.7 Knowledge gap found from the literature review

The vast literatures available on different aspects of the vibration analysis of the damaged structure have been studied in detail in the current chapter. From the literature survey it has been observed that, lots of work has been done using conventional and traditional methods consisting of different calculus methods to find the direct solutions. Various researchers have described several vibration based methods which are necessary to understand the dynamics of the cracked structures which can be used for damage identification more efficiently but this cannot be used for the location of the damage. So the damage detection methods using vibration based methods desperately need some aiding techniques for the localization of the cracks and the prediction of rest of the working life of the structures. Artificial Intelligence techniques have been proved to be very efficient and precise method which can be used as a powerful device for online damage detection. Though not exact but artificial intelligence techniques are capable of producing very near exact locations of the crack which is enough to ring an alarm of a serious catastrophic failure. The artificial intelligence techniques are difficult to choose and they have some drawbacks as no method is perfect. Due to the above stated reasons and the competition to find a better result, the researchers are combining the artificial intelligence techniques to be applied in different fields of research. It has also been proved by different researchers that the hybrid intelligent methods perform better than the standalone methods. Most of the hybrid intelligent methods narrated in this work have not been designed and developed to be applied. Less work has been done on the hybridization of the different population based algorithms. Though several researches have been done based on the hybrid methods for damage detection and location but those are very minor as compared to the other fields of engineering. Some of the hybrid algorithms described in this work is purely new with respect to its development and application.

In this work various methods used are approached and has been formulated systematically for the problem definition to arrive at the required solution. The work contributes towards the identification and location of the damage but it does not predict the rest of the life of the structural element. In this work, all the aspects of the damage detection using vibration parameters have been covered. Using the Theoretical and Finite Element analyses, a single transverse crack has been modeled to extract the vibration parameters using different theories. Then different artificial intelligence techniques and their hybrid methods are designed and developed, keeping in mind the problem definition and the variables related to the problem. These methods are used to locate the crack in a structural element like beam. Finally the test is performed to validate the results from the various methods.

Chapter 3

Dynamic Analysis of structural elements with a transverse hairline crack

Most structural and machine members of engineering applications are subjected to different loads during various operations. The presence of crack changes the nearby stiffness. The change in the local stiffness depends on location and depth of the cracks. Deviations in the dynamic responses of the structural elements have been widely used for the damage assessment. The changes in the physical properties can be used for monitoring safety, performance and structural integrity. This chapter focuses on the theoretical analysis of the vibration characteristics of a beam like structural element.

3.1 Introduction

Most of the studies are made assuming the crack to be open and it remains open during the vibration. But these assumptions are not always correct when the loading in the dynamic condition becomes dominant. During this period, the crack breathes regularly, due to which the structural stiffness changes. The variations in the stiffness induce nonlinearity to the vibration problems. This occurs due to the action of higher harmonic components. The natural frequencies of a breathing crack vary between those of a beam without crack and beam with an open crack. Due to the above stated reasons, the considered work is limited to open crack which makes the problem simpler.

This section of the chapter describes the modeling of a transverse hairline crack. Theoretical analysis of the crack is performed using the strain energy principle at the cracked part of the beam for two end conditions (fixed-free, fixed- fixed). For the two different end conditions, the boundary conditions are different. Applying different boundary conditions the natural frequencies for the two end conditions are determined.

3.2 Evaluation of the Dynamic Responses of a cracked beam from the Strain Energy Release Rate

Figure 3.1 describes the geometry and the loading conditions of the cracked beam. Here 'B' and 'W' represent the breadth and height of the beam respectively. The depth of crack and the crack location for a single crack are given by 'a_1' and 'L_1' respectively and 'L' is the total length of the beam. The crack increases the value of the local flexibility. The change in the local flexibility can be obtained in the matrix form. The beam element is subjected to an axial force (P_1) and bending moment (P_2).

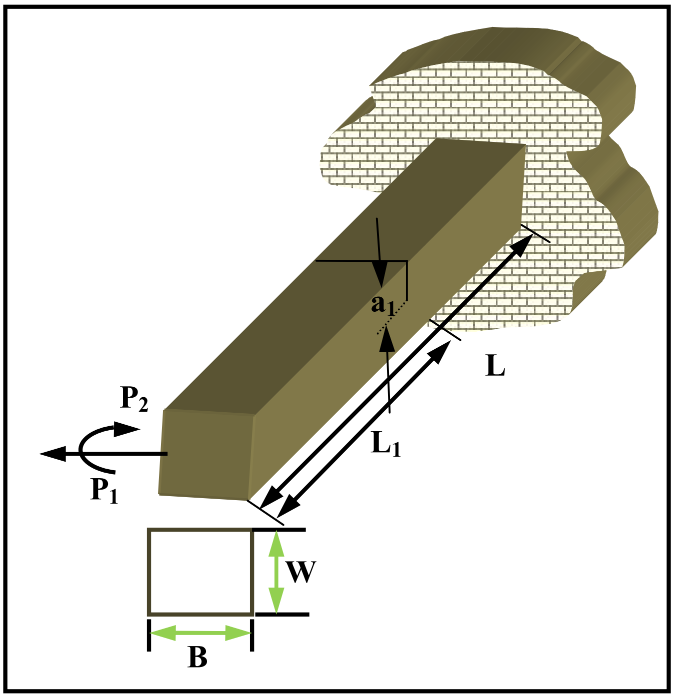


Figure 3.1: Figure of the cracked cantilever beam with the damage parameters

Due to the formation of the crack, some energy is released at the cracked section. This is known as strain energy and it is a type of potential energy. As per [174], the energy release rate due to the strain at the cracked section is given below.

$$S_R = \frac{1}{E'}(K_{11}+K_{12})^2 \text{ where } \frac{1}{E'} = \frac{1-\gamma^2}{E} \text{(plane strain)} \tag{3.1a}$$

$$= \frac{1}{E} \text{(plane stress)} \tag{3.1b}$$

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 are;

$$K_{11}=\frac{P_1}{BW}\sqrt{\pi a}(F_1(\frac{a}{W})) \tag{3.2}$$

$$K_{12}=\frac{6P_2}{BW^2}\sqrt{\pi a}(F_2(\frac{a}{W})) \tag{3.3}$$

Where expressions for F1 and F2 are as follows

$$F_1(\frac{a}{W})=(\frac{2W}{\pi a}\tan(\frac{\pi a}{2W}))^{0.5}\left\{\frac{0.752+2.02(\frac{a}{W})+0.37(1-\sin(\frac{\pi a}{2W}))^3}{\cos(\frac{\pi a}{2W})}\right\} \tag{3.4}$$

$$F_2(\frac{a}{W})=(\frac{2W}{\pi a}\tan(\frac{\pi a}{2W}))^{0.5}\left\{\frac{0.923+0.199(1-\sin(\frac{\pi a}{2W}))^4}{\cos(\frac{\pi a}{2W})}\right\} \tag{3.5}$$

Due to the initiation of the crack, strain energy is released. The strain energy released is defined as 'S_E'. Then by Applying Castiglione's theorem, the additional displacement along the force P_i can be evaluated as:

$$q_i=\frac{\partial S_E}{\partial P_i} \tag{3.6}$$

The strain energy will have the form $S_E=\int_0^{a_1}\frac{\partial S_E}{\partial a}da=\int_0^{a_1}S_R da$ (3.7)

Where, $S_R=\frac{\partial S_E}{\partial a}$ is defined as the strain energy density function.

From (3.6) and (3.7), the additional displacement can be defined as:

$$q_i=\frac{\partial}{\partial P_i}\left[\int_0^{a_1}S_R(a)da\right] \tag{3.8}$$

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

$$C_{ij}=\frac{\partial q_i}{\partial P_j}=\frac{\partial^2}{\partial P_i\partial P_j}\int_0^{a_1}S_R(a)da \tag{3.9}$$

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

$$C_{ij}=\frac{\partial q_i}{\partial P_j}=\frac{\partial^2}{\partial P_i\partial P_j}\int_{-B/2}^{+B/2}\int_0^{a_1}S_R(a)dadz \tag{3.10}$$

Putting the value strain energy release rate from above, equation (3.10) can be modified as;

$$C_{ij}=\frac{B}{E'}\frac{\partial^2}{\partial P_i\partial P_j}\int_0^{a_1}(K_{11}+K_{12})^2da \tag{3.11}$$

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

Applying the above condition equation (3.11) converts to,

$$C_{ij}=\frac{BW}{E'}\frac{\partial^2}{\partial P_i \partial P_j}\int_0^{\xi_1}(K_{11}+K_{12})^2 d\xi \tag{3.12}$$

$$C_{11}=\frac{BW}{E'}\int_0^{\xi_1}\frac{\pi a}{B^2W^2}(F_1(\xi_1))^2 d\xi=\frac{2\pi}{E'}\int_0^{\xi_1}\xi(F_1(\xi))^2 d\xi \tag{3.13}$$

$$C_{12}=C_{21}=\frac{12\pi}{E'BW}\int_0^{\xi_1}\xi F_1(\xi)F_2(\xi)d\xi \tag{3.14}$$

$$C_{22}=\frac{72\pi}{E'BW}\int_0^{\xi_1}\xi F_1(\xi)F_2(\xi)d\xi \tag{3.15}$$

Converting the influence co-efficient into dimensionless form

$$\overline{C_{11}}=C_{11}\frac{E'B}{2\pi},\overline{C_{12}}=C_{12}\frac{E'BW}{12\pi}=\overline{C_{21}},\overline{C_{22}}=C_{22}\frac{E'BW^2}{72\pi} \tag{3.16}$$

The local stiffness matrix can be obtained by taking the inversion of compliance matrix. The stiffness matrix is based on the compliance matrix calculation and is expressed by

$$S=\begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix}=\begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix}^{-1} \tag{3.17}$$

3.2.1 Analysis of vibration responses of the beam element with a single transverse crack

$U_1(x, t)$ and $U_2(x, t)$ are considered as the amplitudes of longitudinal vibration for the sections before and after the hairline crack and $Y_1(x, t)$, $Y_2(x, t)$ are taken as the amplitudes of bending vibration for the same sections (shown in Figure 3.2).

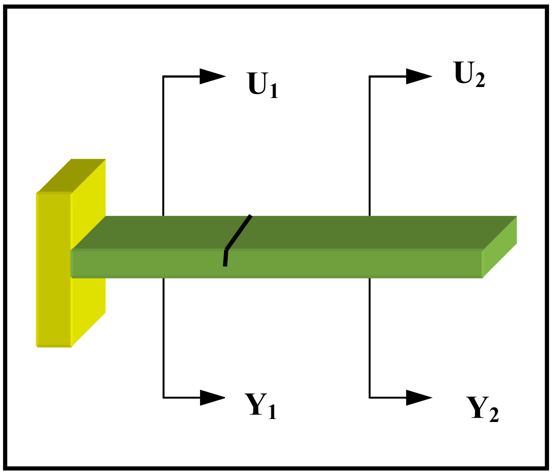


Figure 3.2: Amplitudes of longitudinal and bending vibration

The normal functions for the system can be defined as

$$\overline{U_1}(\overline{x})=A_1\cos(\overline{K_u x})+A_2\sin(\overline{K_u x}) \tag{3.18a}$$

$$\overline{U_2}(\overline{x})=A_3\cos(\overline{K_u x})+A_4\sin(\overline{K_u x}) \tag{3.18b}$$

$$\overline{Y_1}(\overline{x})=A_5\cosh(\overline{K_y x})+A_6\sinh(\overline{K_y x})+A_7\cos(\overline{K_y x})+A_8\sin(\overline{K_y x}) \tag{3.18c}$$

$$\overline{Y_2}(\overline{x})=A_9\cosh(\overline{K_y x})+A_{10}\sinh(\overline{K_y x})+A_{11}\cos(\overline{K_y x})+A_{12}\sin(\overline{K_y x}) \tag{3.18d}$$

Where $\overline{x}=\frac{x}{L},\overline{U}=\frac{u}{L},\overline{Y}=\frac{y}{L},\beta=\frac{L_1}{L}$ (3.19)

$$\overline{K_u}=\frac{\omega L}{C_u},C_u=(\frac{E}{\rho})^{1/2},\overline{K_u}=(\frac{\omega L^2}{C_y})^{1/2},C_y=(\frac{EI}{\mu})^{1/2},\mu=A\rho \tag{3.20}$$

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

$$\overline{U_1}(0)=0;\overline{Y_1}(0)=0,\overline{Y_1}'(0)=0;\overline{U_2}'(0)=(0);\overline{Y_2}''(1)=0;\overline{Y_2}'''(1)=0 \tag{3.21}$$

At the fixed end:

$$\overline{U_1}(\beta)=\overline{u_2}(\beta);\overline{Y_1}(\beta)=\overline{Y_2}(\beta);\overline{Y_1}''(\beta)=\overline{Y_2}''(\beta);\overline{Y_1}'''(\beta)=\overline{Y_2}'''(\beta) \tag{3.22}$$

Also at the free end we have:

$$AE\frac{dU_1(L_1)}{dx}=K_{11}(U_2(L_1)-U_1(L_1))+K_{12}(\frac{dY_2(L_1)}{dx}-\frac{dY_1(L_1)}{dx}) \tag{3.23}$$

Both sides of the above mathematical statement are multiplied by $\frac{AE}{LK_{21}K_{22}}$ to get;

$$M_1M_2\overline{U}'(\beta)=M_2(\overline{U_2}(\beta)-\overline{U_1}(\beta))+M_1(\overline{Y_2}'(\beta)-\overline{Y_1}'(\beta)) \tag{3.24}$$

Similarly, $$EI\frac{d^2Y_1(L_1)}{dx^2}=K_{21}(U_2(L_1)-U_1(L_1))+K_{22}(\frac{dY_2(L_1)}{dx}-\frac{dY_1(L_1)}{dx}) \quad (3.25)$$

Both sides of the above mathematical statement are multiplied by $\frac{EI}{LK_{21}K_{22}}$

$$M_3M_4\overline{Y_1}''(\beta)=M_3(\overline{U_2}(\beta)-\overline{U_1}(\beta))+M_4(\overline{Y_2}'(\beta)-\overline{Y_1}'(\beta)) \quad (3.26)$$

Where, $$M_1=\frac{AE}{LK_{11}},M_2=\frac{AE}{K_{12}},M_3=\frac{EI}{LK_{22}},M_4=\frac{EI}{L^2K_{21}} \quad (3.27)$$

3.2.2 Analysis Dynamic Responses of cracked fixed-fixed beam

All the assumed conditions for the fixed-fixed beam will remain the same, only the boundary conditions will be changed. The diagram of the fixed-fixed beam with the geometry of the crack is shown in Figure 3.3.

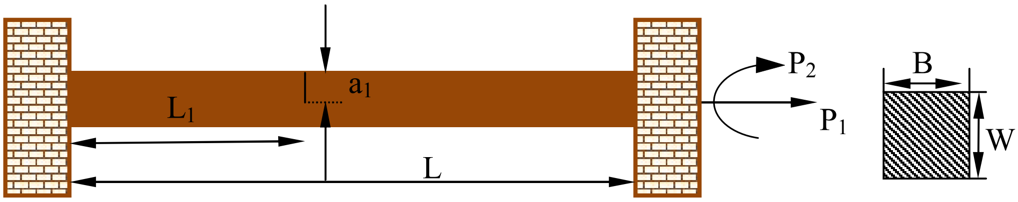


Figure 3.3: Geometry of the cracked fixed-fixed beam

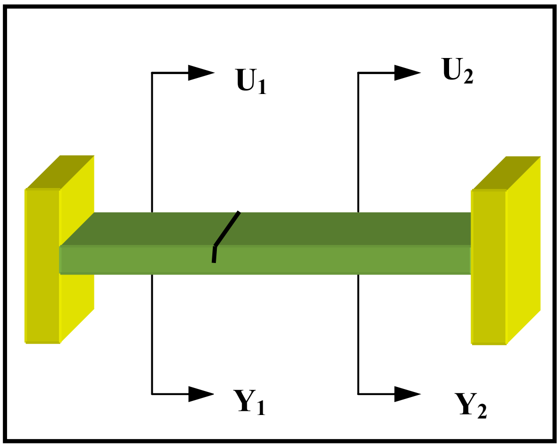


Figure 3.4: Amplitudes of longitudinal and bending vibration in a fixed-fixed beam

Boundary conditions for the fixed-fixed beam are:

$$\overline{U_1}(\beta)=\overline{U_2}(\beta);\overline{Y_1}(\beta)=\overline{Y_2}(\beta);\overline{Y_1}''(\beta)=\overline{Y_2}''(\beta);\overline{Y_1}'''(\beta)=\overline{Y_2}'''(\beta) \quad (3.28)$$

$$\overline{U_1}(0)=0;\overline{Y_1}(0)=0,\overline{Y_1}'(0)=0;\overline{U_2}'(0)=(0);\overline{Y_2}''(1)=0;\overline{Y_2}'''(1)=0 \quad (3.29)$$

$$\overline{U_1}(l)=0;\overline{Y_1}(l)=0,\overline{Y_1}'(l)=0;\overline{U_2}'(l)=(0) \quad (3.30)$$

Application of the boundary conditions to the normal functions and equations, gives the characteristic equation of the system as:

$$|Q| = 0 \quad (3.31)$$

The above described expression is a function of the relative location of the crack (β) and the local stiffness matrix (S) which in turn is a function of the relative crack depth (a1/W) and the natural circular frequency (ω).

Table 3.1: Natural frequencies of cantilever beam and fixed-fixed beam for similar crack depths and crack locations

Sl. No	cd in mm	cl in mm	fnf of (cantilever beam)	snf of (cantilever beam)	tnf of (cantilever beam)	fnf of (fixed- fixed beam)	snf of (fixed-fixed beam)	tnf of (fixed-fixed beam)
1	2.1	125	10.479	65.9494	183.663	67.2448	184.9331	363.136
2	1.9	145	10.4939	65.7864	183.92	67.2909	185.052	363.341
3	1.5	165	10.5059	65.7636	184.078	67.2785	185.016	363.354
4	1.8	175	10.5005	35.665	183.984	67.2816	185.035	363.328
5	1.3	220	10.5274	65.797	184.451	67.3124	185.118	363.492
6	1.1	235	10.5222	65.7734	184.363	67.2728	185.013	363.281
7	1.25	255	10.5258	65.792	184.421	67.2832	185.036	363.338

3.3 Comparison of the results from Theoretical evaluation with Experimental results

For the validation of the theoretical results, experimental analysis is necessary. In this research work two end conditions (fixed-free and fixed-fixed) of the beam are addressed. To get the experimental results for the two end conditions, two experimental set-ups are developed. These experimental set-ups are described in detail in Appendix 1. In the current research an aluminum alloy beam having dimension (8 x 38 x 800 mm^3) has been used to conduct the experiment with two different end conditions. A number of experiments have been carried out using different crack configurations. The experiment is conducted for both cracked and uncracked beams. Figures 3.5(a) and 3.5(b) show the schematic block diagram of the fixed-free and fixed-fixed beam respectively.

The results of the Theoretical and Experimental inspections are compared in Tables 3.2 and 3.3. Several tests are conducted and the first three natural frequencies for each test are recorded. Further the results of these tests are used to make a data base or data pool. This data base is used in later chapters. The Experimental, Theoretical and Finite Element analyses are used as the direct methods of getting the vibration signatures. By giving the geometrical parameters of the crack, the natural frequencies are obtained. These natural frequencies are then treated in different AI based techniques. These proposed methods represent the inverse method for obtaining the crack location which is the main objective of the research work.

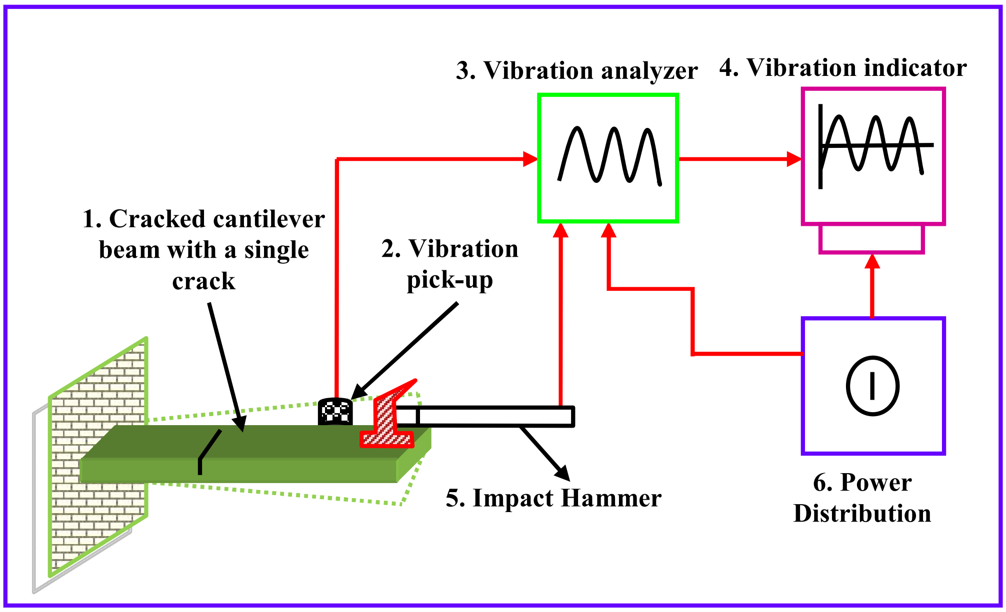


Figure 3.5(a): Pictorial presentation of experimental set up for cantilever beam

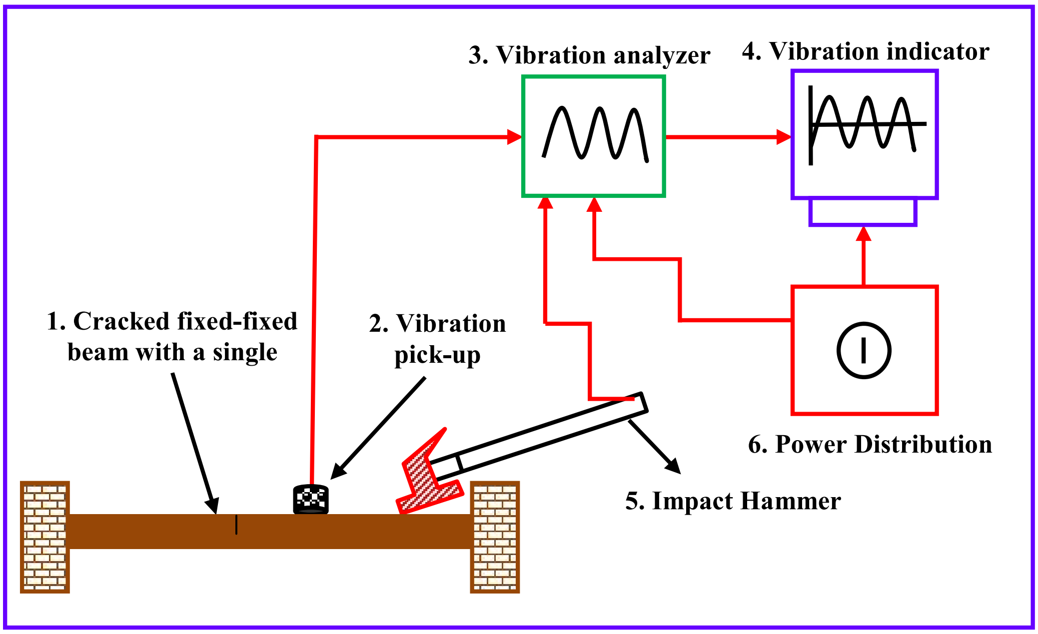


Figure 3.5(b): Pictorial presentation of experimental set up for fixed-fixed beam

Table 3.2: Comparison of the results of experimental analysis and theoretical analysis for cantilever beam

Sl. No	crack depth (relative)	crack location (relative)	Relative natural frequencies from experimental study			Relative natural frequencies from theoretical analysis			Average error in %
			rfnf	rsnf	rtnf	rfnf	rsnf	rtnf	
1	0.3125	0.4375	0.9987	0.9974	0.9938	0.9786	0.9573	0.9739	2.00
2	0.34375	0.46875	0.9995	0.9973	0.9914	0.9794	0.95726	0.9715	2.00
3	0.375	0.5	0.9999	0.9974	0.989	0.9798	0.95752	0.9692	1.99
4	0.1875	0.53125	0.9998	0.9996	0.9977	0.9797	0.95968	0.9777	2.00
5	0.35	0.1875	0.9981	0.9892	0.9996	0.9780	0.94908	0.9795	2.00
6	0.2	0.25625	0.9977	0.9999	0.9982	0.9777	0.95986	0.9782	2.00
7	0.2125	0.26875	0.9979	0.9988	0.9981	0.9779	0.959	0.9781	1.99
8	0.2625	0.275	0.9979	0.9972	0.9977	0.9779	0.95704	0.9777	2.00
9	0.3125	0.29375	0.9945	0.9939	0.9976	0.974	0.95382	0.9776	2.00
10	0.225	0.33125	0.9977	0.9999	0.9982	0.9777	0.95984	0.9782	2.00
Total average error in %									1.99

Table 3.3: Comparison of the results of experimental study and theoretical analysis for fixed-fixed beam

Sl. No	crack depth (relative)	crack location (relative)	Relative natural frequencies from experimental study			Relative natural frequencies from theoretical analysis			Average error in %
			rfnf	rsnf	rtnf	rfnf	rsnf	rtnf	
1	0.15625	0.2625	0.9961	0.9995	0.9981	0.9761	0.9594	0.9781	2.00
2	0.18125	0.2375	0.9957	0.9987	0.9999	0.9757	0.9586	0.9798	2.00
3	0.20625	0.1875	0.9956	0.9985	0.9992	0.9756	0.9586	0.9792	1.99
4	0.21875	0.225	0.995	0.9985	0.9988	0.9750	0.9584	0.9788	2.00
5	0.275	0.1625	0.9954	0.999	0.9993	0.9754	0.9588	0.9793	2.00
6	0.4	0.25	0.9211	0.9219	0.9218	0.9026	0.8818	0.9033	2.00
7	0.367	0.3125	0.9463	0.9460	0.9458	0.9274	0.9061	0.9269	1.99
8	0.2833	0.375	0.9552	0.9551	0.9549	0.9361	0.9150	0.9357	2.00
9	0.25	0.4375	0.9621	0.9618	0.9616	0.9428	0.9217	0.9423	2.00
10	0.2166	0.5	0.9705	0.9703	0.9700	0.9510	0.9304	0.9505	1.99
Total average error in %									1.99

The errors are determined from the comparison of the results of theoretical analysis and experimental analysis. These errors are calculated by using the formulae as given below.

$$\text{Average error in } \% = \frac{\%\text{ error in rfnf} + \%\text{ error in rsnf} + \%\text{ error in rtnf}}{3} \tag{3.32}$$

$$\text{Total average error in } \%= \frac{\text{average error in } \%}{10} \tag{3.33}$$

3.4 Results and Discussion

Every mechanical system needs a mathematical modeling to understand the dynamics of the system. In this problem, the system comprises of cracked beam with a transverse hairline crack. To make the modeling simple, it is assumed that the crack is open and not a breathing crack and the free vibration analysis of the beam are considered. The effect of loading can only be considered in open condition because in close condition the beam may resume the faultless shape. Due to the inception of the crack in a healthy structure there may be dissipation of energy in the form of strain energy.

In this chapter, the strain energy release rate and the Castiglione's theorem are used to find the flexibility influence coefficient. Then the flexibility influence coefficient is used to derive the stiffness matrix. Applying the boundary conditions and solving the determinant given in equation 3.31, the natural frequencies are determined. The first three natural frequencies from of the cantilever and fixed-fixed beams for the similar crack depths and crack locations are provided in Table 3.1. Figure 3.1gives the detail of the crack geometry and Figure 3.2 gives amplitudes of longitudinal and bending vibration for the left and right side of the crack for a cantilever beam. The results from the dynamic analysis of the cracked beam are compared with the results of the experimental analysis for the same crack configuration and the results are given in Tables 3.2 and 3.3. The schematic diagrams of the experimental set-ups are shown in Figures 3.5(a) and 3.5(b). The details of the experimental analysis are described in Appendix 1. From the results, it can be seen that the results of both the analyses are in close agreement with each other and the change in the crack location changes the modal parameters.

3.5 Summary

The dynamic reactions are a standout amongst the most critical variables which should be considered during design of mechanical systems. It is important on the part of the designer to ensure the natural frequency of the system should not match with the excitation frequency. But sometimes due to the loss of integrity, the natural frequencies are changed, which may play an important role in structural failure.

This chapter presents the analysis of dynamics of cracked beam considering two end conditions. From the above analysis it can be observed that while keeping the crack location constant, when the crack depths are increased, the natural frequency of the cracked beam decreases and the reverse result is obtained for crack location. So in this chapter various crack locations and crack depths are taken to notice the change in the first three natural frequencies. The outcomes are contrasted with the outcomes from the theoretical analysis are used to design and develop inverse methods using different AI techniques and hybrid AI techniques. When the results from the dynamic analysis of the cracked beam are compared with the results from the tests, the average percent error was found to be within 2% both for cantilever and fixed-fixed beam.

Chapter 4

Analysis of cracked Structural element using Finite Element Method

The structural elements under loading conditions are subjected to effects impacts that may start initiation of cracks, leading to a serious catastrophic failure. The structural defects change stiffness and damping properties. The crack induces structural flexibility which is a function of crack depth and crack location. The presence of the crack also affects the dynamical mechanical behavior of the structure to considerable amount. So to improve the safety and reliability, it is important to ensure integrity of the structures. It is well known that the change in flexibility changes the natural frequencies and mode shapes. These change in the dynamic responses of the structural elements. The vibration characteristics can be used for online detection of cracks. So the vibration based methods offer an effective, inexpensive and fast method for online health monitoring of structures. This chapter portrays the modular investigation approach utilizing Finite Element Analysis of the cracked structural element.

4.1 Introduction

To obtain the results by numerical simulation a mathematical model must be chosen. After proposing the mathematical model, it is also necessary to solve some higher mathematical model which may include more complex effect. In one dimensional Euler-Bernoulli or Timoshenko beam, the axial displacement is symmetrically located above and below the neutral axis and has the same magnitude with opposite signs. But in a beam having crack, it is difficult to predict the stress and displacement near the crack. So sometimes the existing models are not enough to find out the stress and displacement near the crack vicinity. For accurate modeling of crack, a 3-D finite element model can be proposed. Finite Element Analysis (FEA) was developed by Courant [175] in 1943 to minimize the vibrational calculus to obtain approximate solutions to vibration systems. This chapter is dedicated to the FEA, which has made calculations for complex engineering problems easier than ever. As known to all, modeling is a key activity in engineering analysis. The Finite Element Analysis (FEA) is a dominant numerical tool for fracture mechanics problems. So the FEA can be described as a discrete structure modeling method. This section continues to describe application of FEA in the field of damage detection. This chapter presents the vibrational responses of a beam with a transverse hairline crack. To treat the problem, a 3-D beam model with non propagating hairline crack is considered. The material of the beam is isotropic with linear elastic properties. The displacements are assumed to be small.

4.2 Finite Element Analysis approach for damage detection in cracked beam element

The Euler-Bernoulli [176] beam model is presumed for the finite element evaluation of the beam element with a crack. The crack in this specific case is thought to be an open crack and the damping is not considered in this hypothesis. The following assumptions are made for finite element analysis of the cracked beam.

a. The crack is open and it is not a breathing crack
b. The crack is uniform in propagation
c. There is no shear deformation and rotary inertia effects

The characteristic equation of the beam with a consistent rectangular cross section is given as:

$$[M]\ddot{x}+[C]\dot{x}+[S]x=F\sin(\omega t) \tag{4.1}$$

But it is assumed that there is no damping and there is no external force applied on the system. So the governing equation becomes

$$[M]\ddot{x}+[S]x=0 \tag{4.2}$$

The equation of motion for natural frequencies for undamped free vibration is given in equation (4.2). To solve equation (4.2) it is assumed that

$$\{x\}=\{\phi\}\sin\omega t \tag{4.3}$$

Where

ϕ - The Eigen vector or mode shape

ω - Circular natural frequency

Substituting the differential equation of assumed solution into the equation (4.2).

The equation of motion will be changed to

$$\omega^2[M]\{\phi\}\sin\omega t+[S]\{\phi\}\sin\omega t=0 \tag{4.4}$$

After simplification it becomes

$$([S]-\omega^2[M])\{\phi\}=0 \tag{4.5}$$

The equation is called as Eigen equation. The basic form of Eigen value problem is

$$[A\text{-}\lambda I]x=0 \tag{4.6}$$

A - Square matrix

λ -Eigen values

I - Identity matrix

x- Eigen vector

In structural analysis, Eigen equation is written in terms of S, M, and ω with $\omega^2=\lambda$.

There are two possible solutions for equation (4.5)

1. If $\left|([S]-\omega^2[M])\{\phi\}\right|\neq 0$ is a trivial solution where $\{\phi\}=0$ (4.7)
2. If $([S]-\omega^2[M])\{\phi\}=0$ is a non-trivial solution where $\{\phi\}\neq 0$

$$\left|([S]-\omega^2[M])\right|=0 \tag{4.8}$$

$$\left|([S]-\lambda[M])\right|=0 \tag{4.9}$$

The determinant is zero only at discrete Eigen values

$$\left|([S]-\omega^2[M])\right|\{\phi_i\}=0 \qquad i=1,2,3,.... \tag{4.10}$$

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:

$$[S^e]=\int[B(x)]^T EI[B(x)]dx \tag{4.11}$$

$$[B(x)]=\{H_1''(x)H_2''(x)H_3''(x)H_4''(x)\} \tag{4.12}$$

Where $H_1(x),H_2(x),H_3(x),H_4(x)$ are the Hermitian shape functions (interpolation function) and defined as

$$H_1(x)=1-\frac{3x^2}{l^2}+\frac{2x^3}{l^3} \tag{4.13a}$$

$$H_2(x)=x-\frac{2x^2}{l}+\frac{x^3}{l^2} \tag{4.13b}$$

$$H_3(x)=\frac{3x^2}{l^2}+\frac{2x^3}{l^3} \tag{4.13c}$$

$$H_4(x)=-\frac{2x^2}{l}+\frac{2x^3}{l^2} \tag{4.13d}$$

The beam rigidity EI is assumed to be constant and is given by EI_e within the element. The element stiffness in equation (4.5) is then described as

$$\left[S^e\right]=\frac{EI_e}{l^3}\begin{bmatrix} 12 & 6l & -12 & 6l \\ 6l & 4l^2 & -6l & 2l^2 \\ -12 & -6l & 12 & -6l \\ 6l & 2l^2 & -6l & 4l^2 \end{bmatrix} \tag{4.14}$$

$$\left[S_c^e\right]=\left[S^e\right]-\left[S_c\right] \tag{4.15}$$

Here,

$\left[S_c^e\right]$=stiffness of the beam element with a crack

$\left[S^e\right]$= stiffness of the whole beam element

$\left[S_c\right]$=reduction in stiffness due to the initiation of the crack in the beam element

As described by [177], the reduction in stiffness due to the initiation of the crack in the beam element $\left[S_c\right]$ is given as:

$$\left[S_c\right]=\begin{bmatrix} S_{11} & S_{12} & -S_{11} & S_{14} \\ S_{12} & S_{22} & -S_{12} & S_{24} \\ -S_{11} & -S_{12} & S_{11} & -S_{14} \\ S_{14} & S_{24} & -S_{14} & S_{44} \end{bmatrix} \tag{4.16}$$

Where,

$$S_{11}=\frac{12E(I_e-I_c)}{L^4}\left[\frac{2l_c^3}{L^2}+3l_c\left(\frac{2L_1}{L^2}-1\right)^2\right] \tag{4.17a}$$

$$S_{12}=\frac{12E(I_e-I_c)}{L^3}\left[\frac{l_c^3}{L^2}+l_c\left(2-\frac{7L_1}{L}+\frac{6L_1^2}{L^2}\right)\right] \tag{4.17b}$$

$$S_{14}=\frac{12E(I_e-I_c)}{L^3}\left[\frac{l_c^3}{L^2}+l_c\left(2-\frac{5L_1}{L}+\frac{6L_1^2}{L^2}\right)\right] \tag{4.17c}$$

$$S_{22}=\frac{12E(I_e-I_c)}{L^3}\left[\frac{3l_c^3}{L^2}+2l_c\left(\frac{3L_1}{L}-2\right)^2\right] \tag{4.17d}$$

$$S_{24}=\frac{12E(I_e-I_c)}{L^2}\left[\frac{3l_c^3}{L^2}+2l_c\left(2-\frac{9L_1}{L}+\frac{9L_1^2}{L^2}\right)\right] \tag{4.17e}$$

$$S_{44}=\frac{12E(I_e-I_c)}{L^2}\left[\frac{3l_c^3}{L^2}+2l_c\left(\frac{3L_1}{L}-1\right)\right] \qquad (4.18f)$$

Here,

$l_c=1.5W$

L=total length of the beam

L_1=distance of the crack from the left end

$I_e=\frac{BW^3}{12}$ =moment of inertia of the undamaged beam element

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

It is assumed that the presence of the crack does not affect the mass distribution of the beam. The uniform mass matrix for the beam element is described as:

$$\left[M^e\right]=\int_0^1 \rho A\left[H(x)\right]^T\left[H(x)\right]dx \qquad (4.19)$$

$$\left[M^e\right]=\frac{\rho Al}{20}\begin{bmatrix} 156 & 22l & 54 & -13l \\ 22l & 4l^2 & 13l & -3l^2 \\ 54 & 13l & 156 & -22l \\ -13l & -3l^2 & -22l & 4l^2 \end{bmatrix} \qquad (4.20)$$

The natural frequency of the system then can be calculated from the relation (4.10).

4.3 Results and Discussion

Like the Theoretical method, the Finite Element Analysis is also a direct method to get the vibration parameters. The crack locations are given to the FEA method to get the natural frequencies. Several analyses are done for different crack configurations and the changes in the natural frequencies are noted down. The finite element analysis is done using governing differential equation of the system. The crack induction changes the stiffness of the system but the mass remains the same. The changes in the stiffness matrices have been used to obtain the natural frequencies of the system. This method of calculating the natural frequencies has been carried out using ALGOR software package. To identify the crack presence and to help in the generation of the data base, ALGOR (Version 19) has been used to evaluate the vibration parameters of cracked and uncracked beam. The details of the procedures of ALGOR are described in Appendix 2. The results of the Finite Element Analysis for the initial three modes of the cracked beam are compared with that of the

Theoretical Analysis and Experimental Analysis of the cracked beam and are depicted in Tables 4.1and 4.2.

Table 4.1: Comparison of the results of Experimental Analysis and Finite Element Analysis for cantilever beam

Sl. No	crack depth(relative)	crack location(relative)	Relative natural frequencies from experimental study			Relative natural frequencies from Finite element analysis			Average error in %
			rfnf	rsnf	rtnf	rfnf	rsnf	rtnf	
1	0.15625	0.2625	0.9961	0.9995	0.9981	0.9687	0.9073	0.9639	3.00
2	0.18125	0.2375	0.9957	0.9987	0.9999	0.9695	0.9072	0.9616	3.00
3	0.20625	0.1875	0.9956	0.9985	0.9992	0.9699	0.9077	0.9593	2.99
4	0.21875	0.225	0.995	0.9985	0.9988	0.9698	0.9099	0.9678	2.99
5	0.275	0.1625	0.9954	0.999	0.9993	0.9681	0.8991	0.9696	2.99
6	0.4	0.25	0.9211	0.9219	0.9218	0.9677	0.9097	0.9682	3.00
7	0.367	0.3125	0.9463	0.9460	0.9458	0.9680	0.9089	0.9681	2.99
8	0.2833	0.375	0.9552	0.9551	0.9549	0.9679	0.9070	0.9677	3.00
9	0.25	0.4375	0.9621	0.9618	0.9616	0.9646	0.9037	0.9676	3.00
10	0.2166	0.5	0.9705	0.9703	0.9700	0.9677	0.9097	0.9682	3.00
Total average error in %									2.99

Table 4.2: Comparison of the results of Experimental Analysis and Finite Element Analysis for fixed-fixed beam

Sl. No	crack depth (relative)	crack location (relative)	Relative natural frequencies from experimental study			Relative natural frequencies from Finite element analysis			Average error in %
			rfnf	rsnf	rtnf	rfnf	rsnf	rtnf	
1	0.15625	0.2625	0.9961	0.9995	0.9981	0.9686	0.9073	0.9639	3.00
2	0.18125	0.2375	0.9957	0.9987	0.9999	0.9695	0.9071	0.9616	2.99
3	0.20625	0.1875	0.9956	0.9985	0.9992	0.9699	0.9074	0.9593	2.99
4	0.21875	0.225	0.995	0.9985	0.9988	0.9698	0.9095	0.9677	2.99
5	0.275	0.1625	0.9954	0.999	0.9993	0.9681	0.8995	0.9696	3.00
6	0.4	0.25	0.9211	0.9219	0.9218	0.9677	0.9100	0.9682	3.0
7	0.367	0.3125	0.9463	0.9460	0.9458	0.9679	0.9087	0.9681	2.99
8	0.2833	0.375	0.9552	0.9551	0.9549	0.9679	0.9071	0.9677	3.00
9	0.25	0.4375	0.9621	0.9618	0.9616	0.9646	0.9037	0.9677	3.00
10	0.2166	0.5	0.9705	0.9703	0.9700	0.9677	0.9098	0.9682	3.00
Total average error in %									2.99

4.4 Summary

In this chapter, a simple yet efficient method is employed to understand the dynamics of the damaged structure. The Finite Element Analysis applied is based on the deviation in stiffness due to the change in structural integrity. The change in stiffness has been calculated using Hermitian shape functions. From the analysis, it can be seen that due to the change in crack configuration, the vibration characteristics of the cracked structures are changed. So this method can be used for identification of the presence of the crack. The results of the theoretical, finite element and experimental analyses are found to be close to each other. The natural frequencies obtained using different crack geometry is used to make the database for AI Techniques. The results from these techniques are also compared with the results of Finite Element Analysis in subsequent chapters. When the results from the Finite Element Analysis of the faulty beam are compared with the results from the tests, the average percentage of error is found to be within 3% for both cantilever and fixed-fixed beam. The errors are calculated using equations 3.32 and 3.33.

Chapter 5

Analysis of hybridized Mamdani-Adaptive Genetic-Sugeno model for Damage Detection

Cracks in structural and machine members indicate the amount of serviceability of the structures. Crack initiation is obvious in most of the engineering structures due to environmental and working conditions. Usually a hairline crack is visible and can be inspected using crack gauge, fiber optical sensor or laser sensor. But it becomes very difficult to detect a very small crack whose position is very dangerous for the structural element. Cracks change the dynamic responses of the structure like natural frequencies and mode shapes. The deviations in the dynamic properties can be used to detect the presence of crack. So the vibration based methods are gently getting popularized for crack detection. The Artificial Intelligence techniques with the vibration based methods can make a powerful tool for online detection of the damage. These techniques can learn the offline vibration signatures to evaluate the condition monitoring status of the large complex structures both in static and dynamic conditions.

In this chapter, a knowledge based computational method and an evolutionary algorithm based on the “natural selection” is addressed for the vibration analysis of the cracked structural element. From the invention of this logic, it has been successfully applied to different research fields. Many researchers have also used fuzzy logic and its advance versions in the field of damage detection and localization. In the first section of this chapter, both Mamdani and Sugeno FISs are described for crack detection. Here fuzzy logic has been used to learn the dynamics of the cracked structure for damage detection. Two types of membership functions have been proposed to design the variables of the current problem. The evolutionary algorithm proposed in this chapter is one of the powerful and popular evolutionary algorithms for fault detection. In the second part of the chapter, an Adaptive Genetic Algorithm method has been narrated. In the third and final part of the chapter a 3-stage Mamdani-Adaptive Genetic-Sugeno model has been proposed. In the proposed method, benefits from all the three individual methods are used simultaneously exploited.

5.1 Fuzzy Logic Approach for Damage Detection using Mamdani and Sugeno Fuzzy Inference System

Since several years, fuzzy logic theory has been emerged as the most active areas of research in the application of the fuzzy set theory. This logic based theory is much closer to human thinking and natural language than the traditional logical system. Fuzzy logic provides a mean of using approximate, inexact nature present in the real world problems. The important part of the fuzzy logic FL is a set of linguistic control rules connected by the concept of fuzzy implication and fuzzy associative rules. From the findings of other researchers, it can be observed that FLS provides superior results from those obtained by conventional control algorithms. Fuzzy logic control system becomes useful when the available sources of informations are inexact and uncertain. This logic is a step forward of conventional precise mathematical control and human like decision making.

In fuzzy logic, the data are aggregated from a number of partial truths and the results are predicted when it exceeds some threshold. The benefits of FL are its simplicity and flexibility. Fuzzy logic models, called Fuzzy Inference System (FIS) include a number of fuzzy if-then rules. These rules are written by the designer by using various linguistic variables.

5.1.1 Fundamentals of Fuzzy Logic Approach for Structural Damage Detection

Fuzzy logic can operate on imprecise, noisy inputs, but the output is a very smooth unit. It incorporates simple rule based approach to solve control problems rather than solving it mathematically. The FLS model is empirically based on the designers experience rather than the technical understanding of the system. Fuzzy logic is based on rules, so any reasonable number of inputs (1-8) and numerous outputs (1-4) can be taken. But due to the involvement of more inputs and outputs the rules may become complex. So it is wiser to break the control system into smaller control units. Fuzzy logic can also be applied to nonlinear systems which are difficult to model mathematically. Figure 5.1 shows the block diagram of the FLS for damage detection. The inputs to the FLS are the dimensionless (relative) values of the first three natural frequencies and the outputs from the FLS are the crack depth and crack location (relative).

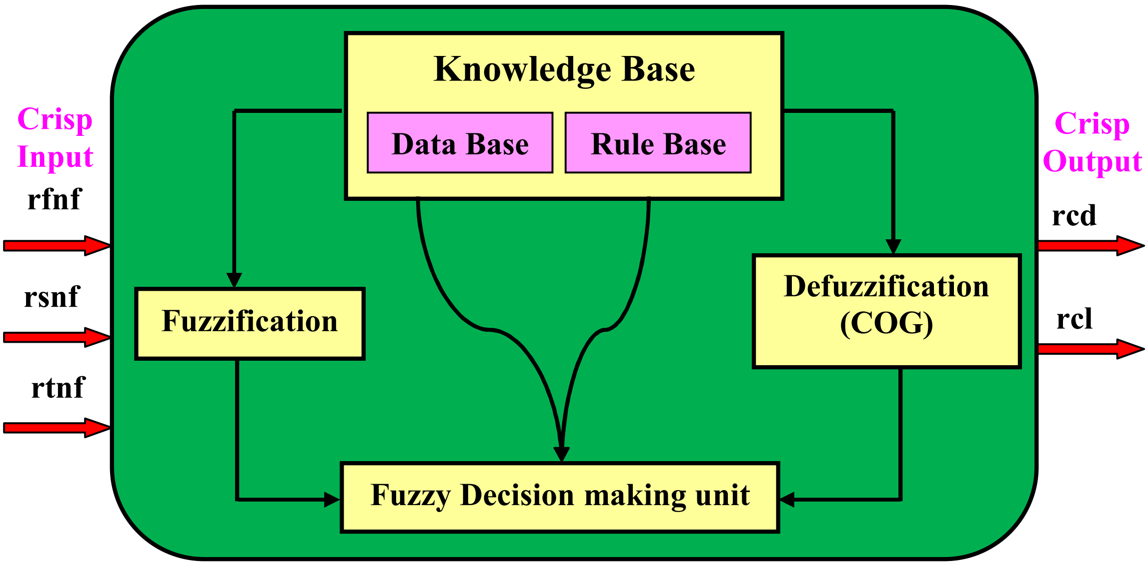


Figure 5.1: Fuzzy logic system for damage detection

Following are some of the fuzzy logic terms which are used to design the Fuzzy Inference Engine in the current work.

5.1.1.1 Fuzzy set

Fuzzy sets are specifically designed to mathematically represent uncertainty and vagueness involved in the problem. A fuzzy set is defined in terms of a membership function, which is a mapping from the universal set 'U' to the interval [0,1]. Fuzzy set theory is a type of infinite valued logic which proposes making of MF to operate over the range of real numbers [0, 1].

Where

$\mu_A : X \rightarrow [0,1]$

A- Fuzzy set

$\mu_A(x)$ - Degree of membership of element 'x' in fuzzy set 'A', for each $x \in X$.

5.1.1.2 Membership functions

The membership functions (MFs) used in FL can be defined as a graphical representation of investment of input information (rfnf, rsnf, rtnf). The rules are used to weigh the input MFs to find the influence of the input MFs on the output sets (rcd, rcl). Once the MFs are construed, scaled and consolidated, they are defuzzified to discover fresh yield values.

There are different types of MFs like triangular, trapezoidal, bell-shaped etc. The choice of MF shape depends on the problem definition and the controller designer.

5.1.1.2(a) Triangular membership function

Triangular and trapezoidal membership functions are otherwise known as piecewise linear functions. Trapezoidal membership function has the shape of a truncated triangular membership function. These membership functions may be symmetrical or asymmetrical in shape. The triangular membership functions are defined as given in equation (5.1). Figure 5.2 describes a triangular membership function with its defining parameters for the problem definition.

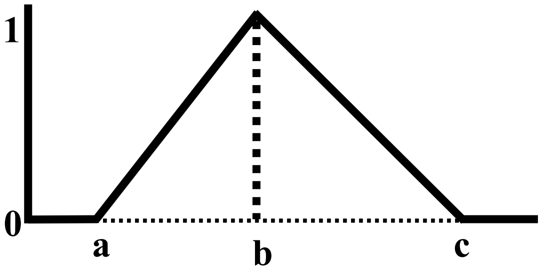


Figure 5.2: Triangular membership function

$$f\left(x,a,b,c\right)=\max\left\{\min\left(\frac{x-a}{b-a},\frac{c-x}{c-b}\right),0\right\} \tag{5.1}$$

The parameters a, b, c are described in the Figure 5.2.

5.1.1.2(b) Gaussian membership function

Gaussian membership function is defined as follows;

$$\mu_A(x,c,\sigma,m)=\exp\left[-\frac{1}{2}\left|\frac{x-c}{\sigma}\right|^m\right] \tag{5.2}$$

Where,

c- Centre of the Gaussian membership function

σ- Width of the Gaussian membership function

m- fuzzification factor usually taken as ‘2’

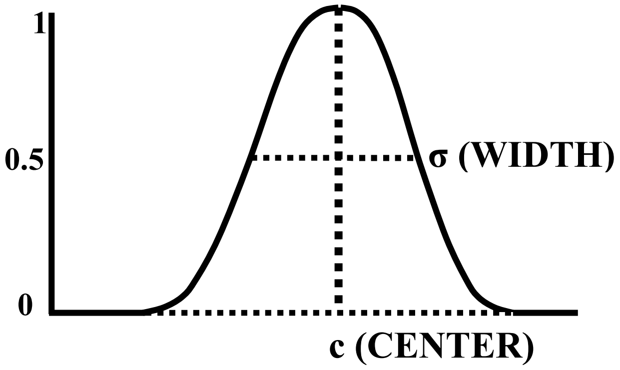


Figure 5.3: Gaussian membership function

Figure 5.3 describes a Gaussian membership function with its defining parameters. The width of the Gaussian membership function is taken as the point where the membership value is '0.5'. From the findings of the different authors, it is observed that a narrow Gaussian membership function with a small width parameter achieves better results than having a Gaussian membership function with large width. As the later leads to high degree of membership value for all inputs which in turn reduces the extractable information.

5.1.1.3 Linguistic variables

The concepts of linguistic variables or fuzzy variables are proposed by Zadeh [178]. They are some linguistic objects or words, rather than numbers. These variables are the objectives that try to define the variable range.

The problem under consideration is a multi input and multi output problem. The rules formation greatly depends on the linguistic variables representing the problem variables. The following table shows the different linguistic variables used for problem variables.

Table 5.1: Illustration of fuzzy linguistic variables used in creating fuzzy rules

Membership Function Name	Linguistic Variables	Description of range of the linguistic Variables
l1f1,l1f2,l1f3	$rfnf_{1to3}$	Lower span of relative first natural frequency in ascending order respectively.
m1f1,m1f2,m1f3	$rfnf_{4,6}$	Medium span of relative first natural frequency in ascending order respectively.
h1f1,h1f2,h1f3	$rfnf_{7,9}$	Higher span of relative first natural frequency in ascending order respectively.
l2f1.l2f2,l2f3	$rsnf_{1to3}$	Lower span of relative second natural frequency in ascending order respectively.
m2f1,m2f2,m2f3	$rsnf_{4,6}$	Medium span of relative second natural frequency in ascending order respectively.
h2f1,h2f2,h2f3	$rsnf_{7to9}$	Higher span of relative second natural frequency in ascending order respectively.
l3f1,l3f2,l3f3	$rtnf_{1to3}$	Lower span of relative third natural frequency in ascending order respectively.
m3f1,m3f2	$rtnf_{4,6}$	Medium span of relative third natural frequency in ascending order respectively.
h1f1,h1f2,h1f3	$rtnf_{7to9}$	Higher span of relative third natural frequency in ascending order respectively.
sd1,sd2,sd3	rcd_{1to3}	Small span of relative crack depths in ascending order respectively.
md1,md2,md3	rcd_{4to6}	Medium span of relative crack depths in ascending order respectively
ld1,ld2,ld3	rcd_{7to9}	Larger span of relative crack depths in ascending order respectively.
sl1,sl2,sl3	rcl_{1to3}	Small span of relative crack locations from the fixed end in ascending order respectively.
ml1,ml2,ml3	rcl_{4to6}	Medium span of relative crack locations from the fixed end in ascending order respectively.
bl1,bl2,bl3	rcl_{7to9}	Bigger span of relative crack locations from the fixed end in ascending order.

5.1.1.4 Fuzzy Logic Rules

In day to day life, decisions are made based on rules. If we will carefully notice all the rules are based on if-then statements. Fuzzy logic systems which try to mimic the human behavior, work in the same way by forming fuzzy rules. The rule base section of the fuzzy inference system works on the application and implementation of the fuzzy rules. ‘If’ part is the precursor part and ‘Then’ part is known as the resulting part. The two fuzzy parts are are associated with connectors like AND, OR, NOT and so forth.

A typical rule in a Mamdani fuzzy system in the current problem is defined as below:

if x_1 is lf, x_2 is mf, x_3 is lf then y_1 is sd, y_2 is ml

Different rules are formed and applied in the Fuzzy Inference System according to the problem definition. These rules are formed keeping in mind how the crack depth and crack location varies with the every loss and gain in the natural frequencies. These rules are totally based on the Theoretical, FEA and Experimental analyses results. Following table shows some of the rules applied in the Fuzzy Inference System.

Table 5.2: Sample rules for the Mamdani fuzzy inference engine

Sl. no	Examples of some fuzzy rules used in Fuzzy Logic System
1	If rfnf is l1f1,rsnf is l2f1,rtnf is l3f1 then rcd is ld1 and rcl is sl1
2	If rfnf is l1f1, rsnf is l2f2, rtnf is l3f3 then rcd is ld1 and rcl is sl2
3	If rfnf is l1f1, rsnf is l2f3, rtnf is l3f3 then rcd is ld2 and rcl is sl2
4	If rfnf is l1f2, rsnf is l2f2, rtnf is l3f2 then rcd is ld2 and rcl is sl2
5	If rfnf is l1f2, rsnf is l2f3, rtnf is l3f2 then rcd is ld3 and rcl is sl3
6	If rfnf is l1f3, rsnf is l2f3, rtnf is l3f3 then rcd is ld3 and rcl is ml1
7	If rfnf is m1f1, rsnf is m2f1, rtnf is m3f1 then rcd is md1and rcl is ml1
8	If rfnf is m1f1,rsnf is m2f2, rtnf is m3f2 then rcd is md1 and rcl is ml2
9	If rfnf is m1f2,rsnf is m2f2, rtnf is m3f2 then rcd is md2 and rcl is ml2
10	If rfnf is m1f2,rsnf is m2f3,rtnf is m3f3 then rcd is md3 and rcl is ml2
11	If rfnf is m1f3, rsnf is m2f3,rtnf is m3f3 then rcd is md3 and rcl is ml3
12	If rfnf is m1f3, rsnf is h2f1, rtnf is m3f3 then rcd is md3 and rcl is ml2
13	If rfnf is m1f3, rsnf is h2f1, rtnf is h3f1 then rcd is md2 and rcl is ml3
14	If rfnf is h1f1, rsnf is h2f1, tnf is h3f2 then rcd is md2 and rcl is bl1
15	If rfnf is h1f1, rsnf is h2f2, tnf is h3f2 then rcd is md1 and rcl is bl2
16	If rfnf is h1f2, rsnf is h2f3, tnf is h3f2 then rcd is md2 rcl is bl1
17	If rfnf is h1f2, rsnf is h2f2, tnf is h3f3 then rcd is md2 and rcl is bl1
18	If rfnf is h1f3, rsnf is h2f2, tnf is h3f3 then rcd is sd2 and rcl is bl2
19	If rfnf is h1f3, rsnf is h2f3, tnf is h3f2 then rcd is sd2 and rcl is bl3
20	If rfnf is h1f3, rsnf is h2f3, tnf is h3f3 then rcd is sd3 and rcl is bl3

5.1.2 Fuzzy inference systems

Fuzzy inference systems are of two kinds i.e., Mamdani FIS and Takagi-Sugeno FIS. In this work, the Mamdani FIS comprises of the following steps. Figure 5.4 describes a Fuzzy Logic System having shuffled membership functions.

1. Fuzzification (Use of membership function for graphical presentation of the database)
2. Rule evaluation (Implementation of the rules)
3. Defuzzification (Obtaining the crisp values of the results)

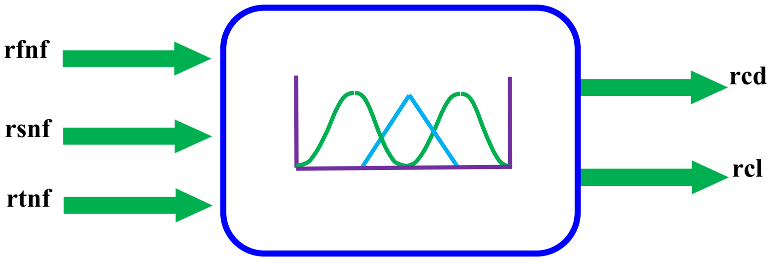


Figure 5.4: Fuzzy Inference Systems with input and output variables

5.1.2.1 Mamdani Fuzzy Inference System for Crack Detection

The conventional systems sometimes contain imprecision, which can be observed from the rules made by the experts. An inference system cannot be made using the two valued or many valued logic. So in 1977, Mamdani [179] suggested a compositional rule based inference system. Mamdani Fuzzy Inference System is widely used for capturing and implementing expert knowledge. It allows describing the expertise intuitive knowledge in a more human like manner. In Mamdani's model the fuzzy rules implication is modeled by the minimum or conjunction operator from compositional rules and for the aggregation of the rules maximum operator is used.

The Fuzzy Logic System consisting of Mamdani fuzzy inference model is implemented through the following steps.

1) *Fuzzification*: First the crisp input (rfnf, rsnf, rtnf) and output (rcd, rcl) variables are fuzzified using fuzzy sets. The degrees of membership of these variables are defined.

2) *Rule aggregation and evaluation*: The fuzzified variables are used to form fuzzy rules. If a fuzzy rule consists of many antecedent parts, they are joined by fuzzy operators (AND or NOT). For Mamdani fuzzy inference, the i'th rule can be mathematically expressed as:

R_i:if$x_1$is$A_{i1}$and$x_2$is$A_{i2}$and.....$x_n$isA_{in},then$y_1$is$B_{i1}$and$y_2$isB_{i2} (5.3)

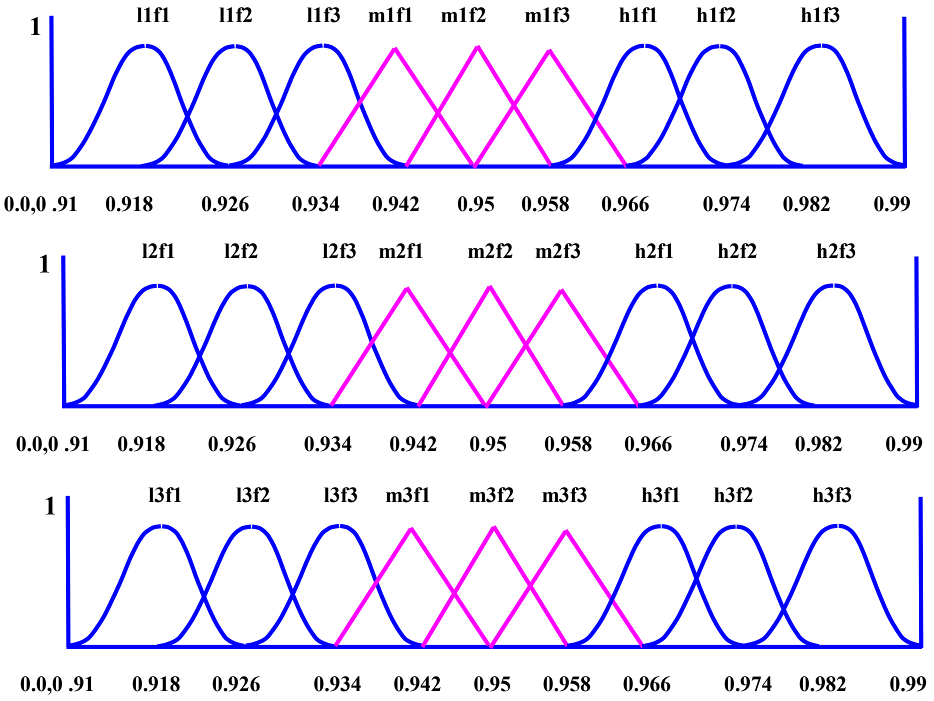
Where,

$A_{i1}, A_{i2}, \ldots\ldots, A_{in}$ and B_{i1}, B_{i2} are the fuzzy sets.

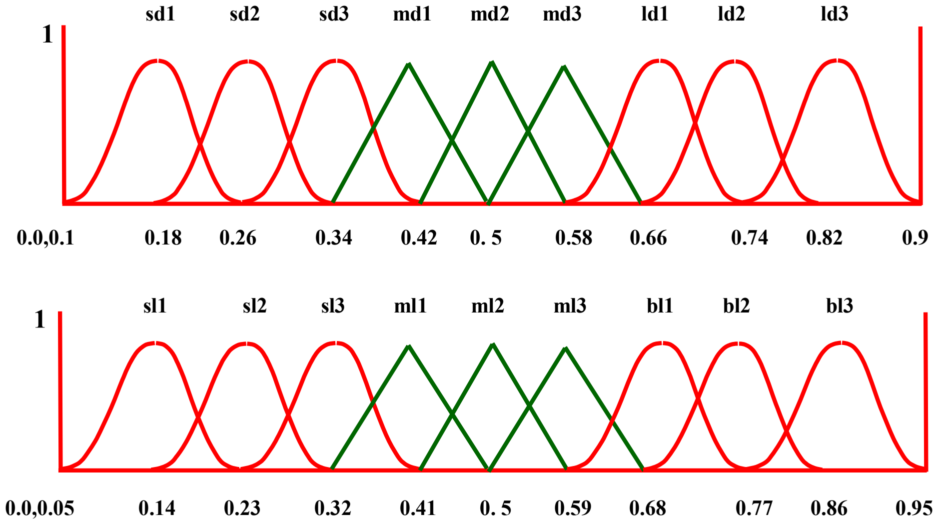
The membership values of all rule consequents are incorporated into a single fuzzy set.

3) *Defuzzification Method*: The most common type of defuzzification method is the centroid method. This defuzzifier method has been used in all the Fuzzy Logic System of this research work using Mamdani FIS. This method finds a point representing the Centre of Gravity (COG) of the aggregated fuzzy set ‘A’ in the interval [a,b]. The other types of defuzzification methods are mean of maximum, weighted average method, height method.

The following figure (Figure 5.5) shows the Mamdani FIS with shuffled Membership Functions applied in this work.



Shuffled Membership Functions (Gaussian and Triangular MF) for input variables (rfnf, rsnf, rtnf)



Shuffled Membership Functions (Gaussian and Triangular MF) for output variables (rcd, rcl)

Figure 5.5: Representation Mamdani FIS with the input and output variables

5.1.2.1(a) Analysis of fundamental Fuzzy Theory in Mamdani FIS

The fuzzy system has been designed and developed using 3 inputs and 2 outputs parameter. The linguistic representations for the input are as follows;

Dimensionless form of first natural frequency = 'rfnf'

Dimensionless form of second natural frequency = 'rsnf'

Dimensionless form of third natural frequency = 'rtnf'

The linguistic terms used for the outputs are

Dimensionless form of crack depth = 'rcd'

Dimensionless form of crack length= 'rcl'

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

If (rfnf is rfnf_i and rsnf is rsnf_j and rtnf is rtnf_k) then (rcd is rcd_{ijk} and rcl is rcl_{ijk}) (5.4)

Where l= 1to 9, m=1 to 9, n=1 to 9

Because of 'rfnf', 'rsnf', 'rtnf' have 9 membership functions each.

From the above expression (5.4), two set of rules can be written

$$\left.\begin{array}{l}\text{If }\left(\text{rfnf is rfnf}_l\text{and rsnf is rsnf}_m\text{and rtnf is rtnf}_n\right)\text{ then rcd is rcd}_{lmn}\\ \text{If }\left(\text{rfnf is rfnf}_l\text{and rsnf is rsnf}_m\text{and rtnf is rtnf}_n\right)\text{ then rcl is rcl}_{lmn}\end{array}\right\} \tag{5.5}$$

As indicated by the typical Fuzzy rationale control technique by [180], an element W_{ijk} is defined for the rules as follows:

$$w_{lmn} = \mu_{fnf_l}(freq_l) \wedge \mu_{snf_m}(freq_m) \wedge \mu_{tnf_n}(freq_n) \tag{5.6}$$

$freq_i$, $freq_j$ and $freq_k$ are the first, second and third natural frequencies of the beam (cantilever, fixed-fixed) with crack respectively. Then Applying composition of fuzzy associative rules of the interference engine [180] the membership values of the relative crack location and relative crack depth (location) can be evaluated as follows.

$$\left.\begin{array}{l}\mu_{rcl_{lmn}}(\text{distance}) = w_{lmn} \wedge \mu_{rcl_{lmn}}(\text{distance}) \ \forall_{\text{location}} \in rcl\\ \mu_{rcd_{lmn}}(\text{deepness}) = w_{lmn} \wedge \mu_{rcd_{lmn}}(\text{deepness}) \ \forall_{\text{depth}} \in rcd\end{array}\right\} \tag{5.7}$$

The general combination of the fuzzy associative rules output fuzzy sets can be composed as follows:

$$\mu_{rcl}(\text{distance}) = \mu_{rcl_{111}}(\text{distance}) \vee .... \vee \mu_{rcl_{lmn}}(\text{distance}) \vee .... \vee \mu_{rcl_{191919}}(\text{distance}) \tag{5.8}$$

$$\mu_{rcd}(\text{deepness}) = \mu_{rcd_{111}}(\text{deepness}) \vee .... \vee \mu_{rcd_{lmn}}(\text{deepness}) \vee .... \vee \mu_{rcd_{191919}}(\text{deepness})$$

The crisp values of crack location and crack depth are evaluated using the center of gravity method as:

$$\left.\begin{aligned}&\text{Crack location in dimensionless form} = \text{rcl} = \frac{\int \text{distance}.\mu_{\text{rcl}}(\text{distance}).\text{d}(\text{distance})}{\int \mu_{\text{rcl}}(\text{distance}).\text{d}(\text{distance})}\\&\text{Crack depth dimensionless form} = \text{rcd} = \frac{\int \text{deepness}.\mu_{\text{rcd}}(\text{deepness}).\text{d}(\text{deepness})}{\int \mu_{\text{rcd}}(\text{deepness}).\text{d}(\text{deepness})}\end{aligned}\right\} \qquad (5.9)$$

5.1.2.2 Sugeno Fuzzy Inference System for crack detection

Other than Mamdani FIS, there is another Fuzzy Inference System known as Sugeno FIS, which is also used in the design of the proposed method. The Sugeno Fuzzy Inference model was proposed by Sugeno [181] in 1985 after the advancement of Mamdani FIS. The fuzzy rule in a Sugeno fuzzy inference model is of the form

$$\text{if} x_1 \text{is} X_1 \text{and} x_2 \text{is} X_2 \text{then} y=f\left(x_1,x_2\right) \qquad (5.10)$$

Where,

x_1, x_2 = input variables

X_1, X_2 =fuzzy sets of the rule antecedent part

y=output variable

$f\left(x_1,x_2\right)$ is a function of the input variables presenting the output variable. The function gives directly the output crisp value. The output function is so carefully chosen that it can model the problem variables (rfnf, rsnf, rtnf) within the fuzzy region specified by the rule antecedent part of the fuzzy rule. The output function is a polynomial function. This could be a first order or zero order polynomial function and the Sugeno model is named accordingly. Sometimes the output is taken as a constant, where it is viewed as a special type of Mamdani FIS.

In Sugeno model, each output has a numerical value. So, the final output is aggregated using weighted average which becomes,

$$y=w_1x_1+w_2x_2+.......+w_nx_n \qquad (5.11)$$

Steps used in Sugeno fuzzy inference modeling for damage detection are as given below.

1. General structure of Sugeno fuzzy inference begins with the fuzzification of the input (rfnf, rsnf, rtnf) and output variables (rcd, rcl) within the defined range utilizing various kinds of membership functions (triangular, trapezoidal, Gaussian etc.) like that of Mamdani FIS.

For the current problem 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 yield variables characterized on reference sets Y_1 and Y_2. Then FIS has three data variables and two yield variables. Further each set $X_{o,}$ $o=1,2,3$ can be divided into $p=1,2,\ldots,n$ fuzzy sets.

$$\mu_{o,1}(x), \mu_{o,2}(x), \ldots\ldots, \mu_{o,p}(x), \ldots\ldots\ldots, \mu_{o,n}(x) \qquad (5.12)$$

Where 'μ' is the membership function values

2. The next step comprises the formation of the fuzzy base rules. The 'l'th if-then rule R_l in Sugeno FIS can be written in the following form

$$R_l{:}\mathrm{if}\,x_1\,\mathrm{is}\,L_{1,i(1,l)}\,\mathrm{and}\,x_2\,\mathrm{is}\,L_{2,i(1,l)}\,\mathrm{and}\,x_3\,\mathrm{is}\,L_{3,i(1,l)}\,\mathrm{then}\,y_1=f_1(x_1,x_2,x_3)\,\mathrm{and}\,y_2=f_2(x_1,x_2,x_3) \qquad (5.13)$$

Where

$L_{1,i(1,l)}, L_{2,i(1,l)}, L_{3,i(1,l)}$ are the linguistic variables

$y_1=f_1(x_1,x_2,x_3)$, $y_2=f_2(x_1,x_2,x_3)$ are linear polynomial functions

$l=1, 2\ldots N$

$$R_l{:}\mathrm{if}\,x_1\,\mathrm{is}\,L_{1,i(1,l)}\,\mathrm{and}\,x_2\,\mathrm{is}\,L_{2,i(1,l)}\,\mathrm{and}\,x_3\,\mathrm{is}\,L_{3,i(1,l)}\,\mathrm{then}\,y_1=k_1\,\mathrm{and}\,y_2=k_2 \qquad (5.14)$$

Where,

k_1, k_2 are constants. Equation (5.14) describes the zero order Sugeno FIS rule.

3. The third step describes the defuzzification procedure in Sugeno FIS. The output weight of y_l of each the l-th if-then rule R_l is aggregated by

$$w_l=\mu(x_1)\,\mathrm{and}\,\mu(x_2)\,\mathrm{and}\,\mu(x_3) \qquad (5.15)$$

The final output after aggregation of 'N' rules is computed as;

$$y=\frac{\sum_{l=1}^{N} y_l w_l}{\sum_{l=1}^{N} w_l} \qquad (5.16)$$

5.1.3 Result Table for Fuzzy Logic Analysis

Table 5.3: Comparison of the results of FLS (Mamdani FIS) with FEA of a cantilever beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the FLS technique	rcl using the FLS technique	percentage error rcd	percentage error rcl	Total Error in %
1	0.9923	0.9912	0.9966	0.325	0.2187	0.3071	0.2066	5.49	5.51	5.5
2	0.9931	0.9926	0.9978	0.3	0.2062	0.2835	0.19488	5.49	5.51	5.5
3	0.9946	0.9942	0.9972	0.2875	0.2312	0.2716	0.2185	5.51	5.49	5.5
4	0.9959	0.99772	0.999	0.125	0.2187	0.1181	0.2066	5.51	5.51	5.51
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2599	0.3425	5.48	5.5	5.49
Total Average Error in %									5.5	

Table 5.4: Comparison of the results of FLS (Mamdani FIS) with Exp. analysis cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the FLS technique	rcl using the FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3249	0.4430	5.48	5.49	5.48
2	0.9974	0.989	0.9999	0.375	0.5	0.3543	0.4726	5.5	5.48	5.49
3	0.99816	0.9982	0.9979	0.25	0.375	0.2362	0.3544	5.49	5.48	5.48
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2067	0.3839	5.47	5.49	5.48
5	0.9892	0.9996	0.9981	0.35	0.1875	0.3307	0.1771	5.49	5.5	5.49
Total Average Error in %									5.48	

Table 5.5: Comparison of the results of FLS (Mamdani FIS) with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the FLS technique	rcl using the FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3602	0.3070	5.51	5.51	5.51
2	0.9966	0.9961	0.9978	0.3625	0.29375	0.3424	0.2775	5.52	5.51	5.51
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3366	0.2598	5.51	5.52	5.51
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3307	0.2716	5.51	5.51	5.51
5	0.9975	0.9991	0.9970	0.4	0.175	0.378	0.1653	5.5	5.51	5.50
Total Average Error in %									5.51	

Table 5.6: Comparison of the results of FLS (Mamdani FIS) with Exp. analysis fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the FLS technique	rcl using the FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9923	0.9912	0.9966	0.325	0.21875	0.2834	0.1712	5.51	5.51	5.51
2	0.9931	0.9926	0.9978	0.3	0.20625	0.3129	0.2539	5.51	5.5	5.50
3	0.9946	0.9942	0.9972	0.2875	0.23125	0.2776	0.1299	5.48	5.49	5.48
4	0.9959	0.9977	0.999	0.125	0.21875	0.3011	0.1476	5.52	5.51	5.51
5	0.9974	0.9977	0.9965	0.275	0.3625	0.1712	0.2244	5.49	5.5	5.49
Total Average Error in %									5.5	

Table 5.7: Comparison of the results of FLS (Sugeno FIS) with FEA of a cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the FLS technique	rcl using the FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.325	0.21875	0.3078	0.2071	5.29	5.3	5.29
2	0.9981	0.9964	0.9977	0.3	0.20625	0.2841	0.1953	5.28	5.29	5.28
3	0.9984	0.999	0.997	0.2875	0.23125	0.2722	0.2190	5.31	5.29	5.3
4	0.9985	0.9991	0.9975	0.125	0.21875	0.1183	0.2071	5.3	5.31	5.30
5	0.9987	0.9999	0.9957	0.275	0.3625	0.2604	0.3432	5.3	5.3	5.3
Total Average Error in %									5.29	

Table 5.8: Comparison of the results of FLS (Sugeno FIS) with Exp. analysis cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the FLS technique	rcl using the FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3256	0.4439	5.28	5.29	5.285
2	0.9974	0.989	0.9999	0.375	0.5	0.3551	0.4735	5.3	5.29	5.295
3	0.99816	0.9982	0.9979	0.25	0.375	0.2367	0.3551	5.3	5.3	5.3
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2072	0.3848	5.28	5.28	5.28
5	0.9892	0.9996	0.9981	0.35	0.1875	0.3315	0.1776	5.28	5.28	5.28
Total Average Error in %									5.28	

Table 5.9: Comparison of the results of FLS (Sugeno FIS) with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the FLS technique	rcl using the FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3610	0.3077	5.31	5.31	5.31
2	0.9966	0.9961	0.9978	0.3625	0.2937	0.3432	0.2782	5.31	5.29	5.3
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3372	0.2604	5.32	5.29	5.30
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3314	0.2722	5.31	5.3	5.30
5	0.9975	0.9991	0.9970	0.4	0.175	0.3787	0.1657	5.31	5.3	5.30
Total Average Error in %									5.3	

Table 5.10: Comparison of the results of FLS (Sugeno FIS) with Exp. analysis fixed-fixed beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the FLS technique	rcl using the FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.3	0.18125	0.2841	0.1717	5.27	5.26	5.26
2	0.9981	0.9964	0.9977	0.33125	0.26875	0.3137	0.2546	5.28	5.26	5.27
3	0.9984	0.999	0.997	0.29375	0.1375	0.2782	0.1302	5.28	5.28	5.28
4	0.9985	0.9991	0.9975	0.31875	0.15625	0.3018	0.1480	5.3	5.25	5.27
5	0.9987	0.9999	0.9957	0.18125	0.2375	0.1716	0.2250	5.27	5.23	5.25
Total Average Error in %									5.26	

5.2 Adaptive Genetic Algorithm for Damage Detection

Genetic Algorithms (GAs) are established on the evolution of natural selection and genetic. This algorithm was first developed by John Holland [182] in the 60s. This is a heuristic search algorithm. The main notion of this search algorithm is to simulate the process necessary for evolution. This stochastic search algorithm provides an intelligent exploitation of search space to solve a problem. The area containing suitable solutions are called search space. Every individual point in the search space is an achievable solution. The search space in GA plays an important role in finding the absolute solution as; Genetic Algorithms (GAs) are random search algorithm. These algorithms can be applied to many real world problems of complex and intricate nature which are tough to be solved by traditional or conventional methods. GA makes it easy to search a large solution space. Although GAs can be used to find solutions to very complicated real world problems, they are very much simple to use and understand. It is able to search through a variety and huge combination of parameters to find the best match. But sometimes the GA becomes unidirectional without expediting the entire search space. The accessibility to the better solution in the search space becomes easier, if the relationship between the independent and dependent variables in a problem is known to the designer. Therefore, in this work *Regression Analysis* has been incorporated for the data analysis of the problem which makes the algorithm more adaptive towards the solution.

The operators and procedures of the natural evolution process are similar to the simple Genetic Algorithm. Feasible solutions in the solution space are ranked by their fitness values for selection. The algorithm's important features are the genetic operators. These operators try to imitate the process of natural selection of the evolution process. The genetic operators, crossover and mutation perform two different roles. Crossover tries to direct the population towards a local solution which leads to premature convergence of the algorithm. But mutation is a divergence operation that tries to introduce diversity in the population, so that there will be more exploitation of the search space. This paves the way towards achieving a better solution. But the mutation amount in every generation is kept small and should affect a few members of a population. Otherwise the entire solution space will be changed and the algorithm will become directionless.

5.2.1 Fundamental parameters of Adaptive Genetic algorithm

The GA starts with asset of solutions known as population (data pool). These solutions are presented by chromosomes. Solutions from one generation are passed forward to the next generation. It is anticipated that the new population offers preferable solution over the old one. Tables 5.11 and 5.12 give the data pool for Genetic Algorithm for different end conditions of the beam.

Table 5.11: Sample data pool for cantilever beam used for GA

Sl.No	rfnf	rsnf	rtnf	rcd	rcl
1	0.9982	0.999	0.9976	0.225	0.33125
2	0.9989	0.9992	0.9981	0.2125	0.3375
3	0.9979	0.9963	0.9986	0.1875	0.25
4	0.9992	0.99734	0.99895	0.15625	0.28125
5	0.9950	0.9982	0.9938	0.3125	0.3125
6	0.9996	0.9996	0.999	0.1625	0.35
7	0.9985	0.999	0.998	0.2	0.34375
8	0.9982	0.999	0.9976	0.225	0.33125
9	0.9989	0.9992	0.9981	0.2125	0.3375
10	0.9996	0.9996	0.999	0.1625	0.35

Table 5.12: Sample data pool for fixed-fixed beam used for GA

Sl.No	rfnf	rsnf	rtnf	rcd	rcl
1	0.9985	0.9985	0.9957	0.1875	0.25
2	09979	0.9940	0.9938	0.3125	0.28125
3	0.9988	0.9999	0.9988	0.125	0.34375
4	0.9927	0.9981	0.9948	0.34375	0.5625
5	0.9985	0.9985	0.9957	0.1875	0.25
6	09979	0.9940	0.9938	0.3125	0.28125
7	0.9938	0.9984	0.9930	0.3125	0.4375
8	0.9969	0.9969	0.9952	0.1875	0.5
9	0.9958	0.9998	0.9940	0.25	0.46875
10	0.99982	0.9989	0.9997	0.1667	0.3125

5.2.1.1 Representation scheme for Adaptive Genetic Algorithm Analysis

Every search and optimization algorithm needs a representation that tries to present a solution to a problem. Encoding or the representation scheme depends on the problem type. Different types of encodings used in GA are binary encoding, permutation encoding, value encoding, tree encoding etc. In this research, binary encoding is used for GA. Figure 5.6 shows the representation of the chromosomes using binary encoding.

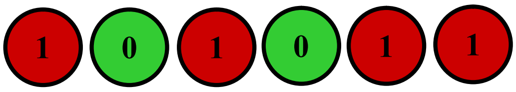


Figure 5.6: Presentation of encoded chromosomes

5.2.1.2 Parent Selection

A GA has several genetic operators; selection is one of them. The selection operation is used to choose parents for reproduction. This operation gives preference to better individuals (solutions), so that they could pass good traits to the next generation. There are many ways of selecting the best chromosomes/individuals, like roulette wheel selection, tournament selection, rank selection and some others.

In the present work, the solutions/individuals are selected according to their fitness values. The fitness value is determined by an objective function/ fitness function.

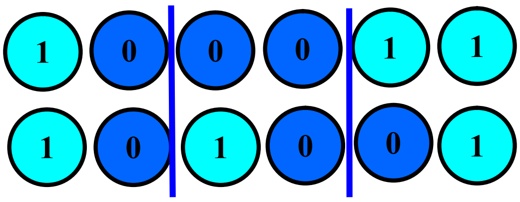
5.2.1.3 Fitness function

As mentioned earlier in selection operation, it is needed to evaluate a solution relative to other potential solutions. The fitness function is useful in evaluating a solution. The fitness values are then used in the process of natural selection to choose potential solutions.

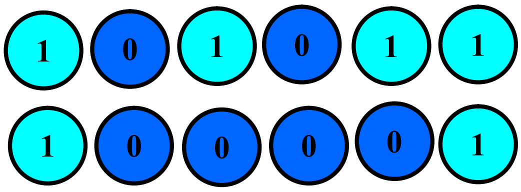
5.2.1.4 Crossover operation

Crossover/reproduction operation is a prime distinguished operator of GA from other optimization methods. Here the individuals, those are selected as best individuals in the selection operation are used as parents. Then a crossover site is selected along the bit strings of the chromosome. Everything after and before the crossover point is exchanged and copied between the parents. The two new offsprings created from this operation are passed into the next generation of population.

In case of binary encoding, the crossover strategies are one point crossover, two point crossover, uniform crossover and arithmetic crossover. In this work, two point crossover is used for the corresponding encoding scheme. Figure 5.7 describes the two point crossover used in this problem.



Parent Chromosomes with binary encoding



Offsprings after crossover

Figure 5.7: Presentation of two point crossover process

5.2.1.5 Mutation operation

After crossover, mutation is applied to all the individuals. In this operation, a portion of the new individuals will have some of their bits flipped. The purpose of mutation is to maintain diversity within the population and escape parameter convergence. Mutation prevents the algorithm to be trapped in a local minimum. Mutation introduces random distribution of genetic information. Mutation is always kept short, within the range 0.001 to 0.01. Figure 5.8 describes the mutation operation used in the current problem.

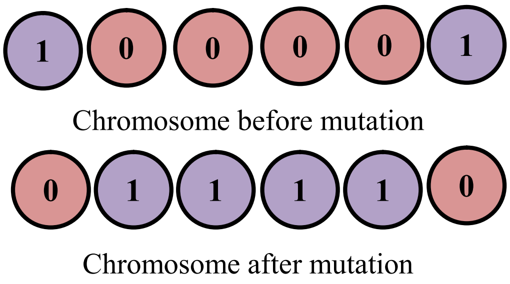


Figure 5.8: Presentation of point mutation

5.2.2 Regression Analysis for the generation of the data pool in GA

The data mining process is used to make best use of data. There are various methods of data mining which is used to model the relationship between the dependent and independent variables, mathematically. Among the various methods, regression is used to develop a best fit mathematical formula for the numerical data. This formula can be referred in future to feed the new data sets for better prediction.

The portion of the damage detection that has been given least attention in the literature is the developments of statistical models to enhance the damage detection process. The statistical models can be developed in three categories namely (1) Regression Analysis, (2) Group Classification and (3) Outlier Detection. Again, the appropriate statistical model use depends on the supervised and unsupervised learning. Unsupervised learning deals only with the data from the uncracked beam element and the supervised learning deals with both types of data from the damaged and undamaged beam elements.

Regression Analysis comes under the category of supervised learning based on the statistical modeling of the problem. Regression Analysis is used to find the relationship between the two variables. This method is mainly a statistics based method. It can be described in the form of Cause (independent variable) and Effect (dependent variable). Several researchers have used Regression Analysis for the data base analysis of damage detection problems but no one has combined it with Genetic Algorithm.

The fundamental equation for the Regression Analysis is

$$Y=p+qX+r \tag{5.17}$$

where,

Y= dependent variable

X=independent variable

p=constant or intercept

q= slope of the regression line or coefficients for the independent variable

r= error term or residual factor

Before doing Regression Analysis, some assumptions must be considered. For the current Regression Analysis method following are the assumptions considered by the author.

1. The expected values for the errors are zero, or we can say there is no residual factor. So the equation (5.17) becomes

   $$Y=p+qX \tag{5.18}$$

2. The values of the independent variables are fixed and they are non-random in nature.
3. The dependency between the dependent and independent variables are linear.

This analysis mainly related to the dynamic responses of the cracked structural element with the damage extent. It is often realized that the damage parameters are often scalar values, so univariate statistical tests can be utilized to find out the possible changes among the parameter vectors associated with a definite location. It is also expected that the computational cost of such statistical testing is less than those of the parameter extraction. The present issue is an instance of Multiple Regression Analysis, because of the vicinity of numerous data and yield variables.

For the present analysis, Y=fnf, snf, tnf and X=cd, cl.

The linear equations for the current problem, relating the dependent (fnf, snf, tnf) and independent (cd, cl) variables are as following

$$Y_1(\text{fnf})=p_1+q_1(X_1)+q_2(X_2) \tag{5.19}$$

$$Y_2(\text{snf})=p_2+q_3(X_1)+q_4(X_2) \tag{5.20}$$

$$Y_3(\text{tnf})=p_3+q_5(X_1)+q_6(X_2) \tag{5.21}$$

For the data extraction using the Regression Analysis method, direct values of the variables are used. After analysis the values of the data are converted to the relative values.

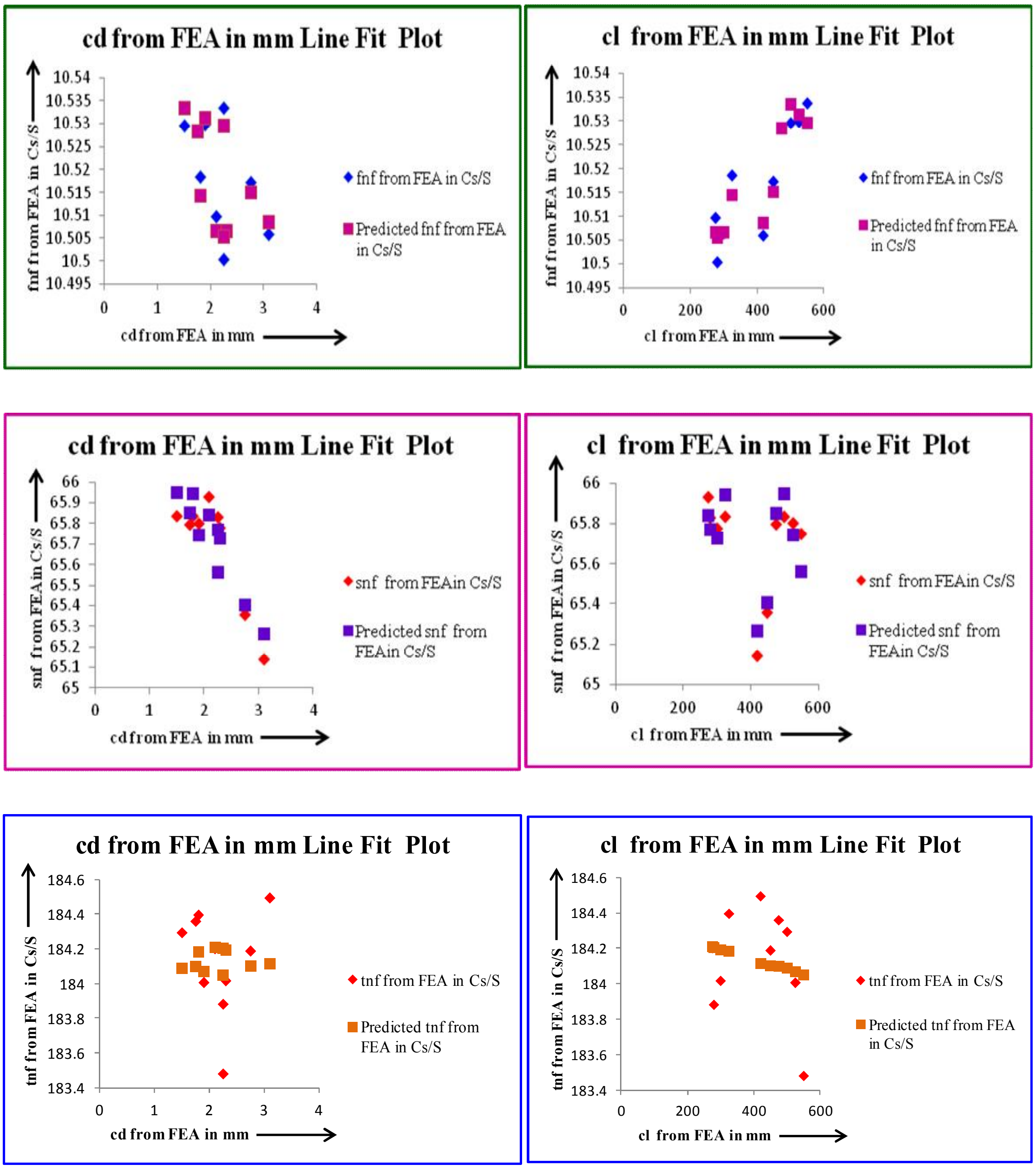


Figure 5.9: Graphs presenting the independent variables (both from FEA and predicted value) vs. dependent variables for cantilever beam

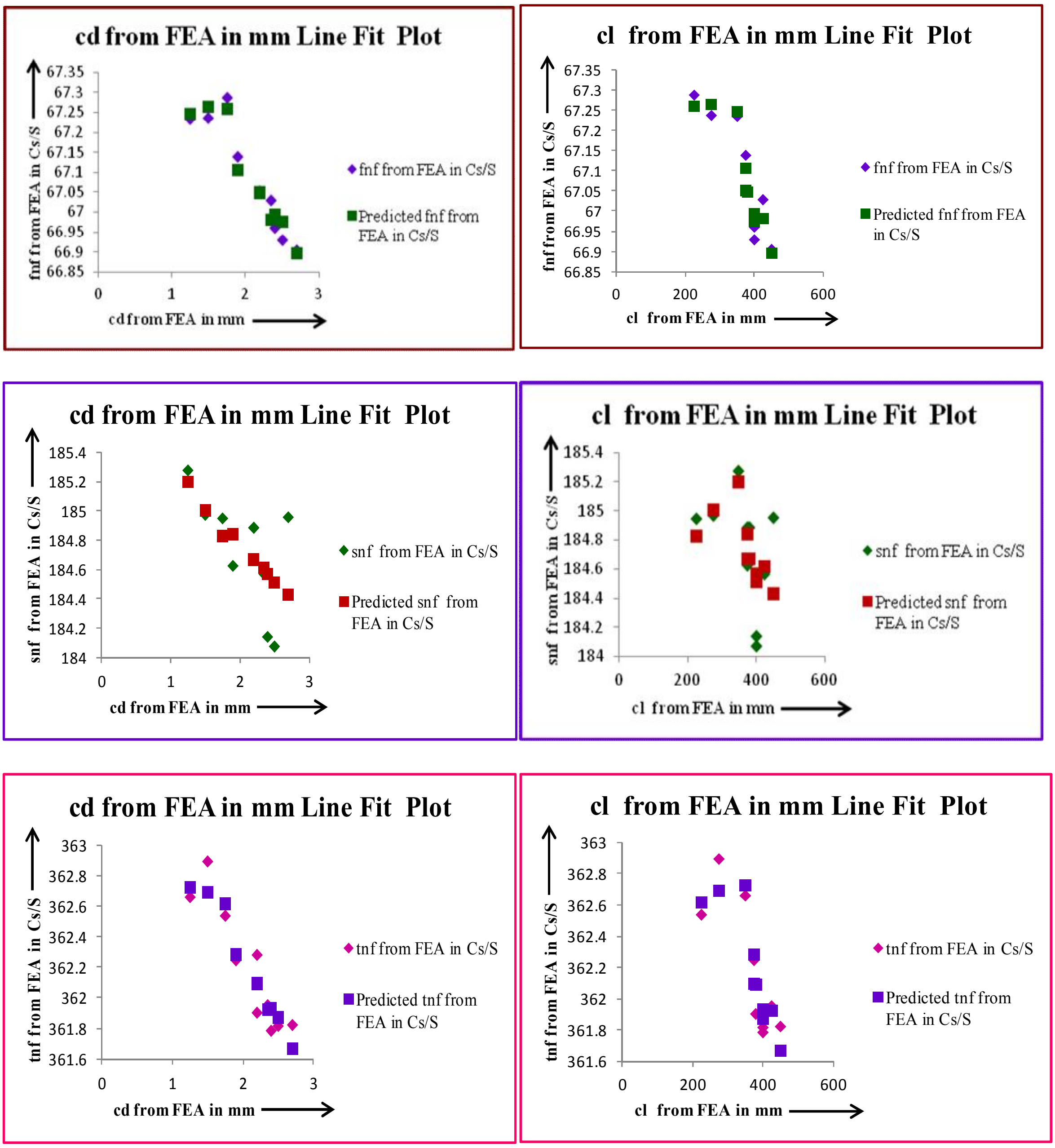


Figure 5.10: Graphs presenting the independent variables (both from FEA and predicted value) vs. dependent variables for fixed-fixed beam

5.2.3 Implementation of Adaptive Genetic Algorithm for fault detection in cracked structures

As we know Genetic Algorithm is a search algorithm, it can be well applied to the current problem. In this problem, it is required to locate the crack depth and crack location using frequencies from the field signals. Then rest of the steps is done according to the Genetic Algorithm. The advancement of the algorithm and the application of the operators mainly depend on the representation scheme adapted for the algorithm. So before the implementation of the algorithm binary encoding is done. Here each individual in the solution space is coded as a finite length component or variable. In GA, individuals/solutions are similar to chromosomes and the variables are similar to the genes. In this approach, each chromosome contains five genes (rfnf, rsnf, rtnf, rcd, rcl). Each gene contains four bits, so each chromosome contains twenty bits. After the representation scheme is applied to all the individuals (chromosomes), the problem proceeds towards the algorithm.

Following are the steps used in the Genetic Algorithm.

1) To start with, all variables and objective function are characterized and selected. The GA starts by elucidating input variables whose values are to be upgraded utilizing objective function and yield variables whose values are to be anticipated utilizing genetic administrators.

   The objective function to be minimized is defined as

   Objective function =

   $$\sqrt{\left(rfnf_{fl}-rfnf_{x_{1,g}}\right)^2+\left(rsnf_{fl}-rsnf_{x_{1,g}}\right)^2+\left(rtnf_{fl}-rtnf_{x_{1,g}}\right)^2} \quad (5.22)$$

   $rfnf_{fl}$= First natural frequency from the working place in the dimensionless form

   $rfnf_x$ = Dimensionless form of first natural frequency

   $rsnf_{fl}$ =Second natural frequency from the working place in the dimensionless form

   $rsnf_x$ = Dimensionless form of second natural frequency

   $rtnf_{fl}$ =Third natural frequency from the working place in the dimensionless form

   $rtnf_x$ = Dimensionless form of third natural frequency

   g =number of generations

2) A data pool or initial population (from regression analysis) generated containing ten numbers of data sets (individuals). The individuals are then normalized to their relative values as the data treated in the Regression Analysis are not normalized. Two parents (i.e., two information set) based on their fitness values are selected from the data pool (i.e., from ten information sets) utilizing the objective function.

3) The selected parents undergo crossover. Here two-point crossovers are used. As the chromosomes contain twenty bits, the crossover points are chosen five bits left and right of the chromosome. Figure 5.11 shows the presentation of parent with crossover points.

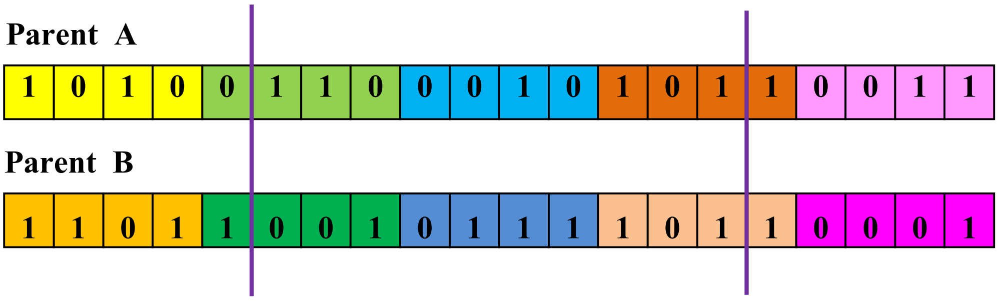


Figure 5.11: Parent chromosomes with crossover points

4) The offsprings (two numbers) from the parents are determined. Figure 5.12 describes the application of two point crossover in the Genetic Algorithm for damage detection.

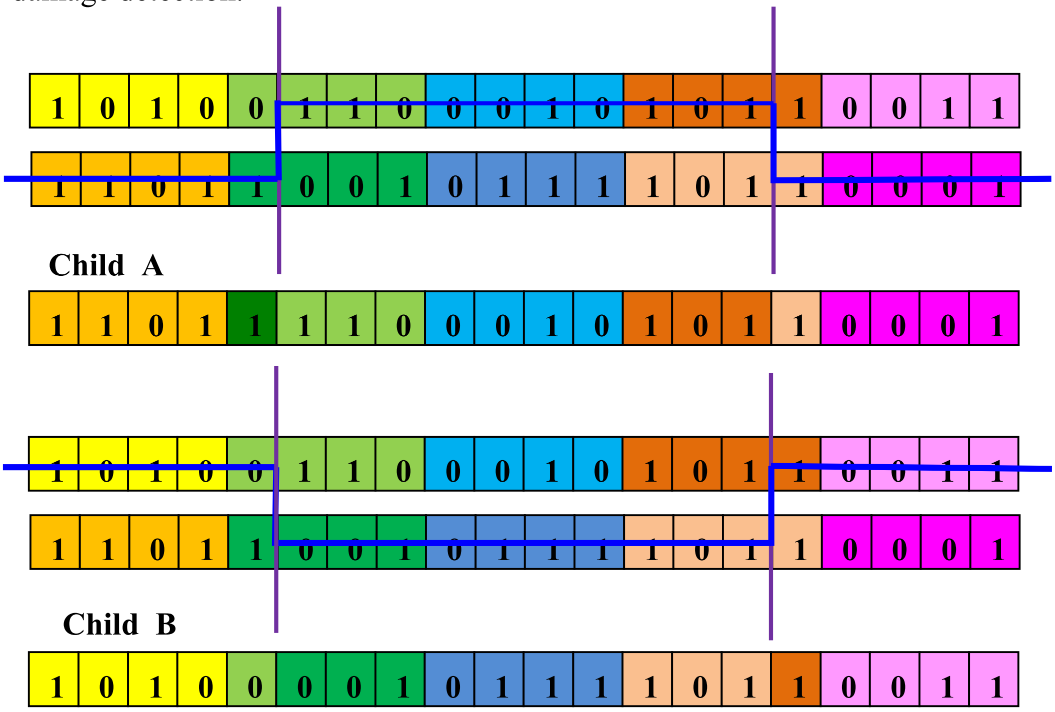
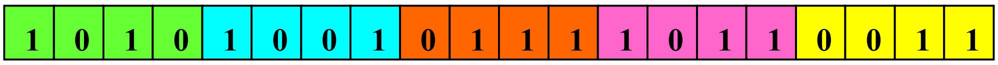
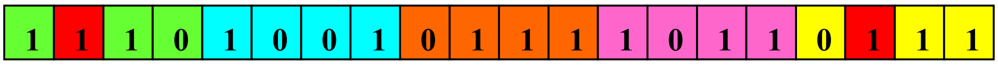


Figure 5.12: Description of two-point crossover implemented in damage detection

5) After crossover, mutation is performed. In the proposed method, a binary encoding scheme is used, so the mutation rate used is 0.1% of the string. As the chromosome consists of 20 bits, only two bits at a time are flipped or altered. Figure 5.13 describes the application of tossing type of mutation in the Genetic Algorithm for damage detection.



Chromosomes before mutation



Chromosomes after mutation

Figure 5.13: Description of mutation process implemented in damage detection

6) Again fitness evaluation of the parents and offsprings are done. Then from the comparison of the fitness values of the parents and children, the best fit member is discovered.
7) After the comparison of the fitness values, if the offspring comes as a best fit, then it is added to the data pool, and another arrangement of information pool is generated. In case a parent comes as the best fit, then the desired output (rcd, rcl), is the output of the parent data set. Steps from 2-10 are repeated in each iteration, till the algorithm meets the threshold values.

Figure 5.14 describes the steps used in flow chart form. The algorithm terminates when it meets the threshold values. The threshold values for GA to stop are as given below. The algorithm stops when it meets any of the criteria first.

i. 50 generations
ii. Maximum time elapsed (running time of the algorithm, i.e., two minutes)

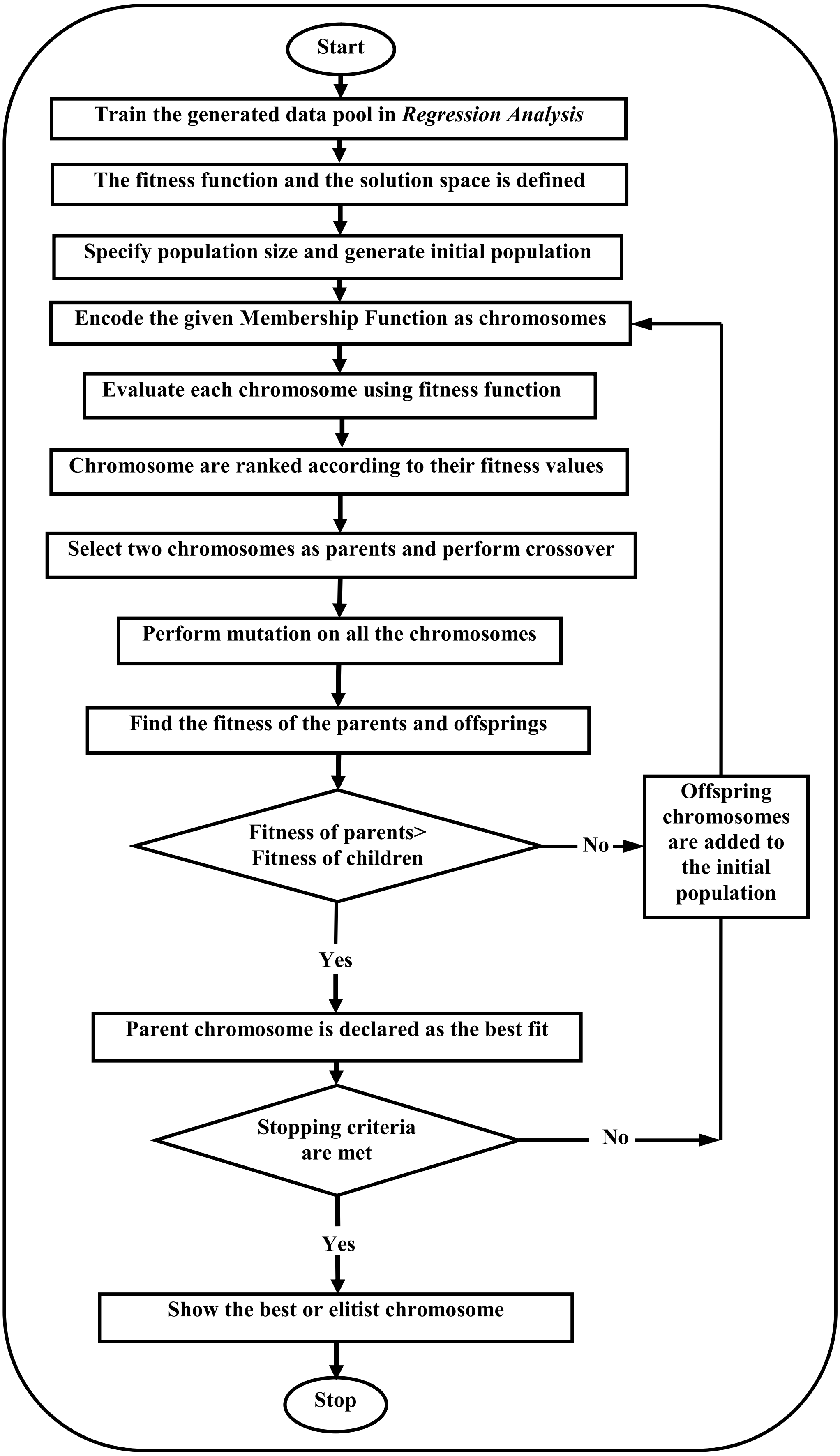


Figure 5.14: Flowchart of Genetic Algorithm for damage detection

5.2.4 Result Table of Adaptive Genetic Algorithm (AGA) Analysis

Table 5.13: Comparison of the results of AGA with FEA of a cantilever beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the AGA technique	rcl using the AGA technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9923	0.9912	0.9966	0.325	0.21875	0.3081	0.2073	5.2	5.2	5.2
2	0.9931	0.9926	0.9978	0.3	0.20625	0.2844	0.1955	5.19	5.21	5.2
3	0.9946	0.9942	0.9972	0.2875	0.23125	0.2725	0.2191	5.2	5.22	5.21
4	0.9959	0.99772	0.999	0.125	0.21875	0.1185	0.2073	5.18	5.2	5.19
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2607	0.3436	5.2	5.2	5.2
Total Average Error in %									5.2	

Table 5.14: Comparison of the results of AGA with Exp. analysis of a cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the AGA technique	rcl using the AGA technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3259	0.4444	5.18	5.18	5.18
2	0.9974	0.989	0.9999	0.375	0.5	0.3555	0.4740	5.19	5.19	5.19
3	0.99816	0.9982	0.9979	0.25	0.375	0.237	0.3555	5.2	5.19	5.19
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2073	0.3852	5.19	5.17	5.18
5	0.9892	0.9996	0.9981	0.35	0.1875	0.3318	0.1777	5.19	5.18	5.18
Total Average Error in %								5.18		

Table 5.15: Comparison of the results of AGA with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the AGA technique	rcl using the AGA technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3613	0.3080	5.22	5.23	5.22
2	0.9966	0.9961	0.9978	0.3625	0.29375	0.3436	0.2784	5.21	5.21	5.21
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3376	0.2606	5.21	5.22	5.21
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3317	0.2725	5.21	5.19	5.2
5	0.9975	0.9991	0.9970	0.4	0.175	0.3791	0.1658	5.22	5.21	5.21
Total Average Error in %									5.21	

Table 5.16: Comparison of the results of AGA with Exp. analysis of a fixed-fixed beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the AGA technique	rcl using the AGA technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.3	0.18125	0.2843	0.1718	5.18	5.19	5.18
2	0.9981	0.9964	0.9977	0.33125	0.26875	0.3140	0.2547	5.18	5.18	5.18
3	0.9984	0.999	0.997	0.29375	0.1375	0.2784	0.1303	5.19	5.17	5.18
4	0.9985	0.9991	0.9975	0.31875	0.15625	0.3021	0.1481	5.17	5.18	5.17
5	0.9987	0.9999	0.9957	0.18125	0.2375	0.1718	0.2251	5.18	5.17	5.17
Total Average Error in %									5.17	

5.3 Analysis of hybridized Mamdani-Adaptive Genetic-Sugeno model

From the review of the literature available on damage detection using Fuzzy Logic and Genetic Algorithm, following observations have been made.

Several authors have used fuzzy logic for damage detection using the Mamdani FIS. The membership functions used in the Mamdani FIS are also different. Some have used the simple membership functions [183] while some others have used combination of membership functions [184]. It has been noticed by the researchers that the Mamdani FIS using the combination of membership functions gives better result than the simple membership functions. Fewer researchers have used the Sugeno model for damage detection. Most of the researchers have used Sugeno model with Artificial Neural Network for damage detection. When the results of the Mamdani FIS and Sugeno FIS are compared, it has been noticed that the Sugeno FIS gives preferred results than the Mamdani FIS. Likewise many researchers have used Genetic Algorithm for damage detection, some of which are also narrated in “Literature Review” chapter. Simple Genetic Algorithm is very easy to understand and simple to apply, once the designer has understood the dynamics of the problem. Though it is very widely used in many of the engineering fields, it has some shortcomings like inability in achieving global solution (optimization). This occurs mainly due to the random search of the solution space which is also time consuming. So in the proposed Adaptive Genetic Algorithm, Regression Analysis has been incorporated to the statistical modeling of the variable relationship, so that the GA will take less time to cover the entire solution space

After analyzing all the above stated factors, the current method is proposed. In the proposed method, 3-stage hybridization method is developed.

5.3.1 Design and Development of hybridized Mamdani-Adaptive Genetic-Sugeno model

The previous sections of this chapter have discussed the benefits of Mamdani FIS, Sugeno FIS and Adaptive Genetic Algorithm. So in this section, a method comprising 3-stage hybridization is used for the damage detection in beams of two end conditions (fixed-free, fixed- fixed). The data pool is treated in multiple stages, finally to give the crack location (rcd, rcl).

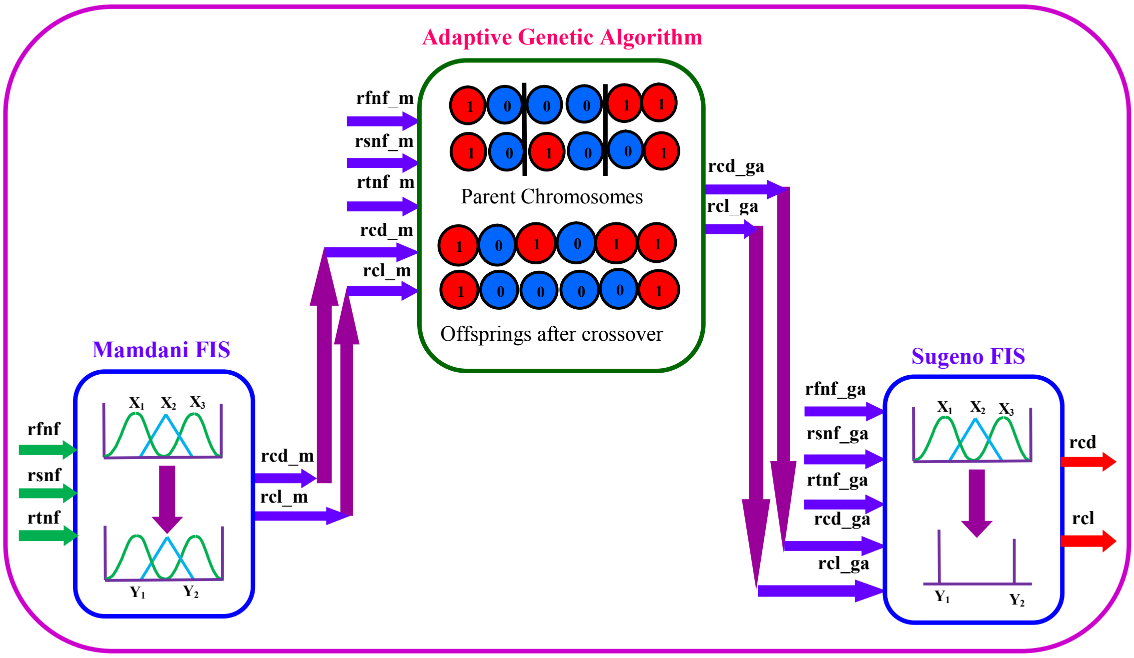


Figure 5.15: Presentation of 3-stage determination of damage location using Mamdani-Adaptive Genetic-Sugeno (MAS) model

In the first stage the data pool is treated in the Mamdani FIS. The Mamdani FIS has been designed using shuffled membership functions comprising of triangular and Gaussian MFs and the efficiency of the Mamdani FIS using shuffled membership functions has already been noticed in Section 5.1 of this chapter. In the Mamdani FIS, changing the input values, the output values are obtained for at least hundred runs. After the training of the data pool in the Mamdani segment, the transit data is generated with crack location as rcd_m and rcl_m. After obtaining the first set of data from Mamdani FIS; it is treated in the Adaptive Genetic Algorithm segment as depicted in Section 5.2 of this chapter.

During the treatment of the data in this segment, the results get closer towards the global solution due to the application of the data in Regression Analysis. After applying Regression Analysis to the hundred data sets, half of the data sets are taken to be trained in the Genetic Algorithm. The crack locations from the Genetic Algorithm are named as rcd_ga and rcl_ga. The GA is then run for hundred times. Out of the hundred runs, fifty different data sets are taken to make the second data pool.

The second data pool is then trained in the Sugeno FIS. After the second stage treatment of the data pool, the data gets more refined. After the training of the second data pool in the Sugeno FIS, the final results of the 3-stage training of the data are obtained with better crack location parameters. Due to the achievements of better results from the Sugeno FIS, it has been kept in the final segment of the training procedure after the Adaptive Genetic Algorithm segment. Figure 5.13 depicts the pictorial presentation of the stages of the 3-stage determination of damage location using Mamdani-Adaptive Genetic-Sugeno model.

5.3.2 Result Table of hybridized Mamdani-Adaptive Genetic-Sugeno (MAS) model

Table 5.17: Comparison of the results of MAS with FEA of a cantilever beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the MAS technique	rcl using the MAS technique	percent age error rcd	percent age error rcl	Total error in %
1	0.9923	0.9912	0.9966	0.325	0.21875	0.3099	0.2086	4.62	4.61	4.61
2	0.9931	0.9926	0.9978	0.3	0.20625	0.2862	0.1967	4.58	4.6	4.59
3	0.9946	0.9942	0.9972	0.2875	0.23125	0.2742	0.2206	4.6	4.58	4.59
4	0.9959	0.9977	0.999	0.125	0.21875	0.1192	0.2086	4.59	4.61	4.6
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2622	0.3458	4.63	4.58	4.60
Total Average Error in %									4.6	

Table 5.18: Comparison of the results of MAS with Exp. analysis of a cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the MAS technique	rcl using the MAS technique	percent age error rcd	percent age error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3278	0.4471	4.62	4.59	4.60
2	0.9974	0.989	0.9999	0.375	0.5	0.3577	0.4769	4.58	4.59	4.58
3	0.99816	0.9982	0.9979	0.25	0.375	0.2384	0.3577	4.6	4.6	4.6
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2086	0.3875	4.6	4.6	4.6
5	0.9892	0.9996	0.9981	0.35	0.1875	0.3338	0.1788	4.59	4.6	4.59
Total Average Error in %									4.59	

Table 5.19: Comparison of the results of MAS with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the MAS technique	rcl using the MAS technique	percent age error rcd	percent age error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3636	0.3100	4.62	4.61	4.61
2	0.9966	0.9961	0.9978	0.3625	0.29375	0.3457	0.2801	4.61	4.63	4.62
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3397	0.2623	4.62	4.59	4.60
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3339	0.2742	4.6	4.62	4.61
5	0.9975	0.9991	0.9970	0.4	0.175	0.3815	0.1669	4.61	4.61	4.61
Total Average Error in %									4.61	

Table 5.20: Comparison of the results of MAS with Exp. analysis of a fixed-fixed beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the MAS technique	rcl using the MAS technique	percen tage error rcd	percent age error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.3	0.18125	0.2861	0.1729	4.6	4.58	4.59
2	0.9981	0.9964	0.9977	0.33125	0.26875	0.3160	0.2564	4.59	4.58	4.58
3	0.9984	0.999	0.997	0.29375	0.1375	0.2802	0.1311	4.58	4.61	4.59
4	0.9985	0.9991	0.9975	0.31875	0.15625	0.3040	0.1490	4.6	4.6	4.6
5	0.9987	0.9999	0.9957	0.18125	0.2375	0.1728	0.2265	4.61	4.61	4.61
Total Average Error in %									4.59	

5.4 Results and Discussion

Fuzzy logic system gives the flexibility to train the imprecise data and get precise result from this system. In the first section of Chapter 5, a method has been presented using Fuzzy Logic System for damage detection. Both types of Fuzzy Inference Systems have been considered in the fuzzy logic section. The Mamdani fuzzy controller has been described in Figure 5.4. The induction model has been composed utilizing two sorts of membership functions to be specific triangular and Gaussian type. The developed Mamdani FIS for damage detection has been described in Figure 5.5. The various linguistic variables used to describe the fuzzy sets are given in Table 5.1. The fuzzy rules are generated using linguistic variables and some of the fuzzy rules are supplied in Table 5.2. The implementation and aggregation of the fuzzy rules are described in Section 5.1.2.1(a). The results from the Mamdani Fuzzy Inference Systems using triangular and Gaussian MFs for fault detection in cantilever and fixed-fixed beam is supplied from Table 5.3 and Table 5.10. In the fuzzy logic section, another inference system using Sugeno model has been applied for damage detection. The Sugeno model directly gives the crisp output values by implementing and aggregating the rule weights using equation 5.16. From the comparisons of the results, it can be observed that the Sugeno model gives better and more converging results than the Mamdani model.

From the design of the FLS and the results produced from the method, it can be observed that FLS has the advantage of storing expert knowledge in the form of fuzzy rules that are easy to conceptualize.

The next section of this chapter deals with the Adaptive Genetic Algorithm. The database used to form initial population for the algorithm is generated using the results from theoretical, finite element and experimental analyses for two different end conditions are given in Tables 5.11 and 5.12. The data base is treated in the Regression Analysis method to obtain the relationship between the dependent and independent variables which is used to limit the randomness of the search process of GA. The genetic operators utilized in this algorithm, like crossover and mutation are described in Figures 5.12 and 5.13 respectively. The flowchart describing the algorithm procedure is presented in Figure 5.14. The selection of parents which is used to search the entire search domain mainly depends on the objective function/fitness function is given in equation 5.22. The results from the method taking two types of beam constraints into consideration are given in Tables 5.13 to 5.16. The errors have been calculated using equations 1.4 to 1.7 of chapter 1.

The third section of this chapter describes the fusion of all three methods as described in the previous section of this chapter. In this part of the chapter namely, Mamdani Fuzzy Inference System, Sugeno Fuzzy Inference System and Adaptive Genetic Algorithm are incorporated together in one frame. All these methods are robust and efficient enough to act as a powerful damage detection device. But in this chapter, an effort is made to combine the efficacy of all these methods to get better damage parameters from the three stage refinement of the data base. The steps used in the proposed method are described in Figure 5.15.

5.5 Summary

The problem of crack detection has created interest among a large number of researchers. A structural model of a cracked structure always carries uncertainties and the measured vibration signals may produce unreliable damage detection method.

In this chapter, the uncertainties associated with the problem of damage detection are presented using Fuzzy Logic System (FLS). This is a nonlinear adaptive control method.

One of the advantages of Fuzzy Logic is that it does not require any mathematical model of the concerned problem. The total average error in Mamdani FIS for cantilever beam and fixed-fixed beam is found to be around 5.5% when compared with the results of Finite Element Analysis and Experimental Analysis respectively for Mamdani FIS. Similarly, for Sugeno FIS, the total average error is within 5.3%. So the proposed method representing a general learning method can train the damage variables efficiently and can significantly reduce the computational time and effort to develop an expert system.

The second section of this chapter describes a global non destructive damage detection method using Adaptive Genetic Algorithm. From the last two decades, Genetic Algorithms are proven to be useful tools for solving various problems. So to have other advantages of the GA, the genetic operators are kept similar to simple GA. The total average error for cantilever beam and fixed-fixed beam is found to be within 5.2% when compared with the results of finite element and experimental analyses respectively. The predetermination of database to guide the population toward the wanted solution make Adaptive Genetic Algorithm more approachable for making an efficient and robust tool for crack detection.

The third section describes the design and development of the Mamdani-Adaptive Genetic-Sugeno (MAS) model. This model incorporates the good nesses of all three methods which are described in this chapter. Here two sets of data pools are generated from the treatment of the original data sets, each time enhancing the convergence efficiency. The total average error for cantilever beam and fixed-fixed beam is found to be around 4.6% when compared with the results of finite element analysis and experimental analysis respectively. From the results it can be analyzed that the proposed model gives better converging results as compared to each individual method, which can be observed from the tables.

Chapter 6

Analysis of Clonal Selection Algorithm for Structural Damage Detection

Damage detection of systems represents an important research topic widely investigated. During the last two decades, several researches have been conducted with reference to beams, trusses, plates, shells, bridges, offshore platforms, and other large civil structures, aerospace and composite structures to detect structural damages by monitoring the dynamic response of the system. Damage in structural and rotating machine elements causes the local reformation in the dynamical parameters of the system. Therefore, changes in the physical properties will cause changes in the modal properties. The aim of this chapter is to derive a simple procedure for estimating the damage in structures based on a data driven pathogen identification technique. The changes in the modal parameters are used as the input variables to find out the damage severity. The responses (natural frequencies) are obtained using Theoretical, Finite Element and Experimental analyses, and then Clonal Selection Algorithm (CSA) is proposed to detect and characterize these defects. This chapter proposes a robust computational algorithm based on the theory of Clonal selection that more accurately takes into account the affinity maturation of the immune response and produces a good converging result.

6.1 Introduction

The Clonal Selection Algorithm is a type of Artificial Immune System, which describes basic features of natural immune system. In Clonal Selection Algorithm the antibodies that can recognize the antigens are selected to proliferate, in other words they undergo replication or cloning [185]. The selected antibodies undergo an affinity maturation process, which improves their affinity to the particular antigens. These antibodies normally bind to the antigens leading to their ultimate elimination by other immune cells. The proliferation used in the Clonal selection theory is a type of mitotic process; the cells divide themselves to give the required progenies, there is no crossover involved in this process. During reproduction, the B-cell progenies go through an affinity maturation (hyper mutation) operation with a powerful selective pressure which results in production of antibodies with higher affinities with the particular antigen. This entire process of mutation and selection is similar to the natural selection of species. The main attribute of the immune response is that the antibodies with higher affinities are selected to become memory cells with long life period. These memory cells become eminent in future responses to the same antigen or a similar one. Figure 6.1 describes the of the Clonal Selection Algorithm features.

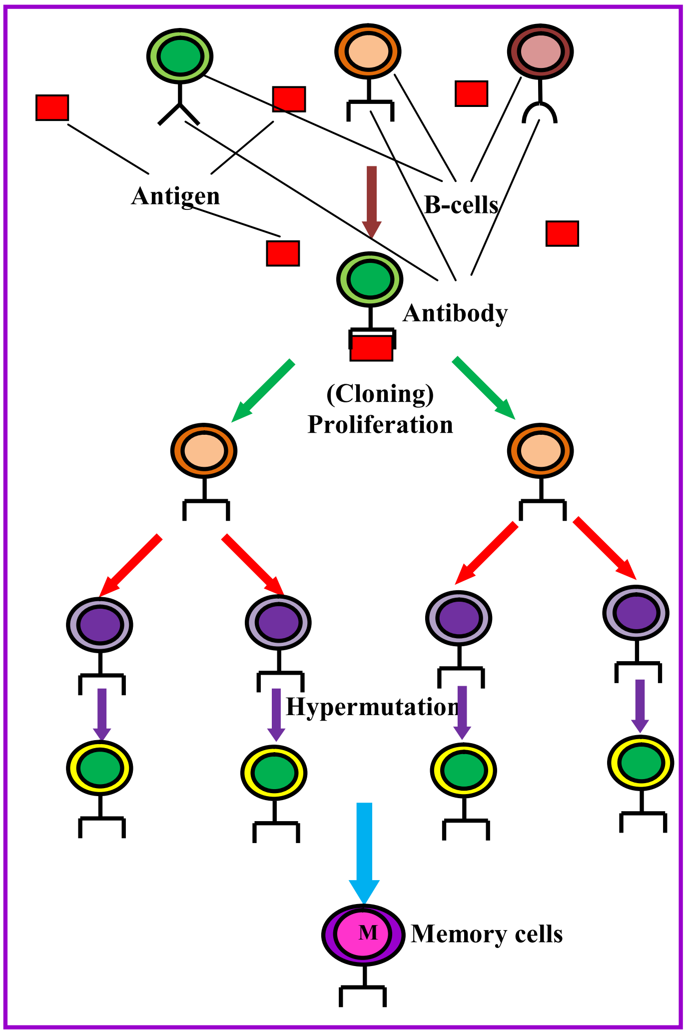


Figure 6.1: Pictorial representation of clonal selection algorithm

6.2 Fundamental Operations in Clonal Selection Algorithm

For successful implementation of the Clonal Selection Algorithm, four important and basic decisions have to be made: Encoding, Similarity Measure, Selection and Mutation.

These operations which form the fundamental elements in designing the methodology for damage detection are described as follows. The major challenge in this method is the encoding of the antibodies and antigens according to the problem variables.

6.2.1 Initialization / Encoding

For the successful running of the algorithm, encoding of the variables is most important. The encoding scheme hugely influences the performance of the fitness function. In most of the algorithm models, the antibodies and antigens are encoded in a similar manner for the ease of handling the variable features. In general, the most common way of encoding/representing is a string of numbers, features or bits. In the current algorithm, the antibodies and antigens are encoded using binary string. The antibodies and antigens are presented in Figure 6.2.

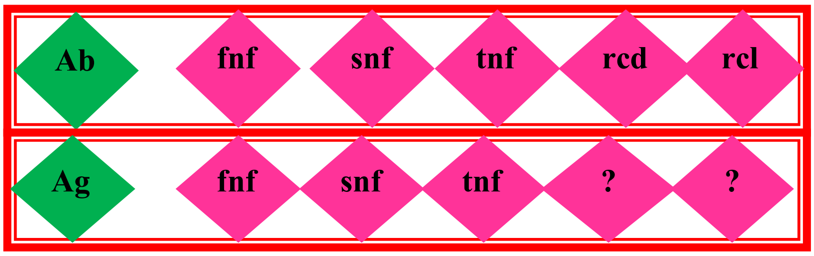


Figure 6.2: Presentation of the antibodies and antigens

6.2.2 Selection

The selection operation in almost all of the Artificial Intelligence Algorithms is based on the fitness of the individuals or solutions. Selection in CSA depends on the measurement of affinity of the antibody towards the antigen. During antigen-antibody interactions similarity/affinity check is applied on entire population of antibodies. A set of ‘n’ antibodies are selected from the entire anti body pool based on the affinity value with the antigen. In this model, the antibodies are selected according to their fitness rank or the affinity towards the antigen.

6.2.3 Similarity or Affinity Measurement

As the system is exposed to the foreign elements, the immune system depends on the affinity values of the antibodies against the antigen. Affinity is a measure of similarity/matching and depends on the problem definition. Affinity Measure/ Similarity measure /Matching rule is an important operation in the design process in developing a Clonal Selection Algorithm. The selection of antibodies depends on the affinity measurement value which is determined by the affinity function. The affinity function is closely related to the representation scheme of the antibodies and antigens. For binary encoding, the best affinity measuring function is Hamming Distance method or its supplement. Hamming Distance checks the number of bit positions that have same values in antigen and antibody. Most of the AIS use the Euclidean distance affinity function for numeric data.

The affinity measurement takes into account the Hamming Distance 'D' between the antigens and antibodies according to the following equation

$$D=\sum_{r=1}^{L}\delta \text{ Where } \delta=\begin{cases}1,\text{if} ab_i \neq ag_i\\0,\text{otherwise}\end{cases} \tag{6.1}$$

6.2.4 Cloning/Proliferation

The Clonal Selection Algorithm is based on the process of copying of the immune system of an organism. Different researchers have addressed different model of Clonal Selection Algorithm but the main computational framework remain the same for all the models. So cloning process is the most important and common operation in all models. The clonal size for each selected antibody is determined by the affinity between the antibody and antigen.

The clonal size could be a constant integer. But in the current algorithm the integer is found out using the following equation

$$C=\sum_{r=1}^{n}\text{round}\left(\frac{\beta.Q}{r}\right) \tag{6.2}$$

Where,

C- Total number of clones generated

n- Selected antibodies

β- Multiplying factor

Q- Total number of antibodies (population size)

r- Rank of the selected antibodies

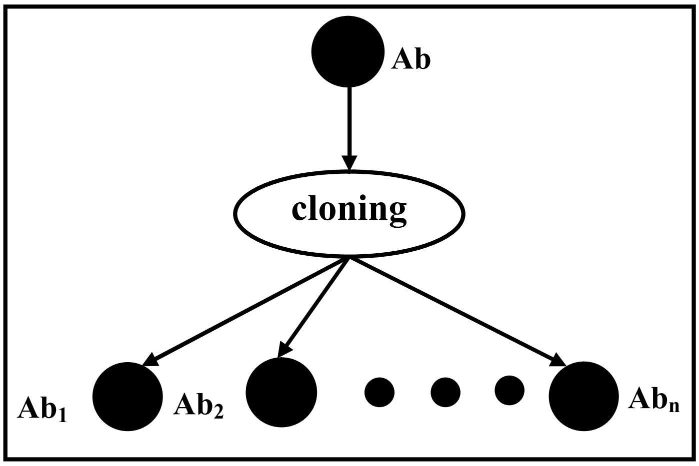


Figure 6.3: Description of Cloning/proliferation process

6.2.5 Somatic Hypermutation

The population of clones is submitted to hypermutation. Usually hypermutation or simple mutation introduced in the algorithm to prevent the algorithm from being trapped in the local solutions and to attain global solution for better solution (antibodies). In this case, point mutation creates antibodies at a rate indirectly proportional to the affinity of the antibody with the antigen. Point mutation creates new antibodies by altering the bits of one or more binary design variables of their parent antibodies.

6.3 Analysis of Clonal Selection Algorithm for damage detection in cracked structures

This chapter proposes a strong computational application of the Clonal Selection Theory, which more accurately considers the affinity maturation of the immune response and produces a good converging result. In this work, Clonal Selection Algorithm is used to find the damage severity in a cracked cantilever beam with single crack. The results from the Clonal Selection Algorithm have been produced in the result table.

The antibodies (Ab) in the current investigation are consisting of ‘rfnf’, ‘rsnf’, ‘rtnf’, ‘rcd’ and ‘rcl’. The antigens are chosen randomly (Ag i.e. ‘rfnf’, ‘rsnf’ and ‘rtnf’) and are introduced to the antibodies in the collection or stock (dataset). The data pools for the two different end conditions (fixed-free, fixed- fixed) of the beam are provided in Tables 6.1 and 6.2. The antigens represent the data from the field i.e., the values of the dynamic characteristics given from the damage site. Here each antibody and antigen is coded using binary encoding scheme. Then the antibody population is subjected to affinity measurement. In the present work, hamming distance method is used for affinity matching operation.

In Clonal Selection Algorithm the antibodies contain the information of both input and output variables but the antigen does not contain any information about the output variables. So the principle point of the algorithm is to reduce the affinity value i.e., lesser the hamming distance more fit is the counter acting antibody or it has more proclivity towards the antigen. At the very first sight, it may appear that the Genetic Algorithm and Clonal Selection Algorithms are similar. But there are many differences like Clonal Selection Algorithm does not include the crossover operation. Similarly the Genetic Algorithm does not produce any memory cell for future access to similar set of natural frequencies (antigens).

Table 6.1: Sample Data pool for cantilever beam used in CSA

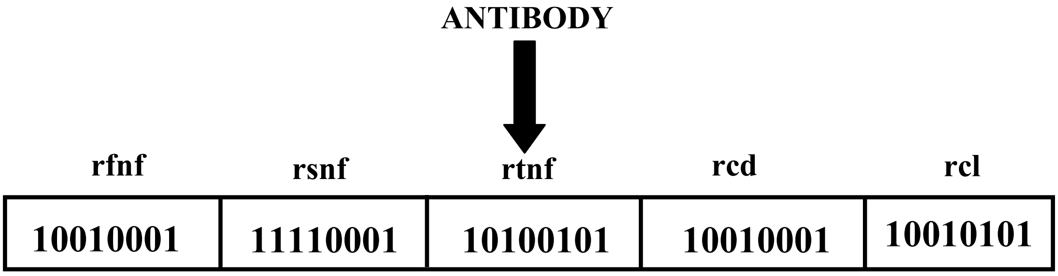
Sl. No	rfnf	rsnf	rtnf	rcd	rcl
1	0.9986	0.9966	0.9981	0.15625	0.1875
2	0.9979	0.9963	0.9986	0.1875	0.25
3	0.9992	0.99734	0.99895	0.15625	0.28125
4	0.9950	0.9982	0.9938	0.3125	0.3125
5	0.9971	0.9983	0.9962	0.28125	0.34375
6	0.9977	0.9999	0.9982	0.2	0.25625
7	0.9979	0.9988	0.9981	0.2125	0.26875
8	0.9979	0.9972	0.9977	0.2625	0.275
9	0.9945	0.9939	0.9976	0.3125	0.29375
10	0.9977	0.9999	0.9982	0.2	0.25625

Table 6.2: Sample Data pool for fixed-fixed beam used in CSA

Sl. No	rfnf	rsnf	rtnf	rcd	rcl
1	0.9952	0.9992	0.9944	0.28125	0.5625
2	0.9960	0.9999	0.9987	0.25	0.25
3	0.9965	0.9945	0.9966	0.5	0.375
4	0.99649	0.9999	0.99509	0.333	0.5
5	0.99979	0.9960	0.9996	0.333	0.3125
6	0.9463	0.9460	0.9458	0.367	0.3125
7	0.9552	0.9551	0.9549	0.2833	0.375
8	0.9621	0.9618	0.9616	0.25	0.4375
9	0.9924	0.9953	0.9944	0.35	0.40625
10	0.9988	0.9993	0.9976	0.15625	0.3125

The Clonal Selection Algorithm for damage detection and localization is described as follows;

(1) First the antibodies and antigens are initialized and encoded. Each antibody represents a solution containing the parameters ('rfnf', 'rsnf', 'rtnf', 'rcd' and 'rcl') of the given problem. Each variable in the antibodies and antigens are encoded into binary strings before proceeding to the algorithm. Figure 6.4 describes the encoded antibody. Each variable in the antibody is coded using eight bits, so the antibody binary string contains forty bits.



rfnf	rsnf	rtnf	rcd	rcl
10010001	11110001	10100101	10010001	10010101

Figure 6.4: Encoding of antibodies

(2) A set (Q) of candidate solutions (antibodies), composed of the subset of memory cells (M) added to the remaining (Q_r) population ($Q = Q_r + M$) is generated.

(3) All the individuals in population Q are evaluated using the fitness function for affinity measurement. Based on the affinity measure results, the 'n' best individuals of the population (Q_n) are selected.

$$\text{affinityfunction}=\sqrt{\left(\text{rfnf}_{\text{fl}}-\text{rfnf}_{x_{1,g}}\right)^2+\left(\text{rsnf}_{\text{fl}}-\text{rsnf}_{x_{1,g}}\right)^2+\left(\text{rtnf}_{\text{fl}}-\text{rtnf}_{x_{1,g}}\right)^2} \tag{6.3}$$

rfnf_{fl}= First natural frequency from the field in the dimensionless form

rfnf_x = Dimensionless form of (relative) first natural frequency

rsnf_{fl} =Second natural frequency from the field in the dimensionless form

rsnf_x = Dimensionless form of (relative) second natural frequency

rtnf_{fl} =Third natural frequency from the field in the dimensionless form

rtnf_x = Dimensionless form of (relative) third natural frequency

g =number of generations

(4) These ‘n’ best individuals of the population reproduce to form a population of clones (C). The number of clones depends directly on the affinity measurement values with the antigen. The clones are generated using equation (6.2). After proliferation, each antibody containing these parameters with good affinity values are replicated. So the information about the good antibodies is also inherited in the next generation of the algorithm. Figure 6.5 describes the cloning process of ‘n’ selected antibodies.

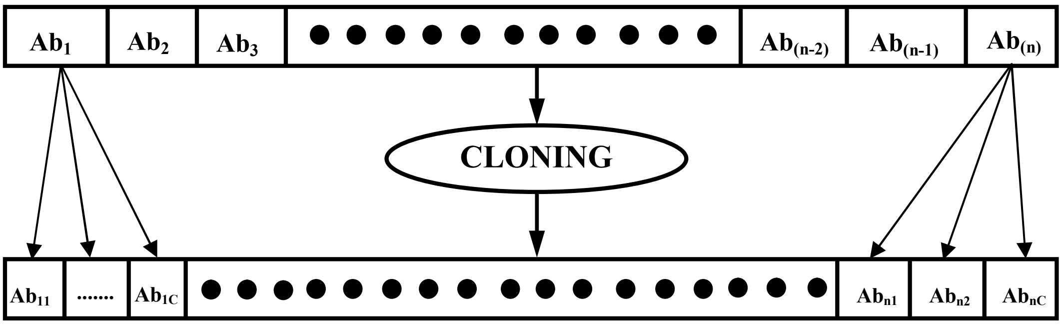


Figure 6.5: Cloning of ‘n’ selected antibodies

(5) After cloning, the population of clones is submitted to hypermutation. Point mutation creates new antibodies by altering the bits of one or more binary string of the parent antibodies. A higher mutation rate does not always guarantee performance enhancement. It also increases the probability of destroying the performance of the algorithm. So the mutation rate is kept between 0.001 to 0.1% of number of bits in the binary string. For this algorithm the mutation rate is kept at 0.1%, so four bits at a time are flipped randomly.

(6) Mutation generates a population of mutated clones (C_m). These mutated clones contain different information of the parameters (rfnf, rsnf, rtnf, rcd and rcl). So the algorithm will be able to search the solution domain avoiding premature

convergence which may occur due to the cloning process, as the informations are repeated during this operation.

(7) The affinity function is again applied to each member of the population (C_m). The highest scoring candidate is credited as the memory cell. If the affinity value for the antigen is greater than the current memory cell, then the new memory cell will replace current memory cell and will become the current memory cell for the next iteration.

(8) The antibodies with trivial affinity scores will be replaced by new randomly generated antibodies. Steps 2-7 are repeated during iterations of the algorithm.

Figure 6.6 shows the flowchart for Clonal Selection Algorithm. Stopping criteria for all the evolutionary algorithms are kept same for fair comparison between all the algorithms.

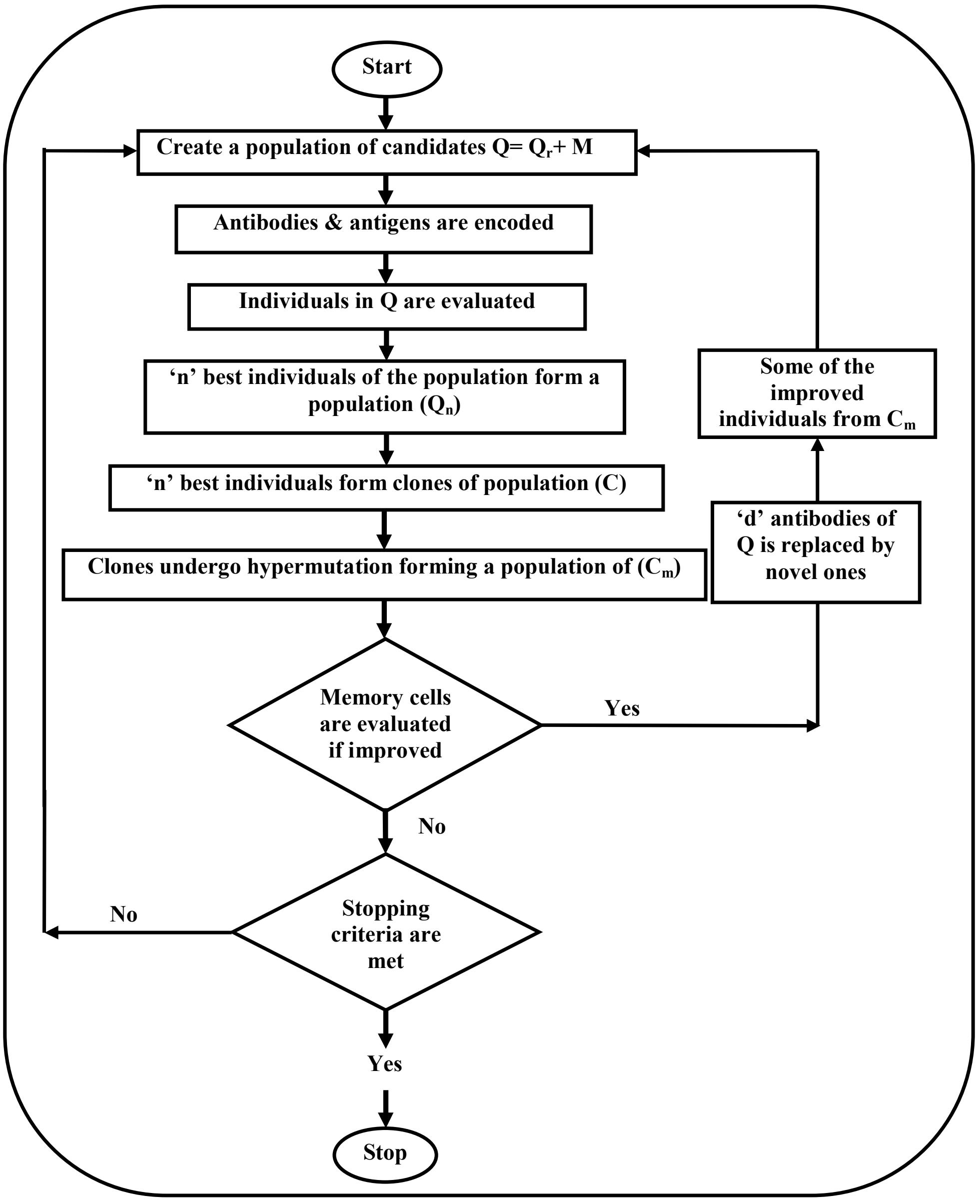


Figure 6.6: Flowchart on clonal selection algorithm

6.4 Result Table

Table 6.3: Comparison of the results of CSA with FEA of a cantilever beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the CSA technique	rcl using the CSA technique	percentage error rcd	percentage error rcl	Total Error in %
1	0.9923	0.9912	0.9966	0.325	0.21875	0.3084	0.2080	5.1	4.9	5
2	0.9931	0.9926	0.9978	0.3	0.20625	0.2853	0.1959	4.9	5	4.95
3	0.9946	0.9942	0.9972	0.2875	0.23125	0.2731	0.2194	5	5.1	5.05
4	0.9959	0.99772	0.999	0.125	0.21875	0.1186	0.2080	5.1	4.9	5
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2615	0.3443	4.9	5	4.95
Total Average Error in %									4.99	

Table 6.4: Comparison of the results of CSA with Exp. analysis of a cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the CSA technique	rcl using the CSA technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3265	0.4453	4.95	4.95	4.95
2	0.9974	0.989	0.9999	0.375	0.5	0.3563	0.4750	4.97	4.93	4.95
3	0.99816	0.9982	0.9979	0.25	0.375	0.2375	0.3562	4.99	4.92	4.95
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2078	0.3860	4.96	4.97	4.96
5	0.9892	0.9996	0.9981	0.35	0.1875	0.3325	0.1781	4.96	4.99	4.97
Total Average Error in %									4.95	

Table 6.5: Comparison of the results of CSA with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the CSA technique	rcl using the CSA technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3621	0.3087	5	5	5
2	0.9966	0.9961	0.9978	0.3625	0.29375	0.3444	0.2790	4.99	5.02	5.00
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3384	0.2612	5	5.01	5.00
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3325	0.2731	4.98	5	4.99
5	0.9975	0.9991	0.9970	0.4	0.175	0.3800	0.1660	4.99	5.1	5.04
Total Average Error in %									5.00	

Table 6.6: Comparison of the results of CSA with Exp. analysis of a fixed-fixed beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the CSA technique	rcl using the CSA technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.3	0.18125	0.2850	0.1722	4.97	4.97	4.97
2	0.9981	0.9964	0.9977	0.33125	0.26875	0.3147	0.2555	4.98	4.93	4.95
3	0.9984	0.999	0.997	0.29375	0.1375	0.2791	0.1306	4.96	4.99	4.97
4	0.9985	0.9991	0.9975	0.31875	0.15625	0.3030	0.1485	4.93	4.96	4.94
5	0.9987	0.9999	0.9957	0.18125	0.2375	0.1722	0.2257	4.95	4.95	4.95
Total Average Error in %									4.95	

6.5 Results and Discussion

An artificial immune based algorithm has been proposed for diagnosing structural faults. The antibodies for damage detection are designed using the database available from different sources containing both the cause (crack configuration) and effect (first three natural frequencies) of vibration. But the antigens contain only the effect (first three natural frequencies) of vibration. The prediction of crack depends on the affinity measurement between the antibodies and antigens which is given in equation 6.3. The cloning process is described in Figure 6.5. The somatic hypermutation operation is similar to mutation operation of Genetic Algorithm. The hamming distance and the number of clones can be calculated using equations 6.1 and 6.2 respectively. The data pool used to form initial population for the algorithm is generated using the results from Theoretical, Finite Element and Experimental analyses for two different end conditions are given in Tables 6.1 and 6.2. The flowchart describing the algorithm procedure is presented in Figure 6.6. The results from the method taking two types of beam constraints into consideration are given in Tables 6.3 to 6.6.

6.6 Summary

Artificial Immune System comprises of different immune power motivated models. Clonal Selection Algorithm is one of the most implemented types of artificial immune based model. As the damage detection is a very difficult problem to be solved by conventional methods and is highly required by the manufacturing industries, aerospace engineering and for structural health monitoring. So in this chapter an alternative computational tool using an appealing metaphor of engineering artificial immune system is proposed for solving the problem of damage detection.

The paradigm is designed and developed, keeping in mind the dynamic changes of the structural element. Here the fundamental properties of the immune system such as diversity, error tolerance and the dynamic learning are exploited to design the model. The total average error for cantilever beam and fixed-fixed beam is found to be within 5% when compared with the results of finite element analysis and experimental analysis respectively.

Chapter 7

Analysis of Fuzzified Differential Evolution Algorithm for Structural Damage Detection

Accurate, indirect and efficient method for damage identification and detection in structures remains one of the challenging problems in engineering. There are number of methods for the detection and localization of the damage in various structural elements like trusses, frames and beams. The traditional types of damage detection methods are not very convenient for online detection of structures. For this type of problems, sometimes sophisticated optimization techniques are required. As previously stated, evolutionary algorithms present one such approach. This chapter focuses on the problem of crack detection by proposing an evolutionary algorithm known as Differential Evolution algorithm. Here mutation and crossover operations are sensible enough to find out the global maximum. This technique can also be considered as one of the inverse engineering method.

7.1 Introduction

Evolutionary Algorithms (EAs) imitate the evolution of species which works on the principle of evolving a population of candidate solutions. Evolutionary Algorithms involve nature-inspired stochastic operations like selection; mutation and recombination are proven to be very efficient in searching a global solution. The Evolutionary Algorithms mainly depend on the encoding methods used to represent the solutions in the algorithm. But the Differential Evolution Algorithm does not depend upon any representation scheme unlike other evolutionary algorithms. In this algorithm, first mutation is imposed on all the individuals rather than crossover/recombination, which initiates the addition of new information before selection. So the searching of the entire solution space become easier for the algorithm and this paves the way to obtain a better solution.

7.2 Fundamental operations in Differential Evolution Algorithm

The Differential Evolution Algorithm (DEA) was proposed by Storn and Price [186]. The algorithm became popular due to its capacity of producing effective results with simplicity. This is a population oriented evolutionary algorithm. It has the capacity of memorizing individual's optimal value by sharing the internal information. First of all, the individuals are initialized within the search space with the upper and lower boundaries defined. In the second stage, which is the evolutionary phase, the individuals undergo mutation, crossover and selection. Here each individual represents a candidate solution to the problem; these individuals are then treated in the fitness function. The fitness function is used to find the fitness of each individual (candidate solution). After finding out the fitness values of each individual, they are selected according to their fitness rank.

The initial population of Differential Evolution (DE) comprises of N_P individuals or candidate solutions. The individuals contain D-dimensional real valued parameters. $P^{(G)}$is the current population composed of encoded with individuals X_i. Figure 7.1describes the idea of the Differential Evolution Algorithm which has been used for crack detection in the current research work.

Here $X_i=\{x_1,x_2,x_3,x_4,x_5\}$- candidate solutions or individuals containing the attribute values

Where,

$x_{1\text{-}5}$- are attributes of the current problem

x_1-rfnf, x_2-rsnf, x_3-rtnf, x_4-rcd, x_5-rcl

G- Number of generations

D- Number of parameters

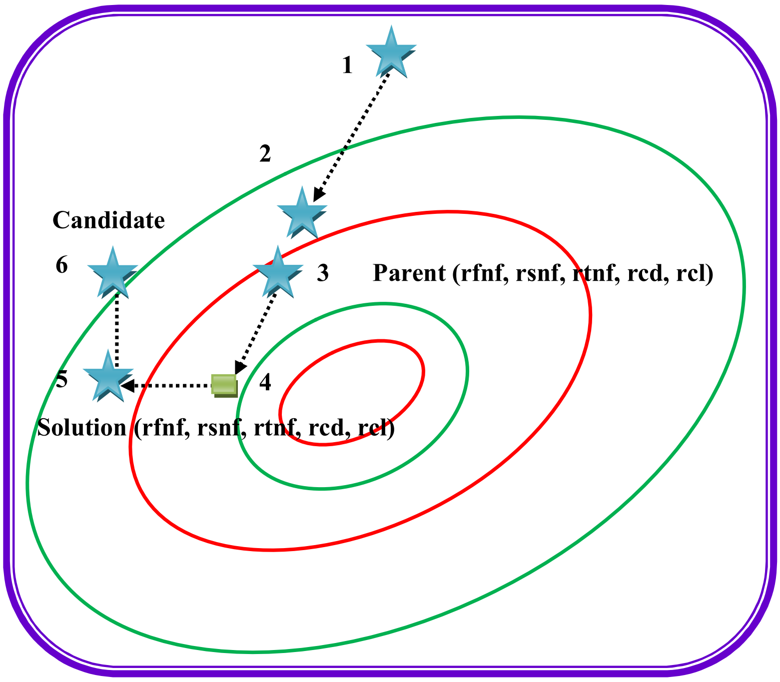


Figure 7.1: Differential Evolution Algorithm for damage detection

$$P^{(G)} = \left[X_i^{(G)}, \ldots\ldots, X_{NP}^{(G)} \right], \text{ here } i=1,\ldots\ldots,N_P \tag{7.1}$$

The vectors mentioned in equation (7.1) contain the decision variables (D) for the current problem. These vectors are called individuals which represent the candidate solutions. These individuals represent the real valued vectors. Figure 7.2 shows the pictorial presentation of the initial vectors presenting the variables.

$$X_i^{(G)} = \left[x_{1,i}^{(G)}, \ldots\ldots\ldots, x_{D,i}^{(G)} \right] \tag{7.2}$$

In the next part of the present section various basic operations of DEA which are applied in the algorithm for damage detection are described in brief.

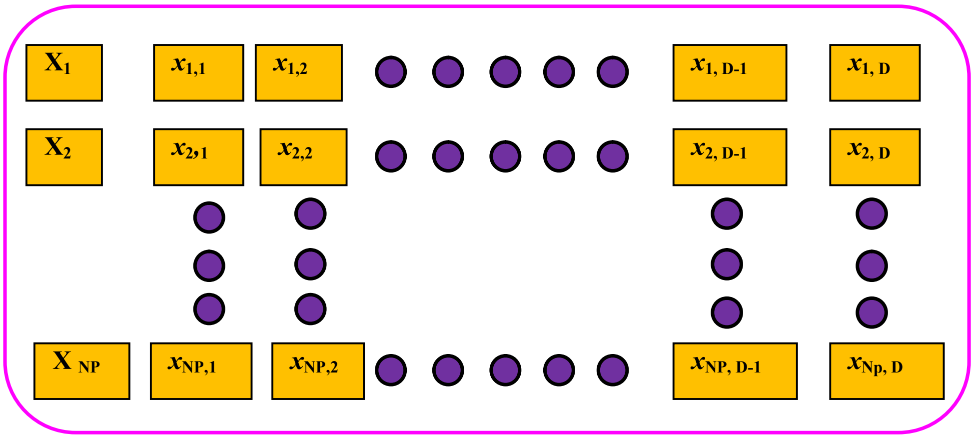


Figure 7.2: Initial population of vectors

7.2.1 Initialization

Initialization is the first operation, which is done by forming an initial population which consists of uniformly randomized individuals. The initial population is so chosen that it could incorporate the entire search space as much as possible for global search. It is constrained by the predefined minimum and maximum limits. A random number generator $rand_j(0,1)$ is used to generate a uniformly random number from within the range [0,1].

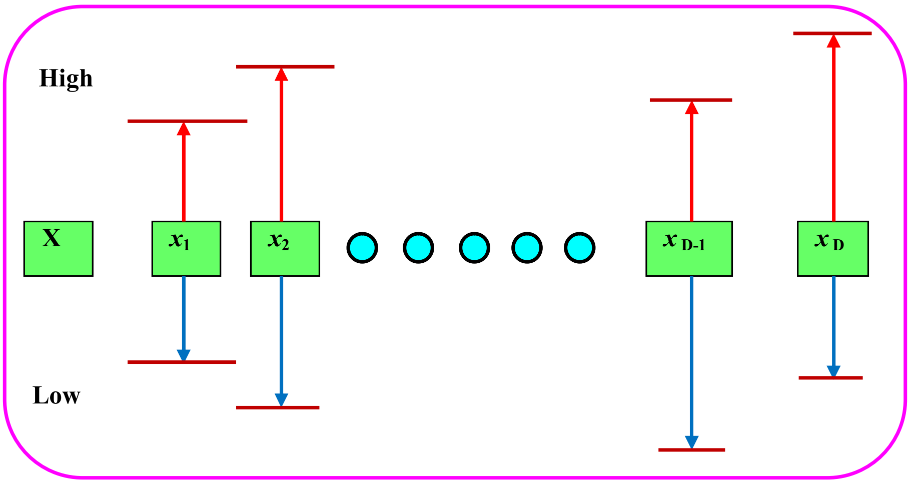


Figure 7.3: Presentation of vectors with its upper and lower limits

$$x_{j,i}^{(0)}=x_j^{min}+rand_j(0,1).\left(x_j^{max}-x_j^{min}\right),\quad j=1 \text{ to } D\ (5),\ i=1 \text{ to } N_p \tag{7.3}$$

X_j^{max} and X_j^{min} are the upper and lower limits of the jth decision variable. The subscript 'j' describes a new randomly generated value is made for each decision variable. This process also initializes the "target vector X_i". Figure 7.4 describes the initialization process.

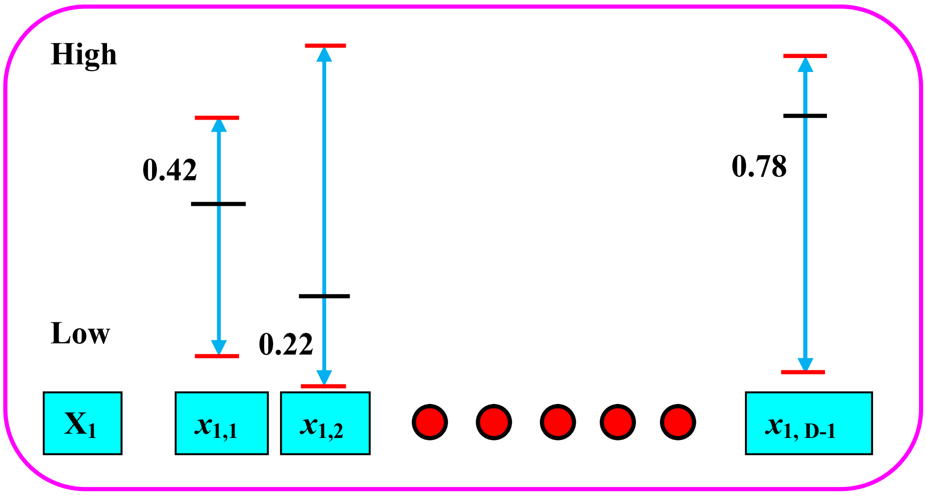


Figure 7.4: Initialization of vectors in DEA

7.2.2 Mutation Operator

Initialization in Differential Evolution leads to mutation and then recombination/crossover. Mutation is applied on a population of Np target vectors to generate a "mutant vector $X_i^{'}$" with respect to each individual. Here $X_i^{'(G)}=\left[x_{1,i}^{'(G)},.........,x_{D,i}^{'(G)}\right]$ is a mutant vector. The most frequently used mutation scheme is given below as

$$X_i^{'(G)}=X_a^G+F\left(X_b^G-X_c^G\right),i=1,........,N_P \tag{7.4}$$

The index of the base vector 'a' is chosen randomly. All the vector indices (a, b, c) are different from each other. The scaling factor $(F)\in(0,1+)$ is a real number. This scaling factor 'F' is used as a controlling factor to the rate at which the population evolves. It is used to make sure that trial vectors do not imitate the target vector so that there will be evolution of population and the total search space will be explored avoiding premature convergence.

7.2.3 Crossover Operator

In DEA, after mutation crossover/recombination is employed to generate "trial vectors $X_i^{''}$", by combining the mutant vectors $X_i^{'}$ and target vectors X_i. This operation is done according to a preselected probability of creating parameters for a trial vector from the mutant vector.

$$X_{j,i}^{''(G)}=\begin{cases}\left(X_{j,i}^{'(G)}\right) \text{if} \operatorname{rand}_j(0,1)\le C_r \text{or } j=j_{rand}\\ X_{j,i}^{(G)} \text{otherwise}\end{cases} \tag{7.5}$$

The crossover probability $C_r\in(0,1)$ is a user defined value. This number is used to control the fragment of parameter values that are copied from the mutant vectors. If the random number $\le C_r$, the trial vector is acquired from the mutant $X_i^{'(G)}$, otherwise the parameter is copied from vector $X_i^{(G)}$. The trial vector with randomly chosen index j_{rand} is taken from the mutant to ensure that the trial does not copy $X_i^{(G)}$. Trial parameter acquires characters of C_r only to approximate the true probability PC_r from the mutant. This is known as binomial crossover. j_{rand} is a randomly taken number within the limit [1, D]. Figure 7.5 describes the generation of trial vectors after recombination.

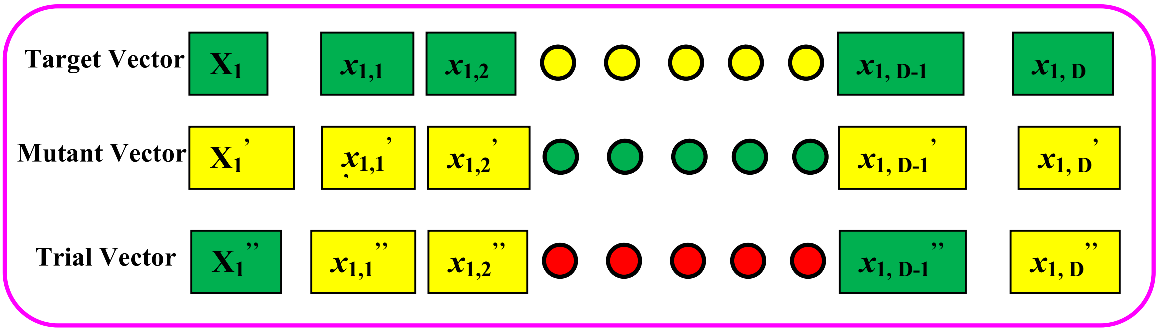


Figure 7.5: Formation of trial vectors through crossover/recombination

7.2.4 Selection Operator

The selection operation is applied on the target vector and their corresponding trial vectors. After the application of mutation and crossover sometimes, the values of some parameters of a newly generated trial vector changes. So a uniform reinitialisation is needed to be applied on them within the pre specified range. Then, the fitness function/objective function values of all trial vectors are evaluated. After that, a selection operation is performed.

If the trial vector, $X_i^{''(G)}$ has an equal or lower fitness function value (optimal) than that of its target vector $X_i^{(G)}$, it replaces the target vector in the next generation. Otherwise, the target vector continues to remain in same position in the population for the next generation as given by equation (7.6)

$$X_i^{G+1} = \begin{cases} \left(X_i^{''(G)}\right) \text{if } f(X_i^{''(G)}) \leq f(X_i^{(G)}), \ i=1,......,N_P \\ X_i^{(G)} \text{otherwise} \end{cases} \qquad (7.6)$$

7.3 Analysis of DEA for damage detection of cracked structural elements

Differential Evolution Algorithm compares the quality of trial vector with the target vector from which it inherits information about the current best solution. This allows the algorithm to integrate crossover and selection more tightly than do other evolutionary algorithms. After the installation of the new population, the process of mutation, crossover and selection is repeated for several generations till the algorithm halts. In each generation, some improved individuals are included in the initial population which can explore the solution space in search for better solutions.

The above 3 steps are repeated generation after generation until some specific termination criteria are satisfied.

The following steps portray the algorithm for Differential Evolution Algorithm.

1. The parameters like scaling factor F, crossover constant C_r, population size N_p, maximum iterations G_{max} and decision variables D (i.e.'rfnf', 'rsnf', 'rtnf', 'rcd' and 'rcl') are first assigned.
2. The iteration is set at G=0, population index i=1and the decision variable at j=1
3. The parent vector is initialized uniformly in the random solution space. The initialization is done using equation (7.3).The initial value of the 'j'th parameter in the 'i'th individual at the generation G=0 is given as;
4. After initialization, the fitness values of the candidate solutions in the initial population are found applying fitness function. The individual with the highest fitness value is selected as the target vector.
5. After initiation, DEA mutates the initial population to create a population of N_p mutant vectors using equation (7.4).
6. After mutation, binomial crossover is employed to generate trial vectors$\left(X_i''\right)$, by mixing the mutant vectors and target vector$\left(X_i\right)$. The crossover is performed using equation (7.5).

7. Sometimes the upper and lower bounds of the newly generated trial vectors exceeds the given value and then they are randomly and uniformly initialized to the initial value given previously. The objective function values of all trial vectors are evaluated. Then the selection operator (according to the fitness rank) determines the population by choosing between the trial vectors and their predecessors (target vectors). Selection is performed using equation (7.6).
8. Once the new population is established, the process of mutation, crossover and selection is repeated for several generations.
9. The algorithm terminates after reaching threshold values for the target vector.

Figure 7.6 describes the flow chart for the Differential Evolution Algorithm.

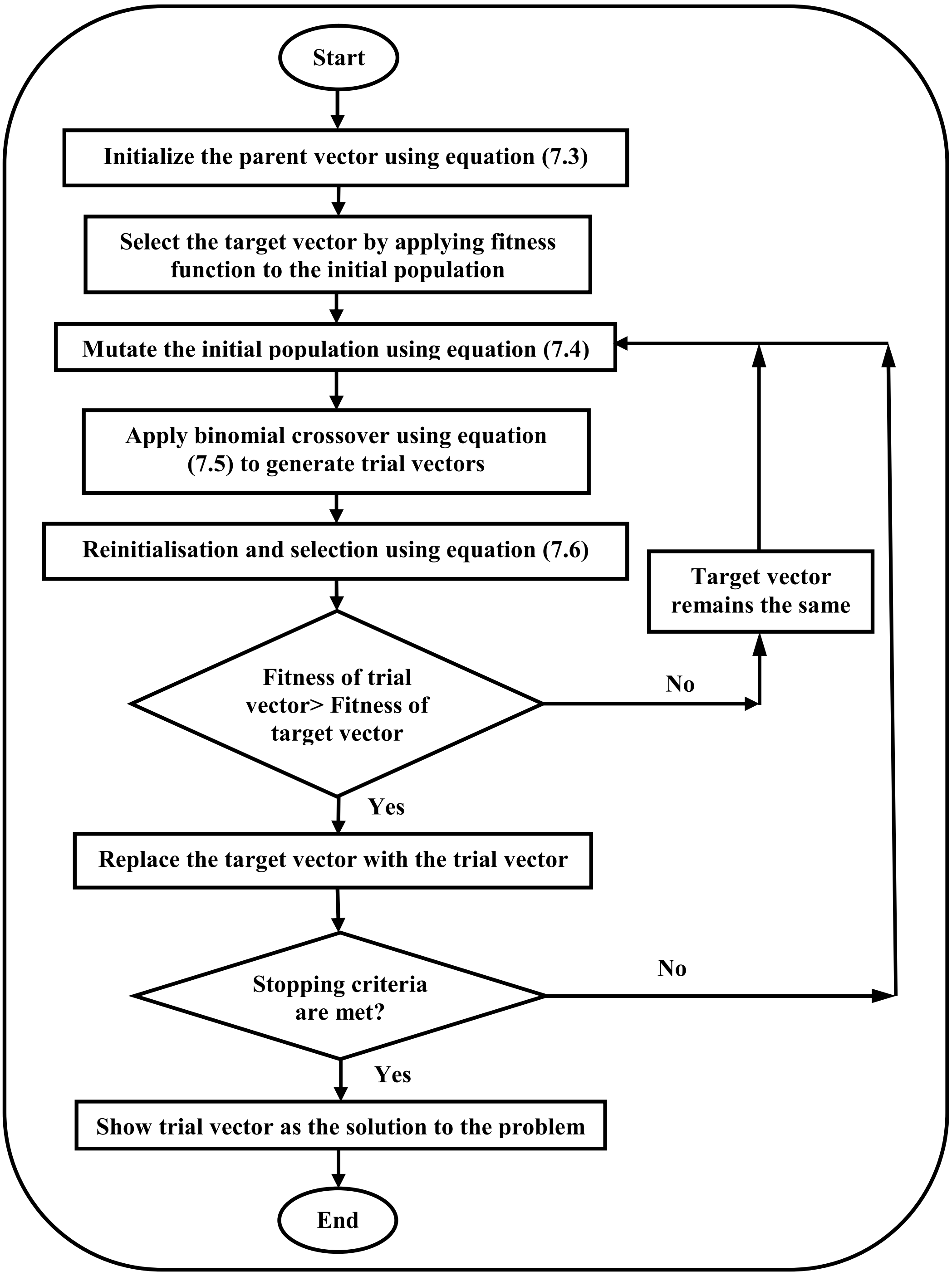


Figure 7.6: Flowchart of Differential Evolution Algorithm for damage detection

7.3.1 Result Tables

Table 7.1: Comparison of the results of DEA with FEA of a cantilever beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the DEA technique	rcl using the DEA technique	percentage error rcd	percentage error rcl	Total Error in %
1	0.9923	0.9912	0.9966	0.325	0.21875	0.3082	0.2074	5.14	5.15	5.14
2	0.9931	0.9926	0.9978	0.3	0.20625	0.2845	0.1956	5.15	5.15	5.15
3	0.9946	0.9942	0.9972	0.2875	0.23125	0.2726	0.2193	5.15	5.14	5.14
4	0.9959	0.99772	0.999	0.125	0.21875	0.1185	0.2075	5.14	5.14	5.14
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2608	0.3438	5.15	5.15	5.15
Total Average Error in %										5.14

Table 7.2: Comparison of the results of DEA with Exp. analysis of a cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the DEA technique	rcl using the DEA technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3260	0.4447	5.14	5.13	5.135
2	0.9974	0.989	0.9999	0.375	0.5	0.3557	0.4743	5.14	5.14	5.14
3	0.99816	0.9982	0.9979	0.25	0.375	0.2371	0.3557	5.14	5.14	5.14
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2075	0.3853	5.13	5.14	5.135
5	0.9892	0.9996	0.9981	0.35	0.1875	0.332	0.1778	5.14	5.14	5.14
Total Average Error in %										5.13

Table 7.3: Comparison of the results of DEA with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the DEA technique	rcl using the DEA technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3615	0.3081	5.17	5.18	5.17
2	0.9966	0.9961	0.9978	0.3625	0.29375	0.3437	0.2785	5.16	5.17	5.16
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3378	0.2608	5.16	5.15	5.15
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3319	0.2726	5.15	5.16	5.15
5	0.9975	0.9991	0.9970	0.4	0.175	0.3793	0.1659	5.16	5.15	5.15
Total Average Error in %										5.15

Table 7.4: Comparison of the results of DEA with Exp. analysis of a fixed-fixed beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the DEA technique	rcl using the DEA technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.3	0.18125	0.2845	0.1719	5.15	5.15	5.15
2	0.9981	0.9964	0.9977	0.33125	0.26875	0.3141	0.2549	5.15	5.14	5.14
3	0.9984	0.999	0.997	0.29375	0.1375	0.2786	0.1304	5.14	5.14	5.14
4	0.9985	0.9991	0.9975	0.31875	0.15625	0.3023	0.1482	5.14	5.15	5.14
5	0.9987	0.9999	0.9957	0.18125	0.2375	0.1719	0.2252	5.15	5.15	5.15
Total Average Error in %										5.15

7.4 Analysis of Fuzzified Differential Evolution Algorithm for Structural Damage Detection

The previous section narrates the fundamentals and the design of the algorithm using Differential Evolution Algorithm for damage detection. The current section of the Chapter 7 aims at proposing a damage detection method by designing a hybridized method using Differential Evolution Algorithm and Fuzzy Logic System for damage detection.

Fuzzy logic has extended use in different research fields of engineering and other applications. It is used as a robust tool to solve complex and intricate problems which cannot be solved by conventional traditional methods. But still it requires some human intervention as it needs the expertise, experience and knowledge in the design of fuzzy MF and formation of fuzzy rules. In the present study an effort is made to design and develop a hybrid optimization technique for automatic adjustment of the fuzzy MF considering fuzzy knowledge based rules and exploiting a nature inspired evolutionary algorithm (GA). From the vast literature available on FLSs, it can be observed less work has been proposed in other fields of complex engineering problems which should be explored and exploited. So this hybrid technique has been applied in the field of damage detection and location of cracked structural elements.

Due to the competition to produce better and better results by using AI techniques, different researchers have tried to hybridize different AI techniques to improve the performance of the AI techniques by using different enhanced operations. Some of the researchers have tuned parameters of DEA using Memtic Algorithm [187], hybridized PSO with DEA [188], some have used FLS for diversity control of population of DEA [189], and some others have used multi objective evolutionary algorithms for enhancement of performance of FLC [190] and have hybridized the Differential Evolution Algorithm and receptor editing property of immune system [191] to be used in the manufacturing industry. But less work has been proposed to integrate FLC and DEA using simple steps to be used in the field of vibration analysis of cracked structures for crack location.

7.4.1 Analysis of Fuzzy Logic parameters in DEA-FLS for damage detection

In this method the FISs are designed using Gaussian membership functions. The piecewise linear membership functions (triangular, trapezoidal) make the system less complex and more understandable but Gaussian membership functions can represent the nonlinearities in the data more precisely. So in this section, Gaussian membership function is used to design and develop the FIS. Figure 7.7 shows presentation of the Gaussian membership function with the defining parameters.

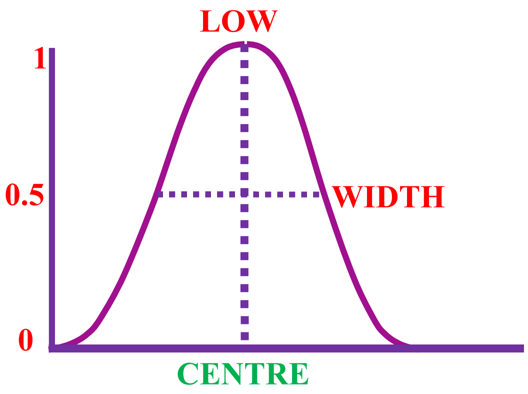


Figure 7.7: Gaussian membership function with the defining parameters

Often it is assumed that the Gaussian membership functions used in a fuzzy inference system intersect at the point where the membership value is ‘0.5’. But it is not always possible to define exactly that point. Sometimes the point where the MFs intersect is defined as ‘x’ or the critical point. So the Gaussian MF needs shape tuning. From the literature available it can be observed that many methods have been formulated to tune the MF parameters of linear MFs like triangular and trapezoidal MFs using different evolutionary algorithms. But less work is done to optimize both the shape of a Gaussian MF and fuzzy rules. So in the present work, an effort is made to optimize both Gaussian MF and the fuzzy rules. Figure 7.8 shows a Mamdani FIS using Gaussian membership functions.

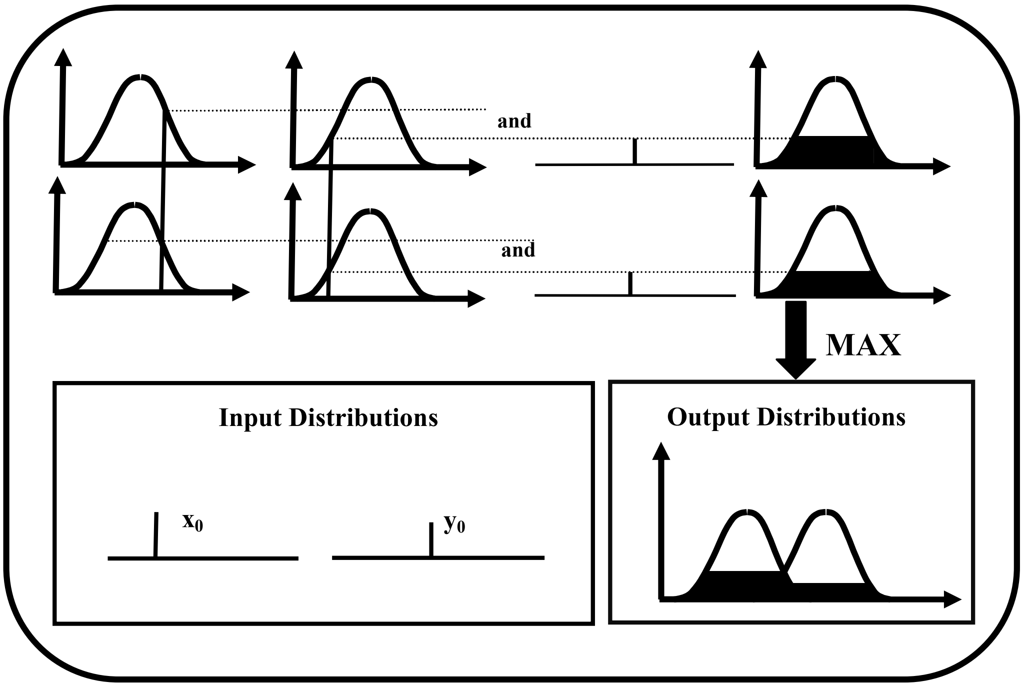


Figure 7.8: A two inputs, two rule Mamdani FIS using Gaussian MFs

The rule base section of the fuzzy inference system works on the application and implementation of the fuzzy rules as described in Chapter 5. After the automatic generation of the fuzzy rules they are aggregated as described in Section 5.1.2.1(a) of Chapter 5. The linguistic variables used and the fuzzy rule structure remain the same as described in Section 5.1 of Chapter 5.

7.4.2 Computation of Membership Function using Differential Evolution Algorithm applied to Damage Detection

In the current work, Gaussian MFs are considered. As the DEA does not require any coding system unlike any other evolutionary algorithms, so the dimensionless relative values of the variables (rfnf, rsnf, rtnf, rcd, rcl) for these two parameters can be used directly. After the defuzzification process, these relative values can be converted to the direct values. The hybridized methodology consists of three major steps i.e., preprocessing, processing, postprocessing. In preprocessing, the individual solutions are fed to the DEA. Then the fuzzy rules obtained, using DEA are fed to the fuzzy inference engine for the implementation and aggregation of the fuzzy rules. In the postprocessing, the results from the FIS are defuzzified to get the crisp result (rcd, rcl) from the methodology. Figure 7.9 describes the proposed methodology in the pictorial form.

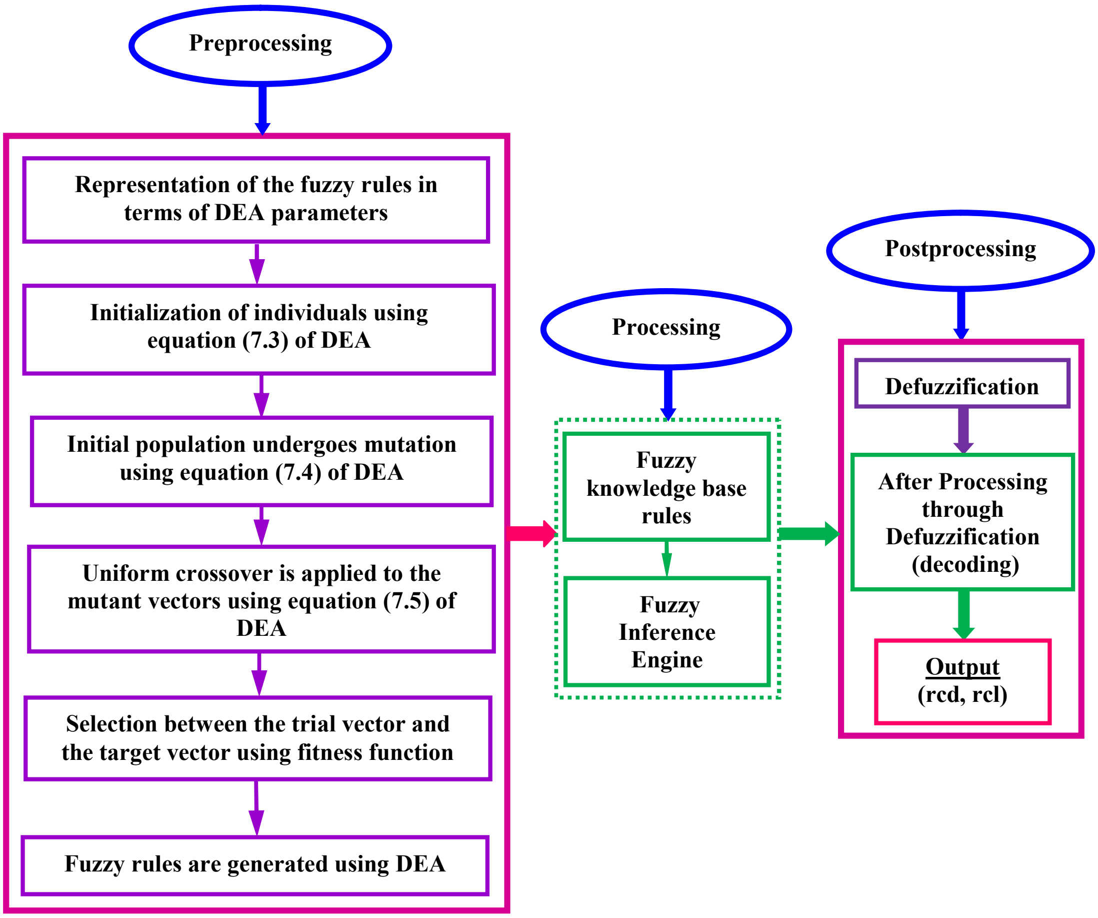


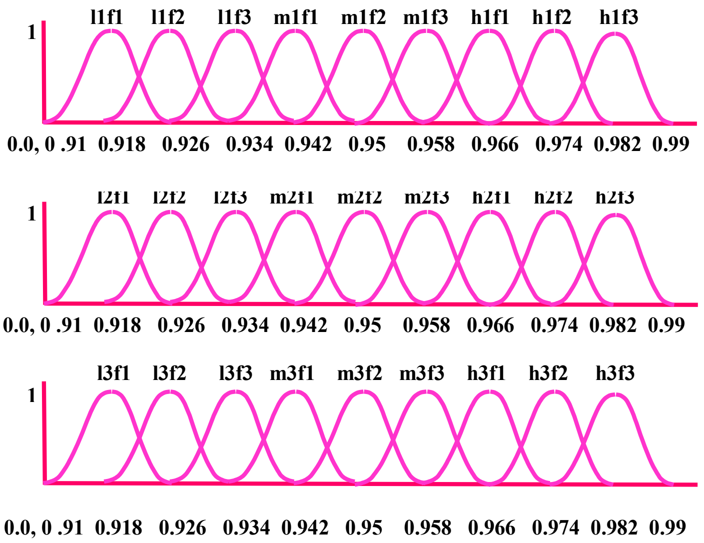
Figure 7.9: Pictorial presentation of hybridized FL system using DEA

Following are the steps used for Computation of MF using Differential evolution algorithm (DEA) described in detail.

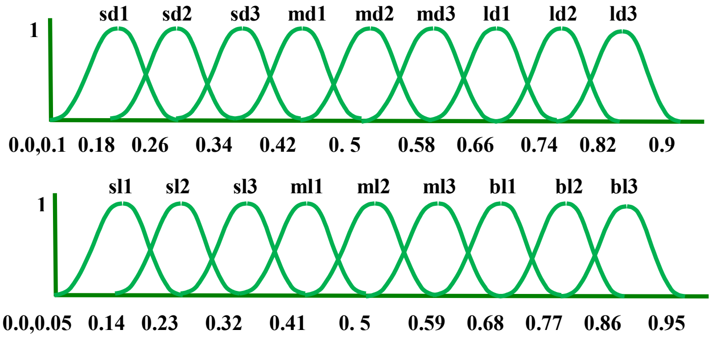
1. The first step of hybridization of the DEA and FLS is to represent the fuzzy rules in terms of DEA parameters.

   Here X_i which is an individual in the population of DEA represents a fuzzy rule. Where, x_1, x_2, x_3, x_4, and x_5 represent the linguistic variables of fuzzy membership functions in a fuzzy rule.
2. Then initialization takes place using equation (7.3) of DEA.
3. The initial population undergoes mutation using equation (7.4) of DEA.
4. Then uniform crossover is applied to the mutant vectors using equation (7.5) of DEA.
5. A fitness function is used to make selection between the trial vector and the target vector, whichever becomes the best fit (solution) replaces the target vector in the next generation. Otherwise if the stopping criteria are met the algorithm stops making the current target vector as the best solution (fuzzy rule).

6. Likewise when twenty five fuzzy rules are generated using DEA, then they are fed to the fuzzy inference systems.
7. After the implementation and aggregation of the fuzzy rules in the inference system, the results are defuzzified using centroid defuzzification in Mamdani FIS.
8. The defuzzification process shows the crisp output from the Mamdani fuzzy inference system. But as described earlier, the Sugeno FIS gives directly the output values using weighted average method.

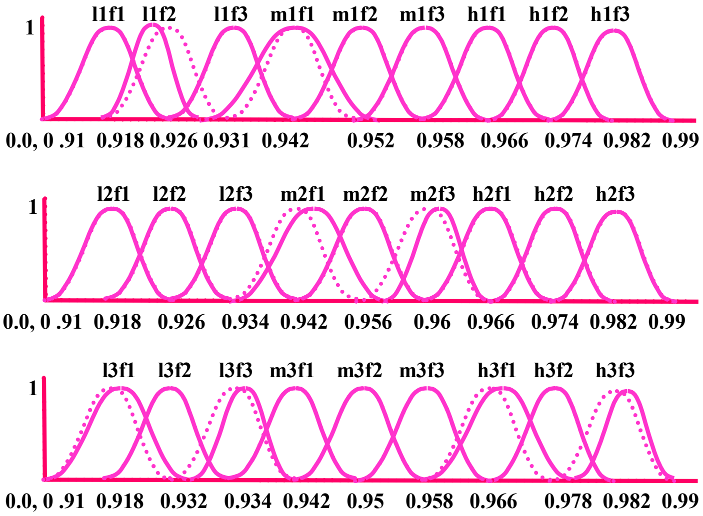


Gaussian Membership Functions for input variables (rfnf, rsnf, rtnf)

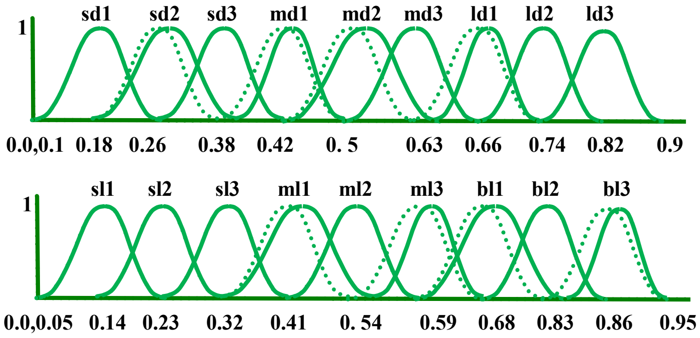


Gaussian Membership Functions for output variables (rcd, rcl)

Figure 7.10 (a): Representation of the variables using Gaussian MFs in DEA-FLS using Mamdani FIS



Gaussian Membership Functions for input variables (rfnf, rsnf, rtnf)



Gaussian Membership Functions for output variables (rcd, rcl)

Figure 7.10(b): Change of shapes of the Gaussian Membership Functions in case of Mamdani FIS after the implementation of DEA

Figure 7.10(b) shows the change in the shape of the Gaussian membership function from that has been assumed in the beginning of the algorithm (Figure 7.10(a)).

7.4.3 Result Tables

Table 7.5: Comparison of the results of DEA-FLS (Mamdani FIS) with FEA of a cantilever beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the DEA-FLS technique	rcl using the DEA-FLS technique	percent age error rcd	percent age error rcl	Total Error in %
1	0.9923	0.9912	0.9966	0.325	0.21875	0.3104	0.2088	4.48	4.51	4.49
2	0.9931	0.9926	0.9978	0.3	0.20625	0.2865	0.1969	4.5	4.5	4.5
3	0.9946	0.9942	0.9972	0.2875	0.23125	0.2745	0.2207	4.52	4.52	4.52
4	0.9959	0.99772	0.999	0.125	0.21875	0.1193	0.2089	4.51	4.47	4.49
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2627	0.3462	4.47	4.48	4.47
Total Average Error in %									4.49	

Table 7.6: Comparison of the results of DEA-FLS (Mamdani FIS) with Exp. analysis of a cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the DEA-FLS technique	rcl using the DEA-FLS technique	percent age error rcd	percent age error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3283	0.4477	4.49	4.49	4.49
2	0.9974	0.989	0.9999	0.375	0.5	0.3581	0.4776	4.5	4.48	4.49
3	0.99816	0.9982	0.9979	0.25	0.375	0.2388	0.3581	4.48	4.49	4.48
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2089	0.3880	4.49	4.48	4.48
5	0.9892	0.9996	0.9981	0.35	0.1875	0.3342	0.1791	4.49	4.48	4.48
Total Average Error in %									4.48	

Table 7.7: Comparison of the results of DEA-FLS (Mamdani FIS) with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the DEA-FLS technique	rcl using the DEA-FLS technique	percent age error rcd	percent age error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3640	0.3103	4.5	4.51	4.50
2	0.9966	0.9961	0.9978	0.3625	0.29375	0.3461	0.2805	4.5	4.5	4.5
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3402	0.2626	4.49	4.49	4.49
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3342	0.2745	4.51	4.5	4.50
5	0.9975	0.9991	0.9970	0.4	0.175	0.382	0.1671	4.5	4.5	4.5
Total Average Error in %									4.5	

Table 7.8: Comparison of the results of DEA-FLS (Mamdani FIS) with Exp. analysis of a fixed-fixed beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the DEA-FLS technique	rcl using the DEA-FLS technique	percent age error rcd	percent age error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.3	0.18125	0.2865	0.1731	4.49	4.49	4.49
2	0.9981	0.9964	0.9977	0.33125	0.26875	0.3163	0.2566	4.5	4.5	4.5
3	0.9984	0.999	0.997	0.29375	0.1375	0.2805	0.1313	4.5	4.49	4.49
4	0.9985	0.9991	0.9975	0.31875	0.15625	0.3044	0.1492	4.49	4.49	4.49
5	0.9987	0.9999	0.9957	0.18125	0.2375	0.1730	0.2268	4.5	4.5	4.5
Total Average Error in %									4.49	

Table 7.9: Comparison of the results of DEA-FLS (Sugeno FIS) with FEA of a cantilever beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the DEA-FLS technique	rcl using the DEA-FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9923	0.9912	0.9966	0.325	0.2187	0.3107	0.2091	4.4	4.4	4.4
2	0.9931	0.9926	0.9978	0.3	0.2062	0.2868	0.1972	4.38	4.38	4.38
3	0.9946	0.9942	0.9972	0.2875	0.2312	0.2748	0.2210	4.39	4.39	4.39
4	0.9959	0.99772	0.999	0.125	0.21875	0.1195	0.2091	4.39	4.38	4.385
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2629	0.3466	4.4	4.38	4.39
Total Average Error in %									4.38	

Table 7.10: Comparison of the results of DEA-FLS (Sugeno FIS) with Exp. analysis of a cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the DEA-FLS technique	rcl using the DEA-FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3286	0.4482	4.38	4.38	4.38
2	0.9974	0.989	0.9999	0.375	0.5	0.3585	0.4781	4.38	4.37	4.37
3	0.99816	0.9982	0.9979	0.25	0.375	0.2390	0.3586	4.39	4.37	4.38
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2091	0.3884	4.39	4.38	4.38
5	0.9892	0.9996	0.9981	0.35	0.1875	0.3347	0.1792	4.37	4.38	4.37
Total Average Error in %									4.37	

Table 7.11: Comparison of the results of DEA-FLS (Sugeno FIS) with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the DEA-FLS technique	rcl using the DEA-FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3645	0.3107	4.39	4.38	4.38
2	0.9966	0.9961	0.9978	0.3625	0.29375	0.3465	0.2808	4.39	4.38	4.38
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3406	0.2629	4.38	4.39	4.38
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3346	0.2748	4.38	4.4	4.39
5	0.9975	0.9991	0.9970	0.4	0.175	0.3825	0.1673	4.37	4.4	4.38
Total Average Error in %									4.38	

Table 7.12: Comparison of the results of DEA-FLS (Sugeno FIS) with Exp. analysis of a fixed-fixed beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the DEA-FLS technique	rcl using the DEA-FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.3	0.18125	0.2868	0.1732	4.37	4.39	4.38
2	0.9981	0.9964	0.9977	0.33125	0.26875	0.3167	0.2570	4.38	4.36	4.37
3	0.9984	0.999	0.997	0.29375	0.1375	0.2809	0.1315	4.36	4.36	4.36
4	0.9985	0.9991	0.9975	0.31875	0.15625	0.3048	0.1494	4.36	4.38	4.37
5	0.9987	0.9999	0.9957	0.18125	0.2375	0.1733	0.2271	4.37	4.35	4.36
Total Average Error in %									4.36	

7.5 Results and Discussion

In Section 7.2 of the chapter, an evolutionary algorithm has been employed for the inverse method of damage detection in beam like structural elements. Like GA and CSA, it does not need a representation scheme but it depends on the initialization of the vectors presenting the individuals (solutions). The individuals are defined using the upper and lower limits which are shown in Figure 7.3. The initial values for the algorithm parameters are so selected that they could cover the entire search domain. Figures 7.2 and 7.3 present the initial populations and vectors with their limits respectively. The crossover operation is described in Figure 7.5. The generation of trial vectors through recombination is done using equation 7.5. Then the selection operation is performed using equation 7.6 to decide which vector (trial vector or target vector) will continue with the algorithm in the next generation. In this algorithm, first mutation is performed using equation 7.4 unlike any other evolutionary algorithm. The flowchart describing the algorithm procedure is presented in Figure 7.6. The results from the method considering two types of beam constraints are given in Tables 7.1 to 7.4.

A hybrid intelligent method using Differential Evolution Algorithm and the Fuzzy Logic System has been suggested in Section 7.4 of Chapter 7. Here the membership functions shape is optimized using the DEA. As this method proposes the combination of the two AI techniques, so the DEA part resembles the algorithm described in Section 7.1 of Chapter 7 and the FLS part resembles some of the portions described in Section 5.1 of Chapter 5. The Gaussian membership functions are used to develop the Fuzzy Inference Model (Mamdani FIS and Sugeno FIS). In Figure 7.10(a) the shapes of the MF taken by the designer before the DEA optimization is shown. As the rules are optimized the center and width value of each MF gets changed, which is given in Figure 7.10(b). Figure 7.9 describes the procedure adopted for hybridized FL system using DEA. Tables 7.5 to 7.12 give the result from the hybridized intelligent technique.

7.6 Summary

To propose an accurate and indirect method of damage detection is one of the challenging problems. Such problems are many times addressed considering the vibration based methods. The total average error is found to be within 5.15%. During the running of the algorithm, it has been found that it works with a faster convergence rate as compared to other evolutionary algorithms. This occurs due to the immediate participation of the newly generated good individuals in the generation of the subsequent candidates.

In the Section 7.4 of Chapter 7, the membership function parameters of the fuzzy logic system are tuned using an evolutionary algorithm. But the working process of the algorithm is different from other evolutionary algorithm and is described in detail in Section 7.1of Chapter 7. The total average error in Mamdani FIS for cantilever and fixed-fixed beam is found to be around 4.5%, when compared with the results of Finite Element and Experimental analyses respectively. The total average error in Sugeno FIS for cantilever and fixed-fixed beam is found to be around 4.4%, when compared with the results of Finite Element and Experimental analyses respectively.

Differential Evolution Algorithm being a simple and powerful evolutionary method is capable of attaining the global solution due to the starting point initialization of the algorithm. For these characteristics it can be used to replace various evolutionary algorithms in many evolutionary algorithm based hybrid systems. For further improvement in the results, Gaussian membership functions are used which can efficiently present the nonlinearities present in the database of the damage detection problem. The robustness and efficiency can be perceived from the results of the proposed technique.

Chapter 8

Analysis of Hybridized Algorithms for Structural Damage Detection

Damages might happen in structural components used in a building or in a rotating machine shaft, in all circumstances safety is the essential need. Beams are most generally utilized components as a part of various building applications and subjected to a wide assortment of loads (static and dynamic). Negligence of any of the auxiliary component might end in a dangerous mishap. To maintain a strategic distance from these circumstances, consistent health monitoring of the structures must be done. To deliver a cost effective method in damage detection, AI based techniques are utilized. But it has been noticed that sometimes the direct applications of the AI techniques could not obtain a fair solution, so hybridization of AI techniques are used. To achieve the synergetic effects from the intelligent methods, hybridization is done. The main challenge of designing a hybrid learning system architecture is to use the information provided by one source of information to counteract with the other expert system. So from the knowledge of their strengths and weaknesses, the hybrid systems are constructed. They are designed in such a way that they can mitigate the limitations and take the advantage to produce systems that are more powerful. This chapter is dedicated to some of the hybrid intelligent methods designed and developed in the research work.

8.1 Automatic design of Fuzzy MF using GA for Structural Damage Detection

In this chapter a hybrid Fuzzy Logic System is suggested, where the fuzzy membership functions is designed automatically using Genetic Algorithm. The hybrid Fuzzy Logic System (Mamdani FIS and Sugeno FIS) has been designed according to the problem definition for damage detection. The designed controllers can also be used as effective tools for online condition monitoring of engineering system.

A robust and optimal FLS system can be built by establishing a fuzzy rule set and using Genetic Algorithms to find an optimal MF. The fuzzification part which is done by designing the fuzzy MFs is an important step, which influences the results of the inference engine. This portion of fuzzy inference engine is common in both types of inference engines (Mamdani FIS and Sugeno FIS). The fault diagnosis is a multi criteria optimization problem for which evolutionary algorithms are best suggested. Since fuzzy logic uses a linear approach to model the nonlinear domain of the damage detection problem, Genetic Algorithm has been simultaneously adapted in the design of the hybrid model to focus on variable selection and tuning within the fuzzy sub-models. As the addressed problem is inherently nonlinear and difficult to be solved effectively by using conventional methods, fuzzy logic modeling has been done to present the problem (Chapter 5).

As described in Section 5.2 of Chapter 5, Genetic Algorithm (GA) is an optimization method inspired from the Darwin’s survival of the fittest and the reproduction strategy. The evolutionary algorithm which looks for the best match in the search domain suits perfectly to be used to adjust the shape of the membership function. Properties of GAs make it to be used as a technique for selecting high performance membership functions for FL systems for vibration analysis of cracked elements. GA is a very potential technique to solve MIMO problem, like the problem addressed here.

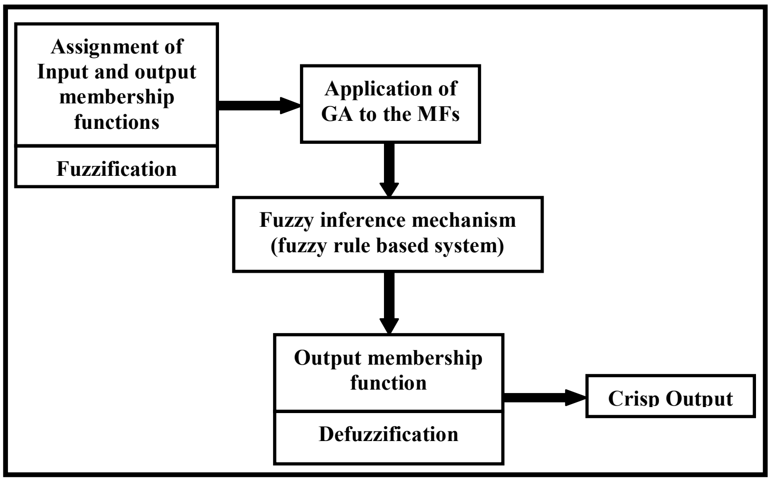


Figure 8.1: Presentation of the fuzzy model for MF optimization using GA

From the literature, it has been noticed that much of the work using hybridization of Genetic Algorithms and Fuzzy Logic is done in the field of vibration control of different materials [192], building structures [193] etc. but less work has been done in the field of vibration analysis of cracked structures for damage detection. Another difference is that most of the researchers have taken the base length of the triangular membership function as the optimizing parameter. In this work, the two side (left and right) values and the center value is considered as the optimizing parameter.

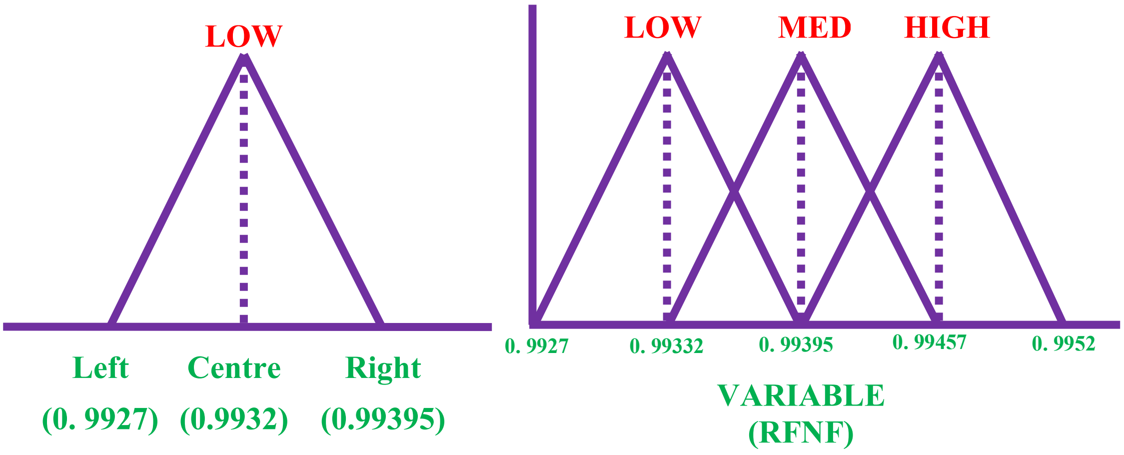


Figure 8.2(a)

Figure 8.2 (b)

Figure 8.2: (a) presentation of MF of rfnf, (b) presentation of input variable rfnf with the end points of MFs in ADMF

The main issue in the design of MF is the parameters (variable definition) involved with it. Based on the given reason the MF optimization can be reduced parameter optimization and can be applied to any problem, well suited to it. In this FLS, triangular membership functions are used to define different fuzzy sets. The triangular MFs are defined by their left, central, and right base values as shown in Figure 8.2. These MFs are already defined in Chapter 5. Here three membership functions are defined corresponding to each input and output variables. We can take number of fuzzy membership functions for each input and output variable so that results will get finer due to the division of the range of the variable. But as the addressed method is not purely based on fuzzy logic and requires encoding operation due to the involvement of GA, so the numbers of MFs are kept small. The large encoding process sometimes stalls the algorithm, so the numbers of fuzzy membership functions are kept limited in this algorithm.

8.1.1 Representation scheme for Automatic design of Fuzzy MF using Genetic Algorithm

Encoding scheme plays an important role in the design of FLC. In this work following encoding system is applied to the parameters. The input and the output variables are fuzzified using three triangular membership functions in Mamdani and Sugeno FIS the input variables are only fuzzified. The different linguistic variables used for input and output variables are given as below:

Input 1: (rfnf): low (l), medium (m), high (h)

Input 2: (rsnf): low (l), medium (m), high (h)

Input 3: (rtnf): low (l), medium (m), high (h)

Output 1: (rcd): small (s), medium (m), large (l)

Output 2: (rcl): small (s), medium (m), big (b)

A fuzzy rule in a Mamdani and Sugeno fuzzy model are represented as below:

R_M:if x_1 is lf, x_2 is mf, x_3 is lf then y_1 is sd, y_2 is ml

R_S:if x_1 is lf, x_2 is mf, x_3 is lf then y_1 is h_1, y_2 is h_2

Figure 8.3 presents one of the input variables with its MFs and linguistic terms. In the design of fuzzy rules in Sugeno fuzzy model, the zero order Sugeno model is considered where the output refers to a constant which can be encoded into binary numbers.

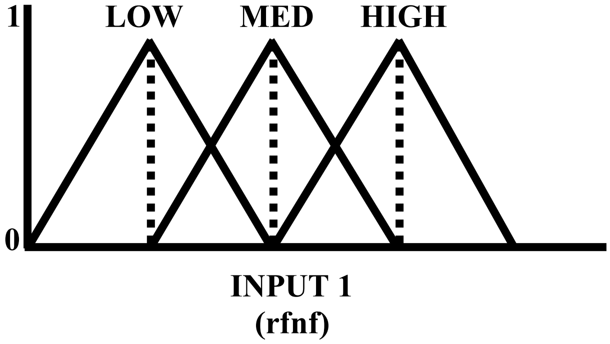


Figure 8.3: Presentation of the variables using three membership functions

Table 8.1: Sample rules for the Mamdani fuzzy inference system for automatic design of fuzzy MF using GA

Sl.no	Illustrations of a few rules utilized as a part of fuzzy controller
1	If rfnf is lf, rsnf is mf, rtnf is lf then rcd is ld and rcl is sl
2	If rfnf is lf, rsnf is lf, rtnf is mf then rcd is ld and rcl is sl
3	If rfnf is lf, rsnf is lf, rtnf is mf then rcd is ld and rcl is ml
4	If rfnf is lf, rsnf is mf, rtnf is lf then rcd is ld and rcl is ml
5	If rfnf is mf, rsnf is lf, rtnf is lf then rcd is ld and rcl is ml
6	If rfnf is mf, rsnf is lf, rtnf is mf then rcd is md and rcl is ml
7	If rfnf is mf, rsnf is mf, rtnf is lf then rcd is ld and rcl is sl
8	If rfnf is lf, rsnf is mf, rtnf is mf then rcd is ld and rcl is ml
9	If rfnf is lf, rsnf is mf, rtnf is mf then rcd is md and rcl is bl
10	If rfnf is lf, rsnf is mf, rtnf is mf then rcd is md and rcl is bl
11	If rfnf is mf, rsnf is mf, rtnf is mf then rcd is md and rcl is bl
12	If rfnf is mf, rsnf is mf, rtnf is hf then rcd is md and rcl is ml
13	If rfnf is mf, rsnf is hf, rtnf is hf then rcd is md and rcl is ml

14	If rfnf is hf, rsnf is mf, rtnf is hf then rcd is md and rcl is bl
15	If rfnf is hf, rsnf is hf, rtnf is mf then rcd is md and rcl is bl
16	If rfnf is mf, rsnf is hf, rtnf is hf then rcd is md rcl is bl
17	If rfnf is hf, rsnf is hf, rtnf is hf then rcd is sd and rcl is ml
18	If rfnf is hf, rsnf is hf, rtnf is hf then rcd is sd and rcl is bl
19	If rfnf is hf, rsnf is mf, rtnf is hf then rcd is sd and rcl is bl
20	If rfnf is hf, rsnf is hf, rtnf is hf then rcd is sd and rcl is bl

Each base value of each membership function base values is coded into five bit binary strings. Each fuzzy rule contains twenty five bits. Figure 8.4 shows the structure of the antecedent and consequent part of the fuzzy rule after encoding to bit strings.

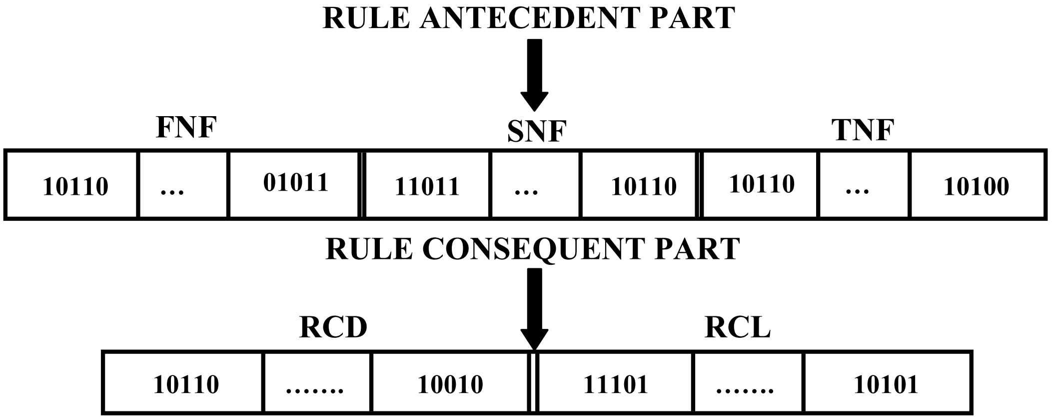
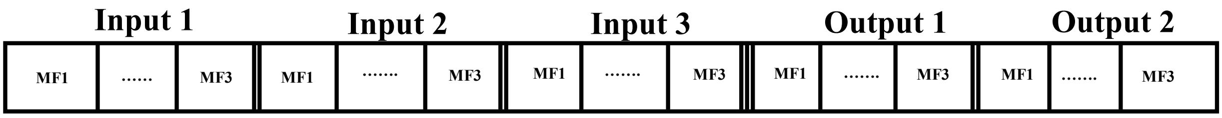


Figure 8.4: Binary presentations of fuzzy rules for Mamdani FIS

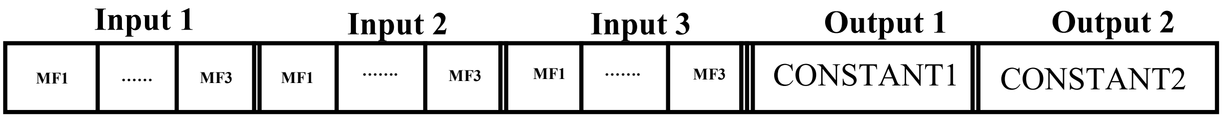
8.1.2 Algorithm of Automatic design of Fuzzy MF using Genetic Algorithm

The following steps are used for the automatic generation of the Fuzzy Membership functions (MFs) by using Genetic Algorithm to optimize the MFs for both Mamdani and Sugeno fuzzy models.

1. The chromosomes are encoded using binary encoding. Here the chromosomes are the fuzzy rules containing the MFs. The MFs are encoded by encoding each parameter of the MF representing it. Each chromosome or individual (MFs in the rule representing the input and output variables) is encoded into binary strings (as described in Section 8.1.1).



Presentation of variables using membership functions in Mamdani FIS



Presentation of variables using membership functions in Sugeno FIS

Figure 8.5: Presentation of fuzzy rules using Mamdani and Sugeno FIS

2. Population size (100) and initial population (6) (chromosomes or individuals) are generated and specified.
3. Fitness Function or Evaluation Function is defined.
4. Each chromosome is evaluated with respect to the already defined Fitness Function as in equation (8.1).

$$\text{FitnessFunction} = \sqrt{\left(\text{rule}_{\text{fld}} - \text{rule}_{\text{x,g}}\right)^2} \qquad (8.1)$$

rule_{fld}= rule from the field
rule_{x}= any rule from the dataset
g= number of generations

5. Crossover is performed on the selected chromosomes. Here two-point crossovers are used. As the chromosomes contain twenty five bits, the crossover points are chosen five bits left of the chromosome and ten bits right of the chromosome. It is taken randomly and is a user defined parameter. The crossover operation can be referred to the “crossover” used in Chapter 5.

   For Sugeno fuzzy model, the output section does not involve any fuzzification method as the outputs are taken to be spikes (zero-order Sugeno FIS). So the output variables do not contain any membership functions. In a Sugeno fuzzy rule the antecedent part consists of fifteen bits and the output constant is coded into five bits. So a Sugeno fuzzy rule contains twenty five bits. For two point Crossover in Sugeno model the crossover points chosen are same as Mamdani FIS.
6. Mutation is performed on all the chromosomes after crossover. In the proposed method, as we have used binary encoding, the mutation rate used is 0.05% of the string. As the chromosome consists of twenty five bits, one bit at a time are flipped or

altered randomly. Mutation operation can be referred to the mutation used in Chapter 5.

7. Again fitness evaluation of the parents and offsprings are done. Then the fitness values of the parents and children are compared, to find out the best fit member. 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.
8. The iterations are stopped after 100 generations or specific time.
9. If the stopping criteria are not met, the algorithm goes to step 3 and is repeated.
10. Likewise some strong rules with MF optimisation are generated and added to the rule table. The rule table for the fuzzy inference systems (Mamdani FIS and Sugeno FIS) is given in Table 8.1.
11. Then the fuzzy rules for the respective FIS are trained in the inference engines.
12. The result is then defuzzified to find the crisp values.

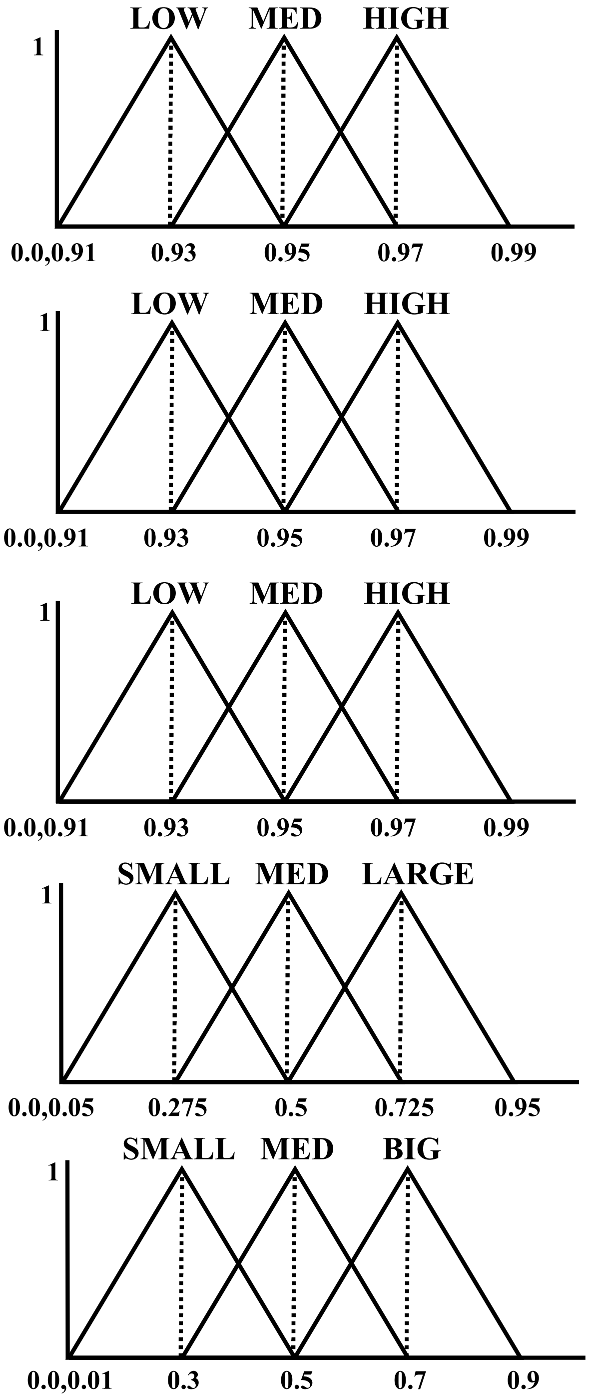


Figure 8.6: Presentation of the input and output membership functions before genetic tuning

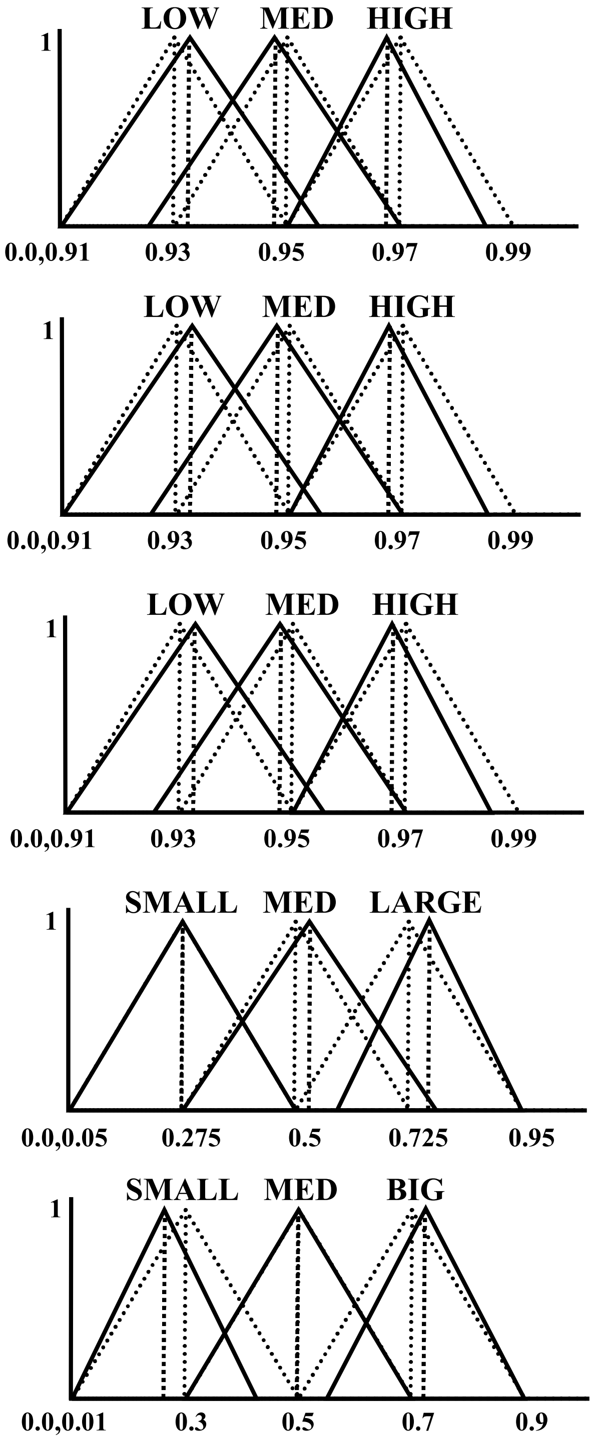


Figure 8.7: Presentation of the input and output membership functions after genetic tuning

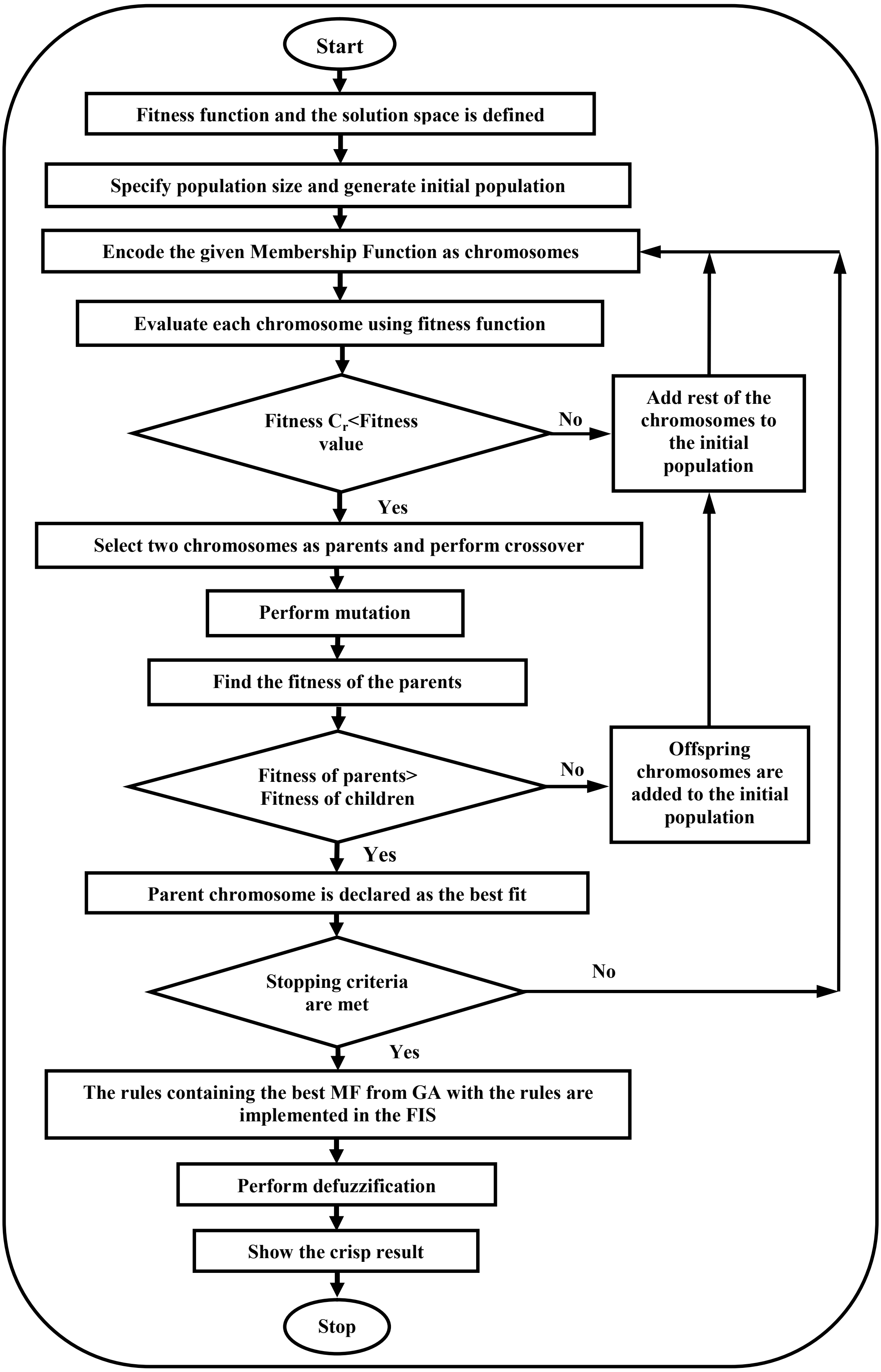


Figure 8.8: Flow chart for the Automatic Design of Fuzzy MF using GA

8.1.3 Result Tables

Table 8.2: Comparison of the results of ADFMF (Mamdani FIS) with FEA of a cantilever beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the proposed method	rcl using the proposed method	percentage error rcd	percentage error rcl	Total error in %
1	0.9923	0.9912	0.9966	0.325	0.21875	0.3087	0.2075	4.99	5.1	5.04
2	0.9931	0.9926	0.9978	0.3	0.20625	0.285	0.1959	5	5	5
3	0.9946	0.9942	0.9972	0.2875	0.23125	0.2728	0.2197	5.1	4.99	5.04
4	0.9959	0.9977	0.999	0.125	0.21875	0.1187	0.2078	4.99	4.99	4.99
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2614	0.3443	4.92	5	4.96
Total Average Error in %									5.00	

Table 8.3: Comparison of the results of ADFMF (Mamdani FIS) with Exp. analysis of a cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the proposed method	rcl using the proposed method	percentage error rcd	percentage error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3269	0.4453	4.88	4.99	4.93
2	0.9974	0.989	0.9999	0.375	0.5	0.3562	0.475	5	5	5
3	0.99816	0.9982	0.9979	0.25	0.375	0.2373	0.3562	5.05	5	5.02
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2078	0.3859	4.98	4.99	4.98
5	0.9892	0.9996	0.9981	0.35	0.1875	0.3325	0.1781	4.99	4.99	4.99
Total Average Error in %									4.98	

Table 8.4: Comparison of the results of ADFMF (Mamdani FIS) with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the proposed method	rcl using the proposed method	percentage error rcd	percentage error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3623	0.3088	4.95	4.98	4.96
2	0.9966	0.9961	0.9978	0.3625	0.29375	0.3445	0.2790	4.96	4.99	4.97
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3385	0.2612	4.98	4.99	4.98
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3326	0.2731	4.97	4.98	4.97
5	0.9975	0.9991	0.9970	0.4	0.175	0.38	0.1662	5	4.99	4.99
Total Average Error in %									4.97	

Table 8.5: Comparison of the results of ADFMF (Mamdani FIS) with Exp. analysis of a fixed-fixed beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the proposed method	rcl using the proposed method	percentage error rcd	percentage error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.3	0.18125	0.2851	0.1722	4.96	4.96	4.96
2	0.9981	0.9964	0.9977	0.33125	0.26875	0.3148	0.2553	4.95	4.97	4.96
3	0.9984	0.999	0.997	0.29375	0.1375	0.2791	0.1306	4.97	4.95	4.96
4	0.9985	0.9991	0.9975	0.31875	0.15625	0.3029	0.1485	4.95	4.95	4.95
5	0.9987	0.9999	0.9957	0.18125	0.2375	0.1722	0.2257	4.96	4.95	4.95
Total Average Error in %									4.95	

Table 8.6: Comparison of the results of ADFMF (Sugeno FIS) with FEA of a cantilever beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the proposed method	rcl using the proposed method	percentage error rcd	percentage error rcl	Total error in %
1	0.9923	0.9912	0.9966	0.325	0.21875	0.3094	0.2082	4.79	4.8	4.79
2	0.9931	0.9926	0.9978	0.3	0.20625	0.2856	0.1963	4.8	4.79	4.79
3	0.9946	0.9942	0.9972	0.2875	0.23125	0.2737	0.2201	4.79	4.79	4.79
4	0.9959	0.99772	0.999	0.125	0.21875	0.1190	0.2082	4.79	4.8	4.79
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2618	0.3451	4.8	4.8	4.8
Total Average Error in %									4.79	

Table 8.7: Comparison of the results of ADFMF (Sugeno FIS) with Exp. analysis of a cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the proposed method	rcl using the proposed method	percentage error rcd	percentage error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3273	0.4462	4.78	4.79	4.78
2	0.9974	0.989	0.9999	0.375	0.5	0.3570	0.476	4.79	4.8	4.79
3	0.99816	0.9982	0.9979	0.25	0.375	0.2380	0.357	4.78	4.78	4.78
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2082	0.3868	4.8	4.78	4.79
5	0.9892	0.9996	0.9981	0.35	0.1875	0.3332	0.1788	4.79	4.8	4.79
Total Average Error in %									4.78	

Table 8.8: Comparison of the results of ADFMF (Sugeno FIS) with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the proposed method	rcl using the proposed method	percentage error rcd	percentage error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3630	0.3094	4.78	4.78	4.78
2	0.9966	0.9961	0.9978	0.3625	0.29375	0.3451	0.2796	4.79	4.79	4.79
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3392	0.2618	4.78	4.79	4.78
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3332	0.2737	4.8	4.78	4.79
5	0.9975	0.9991	0.9970	0.4	0.175	0.3808	0.1666	4.8	4.78	4.79
Total Average Error in %									4.78	

Table 8.9: Comparison of the results of ADFMF (Sugeno FIS) with Exp. analysis of a fixed-fixed beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the proposed method	rcl using the proposed method	percentage error rcd	percentage error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.3	0.18125	0.2857	0.1725	4.76	4.78	4.77
2	0.9981	0.9964	0.9977	0.33125	0.26875	0.3154	0.2559	4.77	4.76	4.76
3	0.9984	0.999	0.997	0.29375	0.1375	0.2797	0.1309	4.77	4.75	4.76
4	0.9985	0.9991	0.9975	0.31875	0.15625	0.3035	0.1487	4.76	4.79	4.77
5	0.9987	0.9999	0.9957	0.18125	0.2375	0.1726	0.2262	4.77	4.75	4.76
Total Average Error in %									4.76	

8.1.4 Results and Discussion

In Sections 5.1 and 5.2 of Chapter 5, both basics of Fuzzy Logic and Genetic Algorithm have been individually used for damage detection and the results found are appreciable. But both the methods involve various limitations. Like the Fuzzy Logic approach consists of human intervention for deciding the shape of the membership function and generation of the fuzzy rules. So in this chapter the automatic shape design is done by the Genetic Algorithm and the entire problem can be treated as an optimization problem to find the crack location efficiently. Figure 8.1 shows the fuzzy model for MF optimization using GA and the binary presentation of the fuzzy rules is described in Figure 8.4. The rules involving the linguistic variables used for describing the three triangular MFs are given in Table 8.1. The change in shape of the membership function is shown in Figure 8.7. The flowchart for the Automatic Design of Fuzzy membership function is shown in Figure 8.8. This algorithm tries to exploit the features of Genetic Algorithm like convergence towards the elitist solution and simplicity. The results from the method taking two types of beam constraints into consideration are given in Tables 8.2 to 8.9. The result table gives the result from both the inference systems (Mamdani FIS and Sugeno FIS).

8.2 Automatic Tuning of Fuzzy Rules Base System using Genetic Algorithm

Structural and industrial elements are subject to many known and unknown malfunctions during their service life leading to crack formation eventually reducing the efficiency and leading to system breakdowns. To avoid any severe catastrophic failure early detection of incipient cracks are desired. Fault diagnosis basically tries to define the relation between the cause and its effect. But this is a difficult task because the responses that describe the fault modes are frequently vague or incomplete. So the online condition monitoring method requires improved intelligent techniques which can handle these vagueness and nonlinearities in the problem domain.

In this section a fuzzy logic model has been proposed which can handle the vagueness of the data generated from the faulty structural element. In the previous section, a fuzzy model is proposed to automatically design the MF to deal with the uncertainties but this still needs human intervention to generate the fuzzy rules in a fuzzy rule based model, so to control this difficulty an attempt has been made to design and generate fuzzy rules automatically, which has the inherent quality to adjust the fuzzy membership functions.

8.2.1 Design of Automatic Tuning of Fuzzy Rules Base System (ATFRBS) for damage detection

The performance of the Fuzzy Logic System depends on the fuzzy membership functions and fuzzy rules simultaneously. So it is very much needed to optimize or adjust the parameters according to the problem domain. Fuzzy rules are usually generated using linguistic terms, in the if-then format and it largely depends on the human expertise to derive them. In all conditions, the correct choice of the fuzzy membership function with the linguistic variables plays an important role in the performance of Fuzzy Logic System. It is very difficult to present the expert's knowledge perfectly through the linguistic variables. The rule base of a Fuzzy Logic System has many parameters which must be adjusted. These parameters are capable to alter or modify the system performance. In the present section of the Chapter 8, Genetics and Fuzzy Logic based adaptive learning method has been proposed that automatically designs fuzzy rules. This method uses linguistic values with membership function as antecedent and consequent fuzzy sets.

Several researchers have narrated use of different AI techniques for the optimization of the fuzzy parameters and the automatic generation of the fuzzy rules. For this they have used Neural Network [194], multi-objective Genetic Algorithm [195], etc. Many of the researchers also have optimized fuzzy rules for fuzzy classifiers [196], type-2 fuzzy classifiers [197], fuzzy clusters [198] etc.

From the vast literature present it can be observed that less work has been done for optimization and automatic generation of the fuzzy rules and no work comprising this method has been proposed for solving the damage detection problems in structural elements. In this work a method is presented to tune the membership functions as well as fuzzy rules using Genetic Algorithm.

The previous work proposed (Automatic Design of Fuzzy Membership Function) in Section 8.1, still needs human experts to handle the control system. In 'ADMF' only the membership functions are optimized, but the fuzzy rules which form the skeleton of the fuzzy rule based system still needs human expertise for its generation. Since membership functions and fuzzy rules are complimentary, the same approach can even be used to determine a complete near-optimal fuzzy controller.

So to overcome the above stated problems, in this work a method is proposed which can design both membership functions and fuzzy rules automatically.

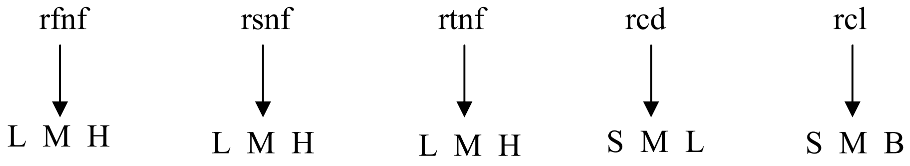
8.2.1.1 Representation scheme for Automatic Tuning of Fuzzy Rules Base System

Before proceeding towards the algorithm, the representation scheme for the Genetic Algorithm must be clearly defined, so this section describes the various encoding systems used for the development of the current algorithm. Different rules and the linguistic variables used in the encoding system are described in Section 8.1.1. Two different types of fuzzy rules used in the Mamdani and Sugeno fuzzy models are given below.

R_M:if x_1 is lf, x_2 is mf, x_3 is lf then y_1 is sd, y_2 is ml

R_S:if x_1 is lf, x_2 is mf, x_3 is lf then y_1 is h_1, y_2 is h_2

The membership functions are represented using triangular shape like in Section 8.1 of Chapter 8. They are defined by three parameters i.e., left, right and center value of the triangular membership function. In this method, each chromosome contains both MFs and fuzzy rules. The membership functions are encoded using real numbers and the fuzzy rules are encoded using binary numbers. Figure 8.9 shows the encoding of the chromosomes for ATFRBS.



RULE: if x_1 is LF, x_2 is MF, x_3 is LF then y_1 is SD, y_2 is ML

RULE: **100** **010** **100** **100** **010**

Figure 8.9: encoding of the chromosomes for ATFRBS

After defining the encoding scheme for the current algorithm, the crossover points which play an important role in the transfer of information are defined. Three points (CP_R, CP_D, CP_{MF}) are chosen within the fuzzy rule for doing crossover and CP_E is used as the end point of the rule. CP_R is the point within the rule string. It is located seven bits from the beginning of the rule string. CP_D is the point between the rule string and membership function boundary. CP_{MF} is used to cut the membership function fragment. This can be chosen randomly, in between the defining points (left, centre and right values) of the membership function. Here it is chosen at the right parametric value of the second variable (rsnf). The crossover points are same for both the parents.

In case of Sugeno FIS the membership function part contains only three membership function parameters for input variables and the outputs are represented by constants. So the point CP_{MF} can be taken at any point in the MF value and output constants. The end point CP_E remains the same for both the models.

8.2.1.2 Algorithm of Automatic Tuning of Fuzzy Rules Base System

1. Population size (7) and initial population (chromosomes or individuals) are specified and generated.
2. Fitness Function or Evaluation Function is generated considering the objective of the problem.

   Exactness= (number of parameters matched) / (total number of parameters)

   For this case the total number of parameters is fifteen in case of Mamdani model and eleven for Sugeno model.

   Rule factor= (number of rules in the current generation) / (total number of rules in the population)

   In this case the initial population consists of four rule sets and each rule set comprises of three rules. So the initial population contains twelve numbers of rules.

   The rules represent the data from the expertise and historical records. The more the similarity between the rule from the field and from the data base, the better will be the result. So the main object of the algorithm is to increase the exactness and decrease the rule factor. So the objective function for the algorithm can be defined as follow.

   $$F(x) = \text{exactness} / \text{rule factor} \quad (8.2)$$
3. The initial rule sets with their MFs are generated. These rule sets are generated using the database from different conventional methods like theoretical, finite element and experimental analyses.
4. Each individual representing a rule set is encoded. Figure 8.11 presents the encoded rules and Figure 8.12 presents the membership functions which are a subset of the former.
   a) Each linguistic variable in a rule is coded using ‘1’ or ‘0’.

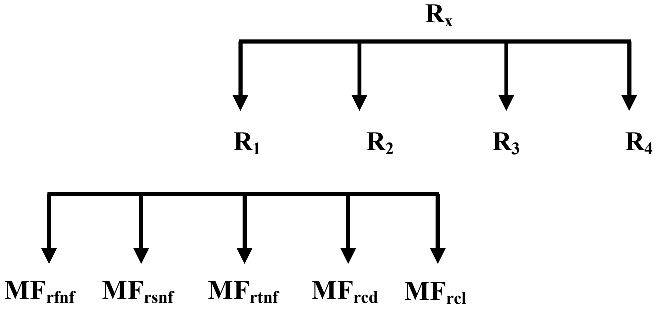


Figure 8.10: Presentation of rule set with the rules and MFs in ATFRBS

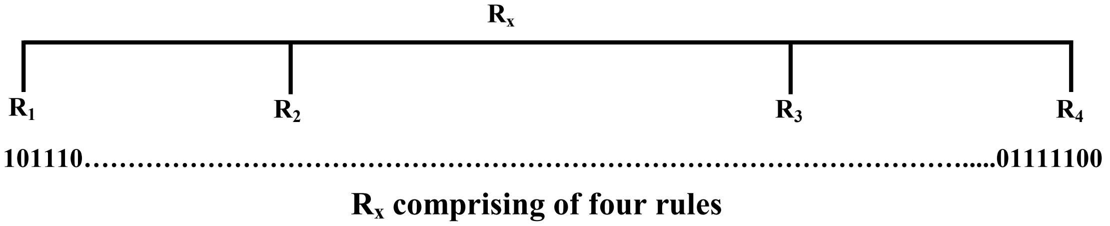


Figure 8.11: R_x comprising of four rules in ATFRBS

b) Each MF is coded by using real number. The MF is represented by using its left, right and centre point.

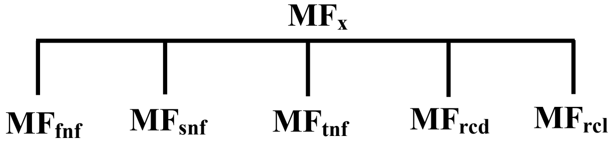


Figure 8.12: Membership function representation in ATFRBS

5. The crossover operator produces two offspring by exchanging the two substrings between CP_{RS}, CP_D, CP_{MF} and the end points of both parents.

R_{11} R_{12} R_{1K} MF_{rfnf}..MF_{rcl}
RS_1+MFS_1 :101001.....011001....110101...........0.991, 0.99275, 0.9945...........................0.3275,0.41375,0.5

R_{21} R_{12} R_{2L} MF_{rfnf}...mf_{rcl}
RS_2+MFS_2 :111001.......110101...010010.........0.9945,0.99625,0.998,........................... 0.155,0.24125,0.3275

STRING PRESENTATION BEFORE CROSSOVER

Figure 8.13: String presentation before Crossover in ATFRBS

6. The substring from CP_{R1} to CP_{D1} is exchanged with that substring from CP_{R2} to CP_{D2} and the substring from CP_{MF1} to CP_{E1} is exchanged with that from CP_{MF2} to CP_{E2}. Figure 8.14 shows the binary string with the crossover points before crossover and Figure 8.15 shows the two offspring generated after crossover. The

crossover points for Sugeno FIS have already defined and they do not differ much from the Mamdani FIS. For convenience the membership function part is coded using real numbers, so that the developer will not face any hurdles in encoding the segments of Sugeno FIS.

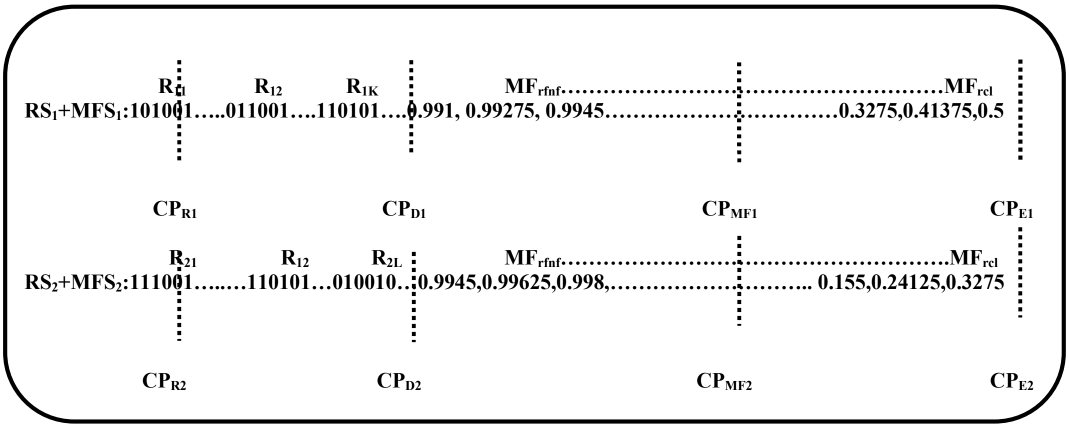


Figure 8.14: String presentation before crossover with crossover points in ATFRBS

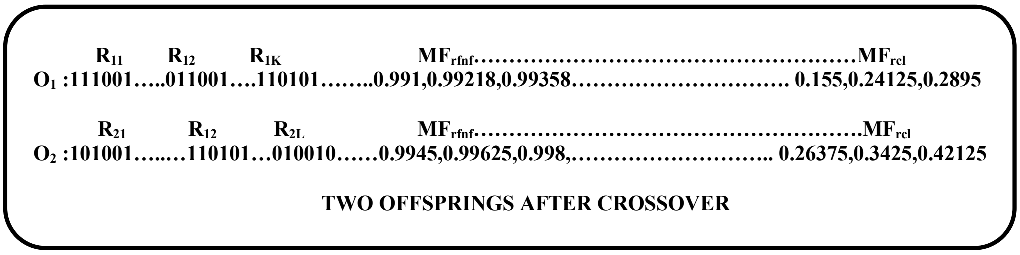


Figure 8.15: Two offsprings after crossover in ATFRBS

7. After offspring fuzzy rule sets and their membership functions have been generated by two-substring crossover operation, the order of a newly generated fuzzy membership function may be destroyed. These fuzzy memberships thus need rearrangement according to their centre values.
8. This method comprises of two different encoding schemes is for rule set part and membership function part, so two different mutation types is used for both the parts. In the rule set section bit inversion type of mutation is used and for membership function section, a small value is either added or subtracted from the membership function parameters. It is assumed that ‘l’, ‘c’ and ‘r’ represent the left, centre and right end value of the triangular membership function. A small value ‘η_{exp}’ is added to the end values by the mutation operator and ‘η_{cont}’is subtracted from the membership function parameters. Due to the addition or subtraction of the small value there will be no change in the centre of the

membership function as all the parameters added by the same amount. So this type of mutation does not require any rearrangement which may be required in some other cases. The mutation operation in Sugeno FIS is applied in the same way as Mamdani FIS. Figure 8.16 shows chromosomes after mutation.

R_{11} R_{12} R_{1K} MF_{FNF}……………………………………MF_{RCL}
RS_1+MFS_1 :101001…..011001….110101……….0.99275,0.9945,0.99625………………0.26375,0.3425,0.42125

AFTER MUTATION
R_{11} R_{12} R_{1K} MF_{FNF}………………………………………MF_{RCL}
RS_1+MFS_1 :100001…..110011….100101………..0.99277,0.99452,0.99627…………..0.26377,0.34252,0.42127

Figure 8.16: Chromosomes after mutation in ATFRBS

9. Again fitness evaluation of the parents and offsprings are done. In the procedure of examination, if the offspring comes as a best fit, then it is added to the data pool, and another arrangement of information pool is generated.
10. If the stopping criteria are not met go to step 3 and repeat the algorithm.
11. Likewise some strong rules are generated and added to the rule table. The rule table for the fuzzy inference engine is given in Table 8.1 of chapter 8.
12. Then by using Mamdani FIS and Sugeno FIS (Fuzzy inference Systems) to all these rules, the solution is obtained for each inference system separately.
13. The result is then defuzzified in Mamdani FIS to find the crisp values and the Sugeno FIS gives directly the crisp values for results.

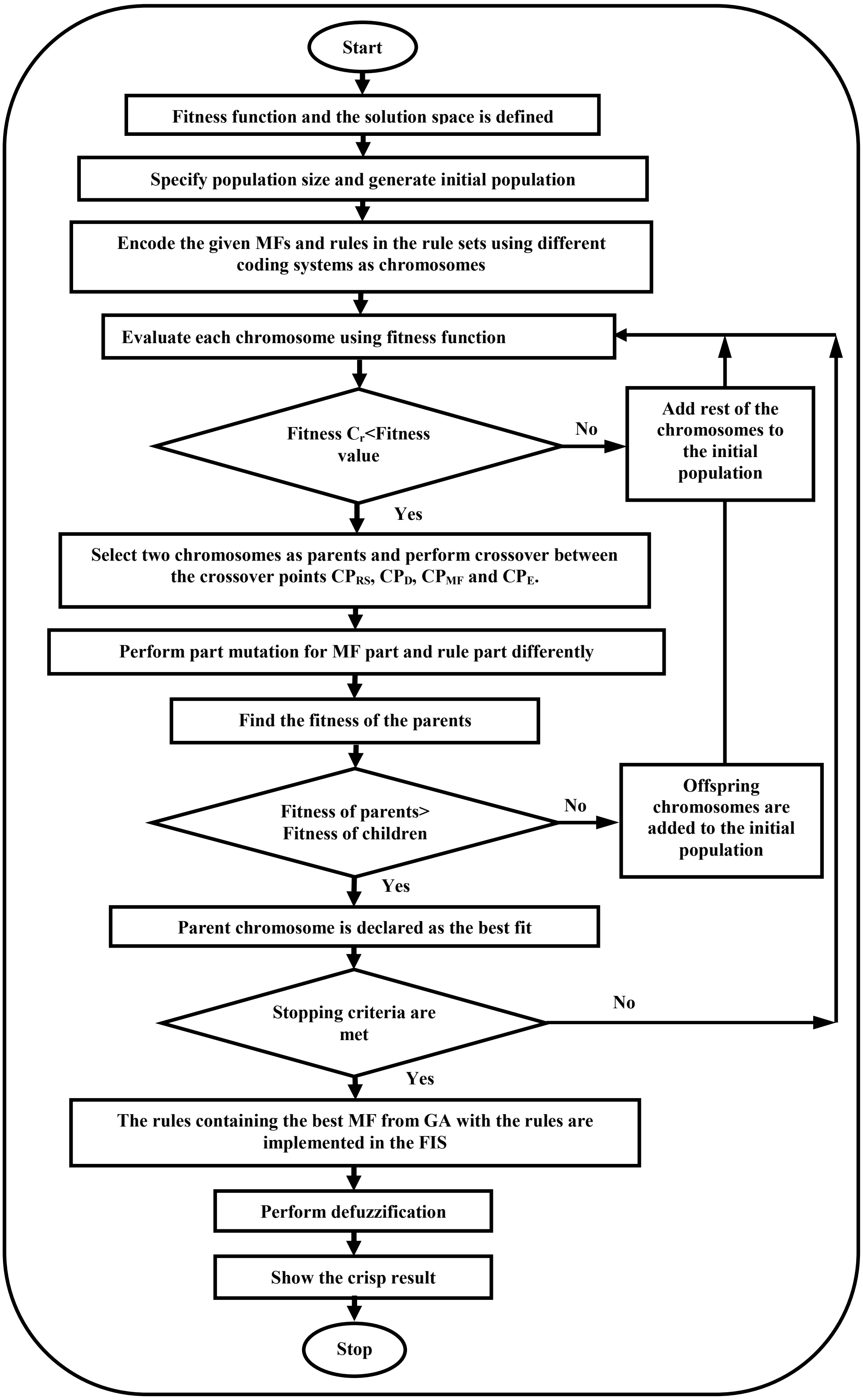


Figure 8.17: Flow chart for ATFRBS

8.2.2 Result Table

Table 8.10: Comparison of the results of ATFRBS (Mamdani FIS) with FEA of a cantilever beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the ATFRBS technique	rcl using the ATFRBS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9923	0.9912	0.9966	0.325	0.21875	0.3094	0.2082	4.8	4.8	4.8
2	0.9931	0.9926	0.9978	0.3	0.20625	0.2856	0.1963	4.8	4.81	4.80
3	0.9946	0.9942	0.9972	0.2875	0.23125	0.2737	0.2201	4.79	4.78	4.78
4	0.9959	0.99772	0.999	0.125	0.21875	0.1190	0.2082	4.78	4.81	4.79
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2617	0.3451	4.81	4.8	4.80
Total Average Error in %									4.79	

Table 8.11: Comparison of the results of ATFRBS (Mamdani FIS) with Exp. analysis of a cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the ATFRBS technique	rcl using the ATFRBS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3272	0.4462	4.8	4.8	4.8
2	0.9974	0.989	0.9999	0.375	0.5	0.3570	0.4761	4.79	4.78	4.78
3	0.99816	0.9982	0.9979	0.25	0.375	0.2380	0.3570	4.77	4.79	4.78
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2082	0.3867	4.78	4.79	4.78
5	0.9892	0.9996	0.9981	0.35	0.1875	0.3332	0.1785	4.8	4.78	4.79
Total Average Error in %									4.78	

Table 8.12: Comparison of the results of ATFRBS (Mamdani FIS) with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the ATFRBS technique	rcl using the ATFRBS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3629	0.3093	4.8	4.81	4.80
2	0.9966	0.9961	0.9978	0.3625	0.29375	0.3451	0.2796	4.79	4.8	4.79
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3391	0.2618	4.8	4.79	4.79
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3331	0.2737	4.81	4.79	4.8
5	0.9975	0.9991	0.9970	0.4	0.175	0.3808	0.1665	4.8	4.81	4.80
Total Average Error in %									4.8	

Table 8.13: Comparison of the results of ATFRBS (Mamdani FIS) with Exp. analysis of a fixed-fixed beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the ATFRBS technique	rcl using the ATFRBS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.3	0.18125	0.2856	0.1725	4.79	4.81	4.8
2	0.9981	0.9964	0.9977	0.33125	0.26875	0.3154	0.2558	4.78	4.79	4.78
3	0.9984	0.999	0.997	0.29375	0.1375	0.2796	0.1309	4.79	4.8	4.79
4	0.9985	0.9991	0.9975	0.31875	0.15625	0.3034	0.1487	4.79	4.8	4.79
5	0.9987	0.9999	0.9957	0.18125	0.2375	0.1725	0.2260	4.78	4.81	4.79
Total Average Error in %									4.79	

Table 8.14: Comparison of the results of ATFRBS (Sugeno FIS) with FEA of a cantilever beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the ATFRBS technique	rcl using the ATFRBS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9923	0.9912	0.9966	0.325	0.21875	0.3097	0.2084	4.7	4.7	4.7
2	0.9931	0.9926	0.9978	0.3	0.20625	0.2859	0.1965	4.7	4.7	4.7
3	0.9946	0.9942	0.9972	0.2875	0.23125	0.2740	0.2203	4.69	4.7	4.69
4	0.9959	0.99772	0.999	0.125	0.21875	0.1191	0.2084	4.68	4.69	4.68
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2620	0.3454	4.7	4.69	4.69
Total Average Error in %									4.69	

Table 8.15: Comparison of the results of ATFRBS (Sugeno FIS) with Exp. analysis of a cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the ATFRBS technique	rcl using the ATFRBS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3275	0.4468	4.7	4.68	4.69
2	0.9974	0.989	0.9999	0.375	0.5	0.3574	0.4765	4.67	4.69	4.68
3	0.99816	0.9982	0.9979	0.25	0.375	0.2382	0.3574	4.69	4.69	4.69
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2085	0.3871	4.68	4.7	4.69
5	0.9892	0.9996	0.9981	0.35	0.1875	0.3335	0.1787	4.7	4.68	4.69
Total Average Error in %									4.68	

Table 8.16: Comparison of the results of ATFRBS (Sugeno FIS) with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the ATFRBS technique	rcl using the ATFRBS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3632	0.3096	4.71	4.71	4.71
2	0.9966	0.9961	0.9978	0.3625	0.29375	0.3454	0.2799	4.7	4.7	4.7
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3395	0.2620	4.69	4.7	4.69
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3335	0.2740	4.71	4.69	4.7
5	0.9975	0.9991	0.9970	0.4	0.175	0.3812	0.1667	4.69	4.7	4.69
Total Average Error in %									4.7	

Table 8.17: Comparison of the results of ATFRBS (Sugeno FIS) with Exp. analysis of a fixed-fixed beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the ATFRBS technique	rcl using the ATFRBS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.3	0.18125	0.2859	0.1727	4.7	4.7	4.7
2	0.9981	0.9964	0.9977	0.33125	0.26875	0.3157	0.2561	4.69	4.69	4.69
3	0.9984	0.999	0.997	0.29375	0.1375	0.280	0.1310	4.67	4.69	4.68
4	0.9985	0.9991	0.9975	0.31875	0.15625	0.3038	0.1489	4.69	4.68	4.68
5	0.9987	0.9999	0.9957	0.18125	0.2375	0.1728	0.2264	4.65	4.65	4.65
Total Average Error in %									4.68	

8.2.3 Results and Discussion

An optimization method for automatic generation and design of fuzzy rule base has been proposed. Both representative data and expert knowledge are included in designing fuzzy rules, which conventionally include expert knowledge. The time required for the execution of the algorithm depends on the computer speed, not on human experts thus much time can be saved.

In the Automatic Tuning of Fuzzy Rules Base System binary encoding is used to encode the rules of a rule set, real type of encoding is done to encode the MFs in the rules of the rule set which is described in Figure 8.13. Four points are chosen for doing crossover and the points are described in the algorithm section shown in Figure 8.14. In the present algorithm two part mutation has been used for the rule set part and the membership function part. Figure 8.16 shows chromosome strings after mutation. In this technique both rules and MFs are simultaneously optimized. From the result table it can be observed that it gives more convergent results. The results from the method taking two types of beams (cantilever beam and fixed-fixed beam) into consideration are given in Tables 8.10 to 8.17.

8.3 Analysis of Hybridized CSA-FLS for Structural Damage Detection

All physical structures are subjected to damage. This may occur due to over stressing during operation in extreme environmental condition or due to any accidental encounter. The present crack may grow during working and may lead to failure if the crack grows beyond critical limit. So it is needed to investigate for the fault occurrence in structures at the earliest possible stage. To get better results with least time consumption the vibration based methods are now combined with different Artificial Intelligence techniques. These types of methods are getting popularized for their convenient approach to online fault detection methods for structural elements. These methods present the modern signal processing techniques and AI techniques together as a robust tool.

Artificial immune system is a machine learning algorithm that works on the principle of advantages of the natural immune system. Clonal Selection Algorithm (CSA) is one of the AIS, which is based on clonal selection theory (CST) of acquired immunity. The working procedure and the performance have been described in Chapter 6. From the results in this chapter, it has been observed that CSA performs better than GA. So in this section of the chapter a hybrid method using CSA and FLS has been proposed.

The main aim of any FLS is to define the membership functions and the major issue in the design of MF is the determination of the parameters (variable definition) involved with it. Some of the researchers have used Genetic Algorithm and Fuzzy Logic together, but in this case the results from the Genetic Algorithm layer is trained again in the fuzzy logic layer for refinement [199], some have used hybridized membership functions to be applied in the Fuzzy Inference System [200].

The characteristics of different AI algorithms are different. The results from the algorithms for different problems vary from each other, and there is no best algorithm for all problems. So many researchers have been trying to hybridize different AI algorithms for efficient and effective applications. To improve the quality of the MFs, some other methods such as GA, tabu search (TS) [201] etc. have been proposed by different authors. In recent years, to improve the performance of the Fuzzy Logic System, artificial immune system has been used to integrate with Fuzzy Rule-Based Pattern Classification. All these methodologies have been used in different fields like pattern recognition, banks financial institutions, use of electromagnets in maglev transportation vehicles [202].

After analyzing the literatures, an effort has been made in the current work for the adjustment of the MF shape (optimization of the parameters). In the previous sections of the thesis, MF has been optimized using GA and DEA (Automatic Design of the Fuzzy MFs and hybrid DEA-FLS). But when the efficiency of the CSA is compared with DEA and GA, it can be perceived that CSA gives better results than both the algorithms. So this section proposes a method to hybridize CSA and FLS for fuzzy MF parameter adjustment.

8.3.1 Analysis of Fuzzy Logic parameters for damage Detection in CSA-FLS

In the design of a Fuzzy Logic System, proper placement of membership functions with respect to fuzzy variables is important. As such, there is no rule and restriction for assignment of fuzzy membership functions, but developer must be well aware of the mathematical model of the membership functions.

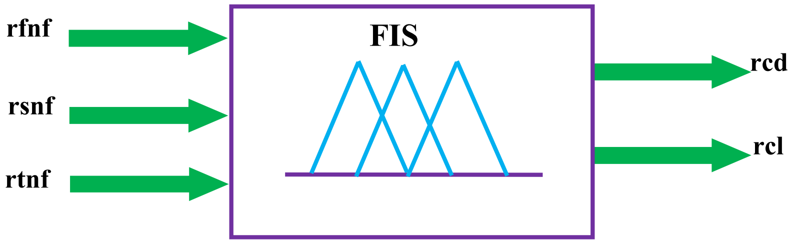


Figure 8.18: Fuzzy Controller with its input and output variables used in CSA-FLS

The proposed fuzzy system uses both Mamdani and Sugeno fuzzy model. Fuzzy linguistic variables are defined before assigning different membership functions and definition of their ranges. These linguistic variables play a major role during the formation of the rule table. The linguistic variables used for input and output variables are imported from section 8.1 of Chapter 8, (Table 8.1). The details of the FLS parameters are already defined and described in section 8.1 of Chapter 8.

8.3.2 Computation of Membership Function using Clonal Selection Algorithm applied to Damage Detection

Following are the steps used for Computation of MF using Clonal Selection Algorithm.

1. Before applying CSA to the fuzzy MFs in the fuzzy rules, coding is necessary. Here each antibody is represented by a fuzzy rule consisting of fuzzy MFs. The base values for each membership function and the constants for the Sugeno fuzzy rule is coded into six bit binary strings. So the Mamdani and Sugeno fuzzy rule consists of thirty bits. Figures 8.19 and 8.20 show the structure of the antecedent and consequent part in the fuzzy rule after encoding to bit strings for both Mamdani and Sugeno FIS.

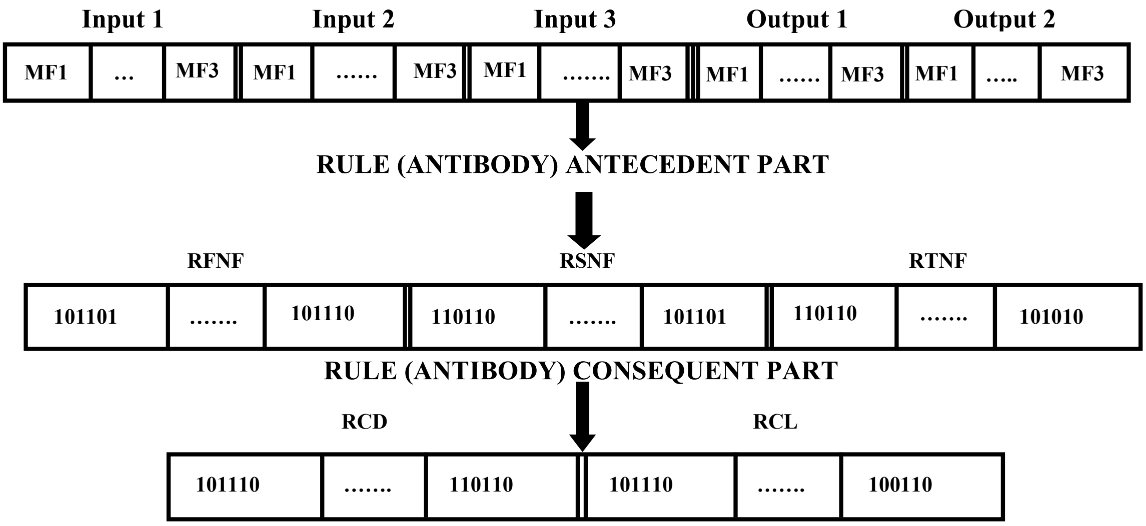


Figure 8.19: Binary presentation of fuzzy rules with their MFs in CSA-FLS for Mamdani FIS

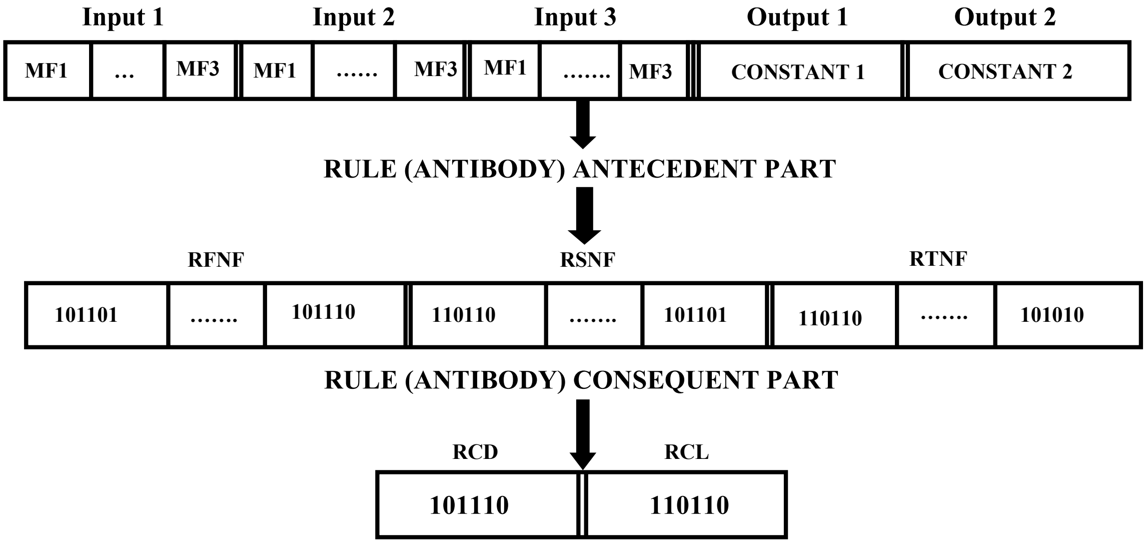


Figure 8.20: Binary presentation of fuzzy rules with their MFs in CSA-FLS for Sugeno FIS

2. After coding an initial population of antibodies, containing fifteen antibodies is generated randomly.
3. Then affinity measurement is performed on all the antibodies in the population. Actually affinity measurement is a type of fitness evaluation process.

$$\sqrt{\left(rfnf_{fl}-rfnf_{x_{1,g}}\right)^2+\left(rsnf_{fl}-rsnf_{x_{1,g}}\right)^2+\left(rtnf_{fl}-rtnf_{x_{1,g}}\right)^2} \qquad (8.3)$$

   $rfnf_{fl}$= First natural frequency from the field in the dimensionless form
   $rfnf_x$ = Dimensionless form of (relative) first natural frequency
   $rsnf_{fl}$ =Second natural frequency from the field in the dimensionless form
   $rsnf_x$ = Dimensionless form of (relative) second natural frequency
   $rtnf_{fl}$ =Third natural frequency from the field in the dimensionless form
   $rtnf_x$ = Dimensionless form of (relative) third natural frequency
   g =number of generations

4. After finding out the affinity values (fitness values) of all the antibodies, n (7) antibodies are selected according to their affinity values.
5. Then the selected numbers of antibodies are cloned, proportional to their affinity values. Cloning can be defined as affinity proportional reproduction.
6. After Cloning, the new antibody population is mutated. Here point mutation is used for performing mutation. A point mutation operates at a rate inversely proportional to the affinity of antibodies. Point mutation generates new antibodies by alternating the bits of one or more binary design variables of their parent antibodies.

7. This way the steps from 1-6 are repeated for thirty iterations and then the antibody with the maximum affinity is selected as the best solution.
8. Likewise the best twenty solutions (fuzzy rules) are selected and implemented in the Fizzy Inference System.
9. Then the centroid method of defuzzification is used for the calculation of the output. As each rule consists of different fuzzy variables used and the MFs, the shape of the MF is also changed and optimized according to the best solution.

Figure 8.21describes the above steps used in the design of the CSA-FLS hybridization.

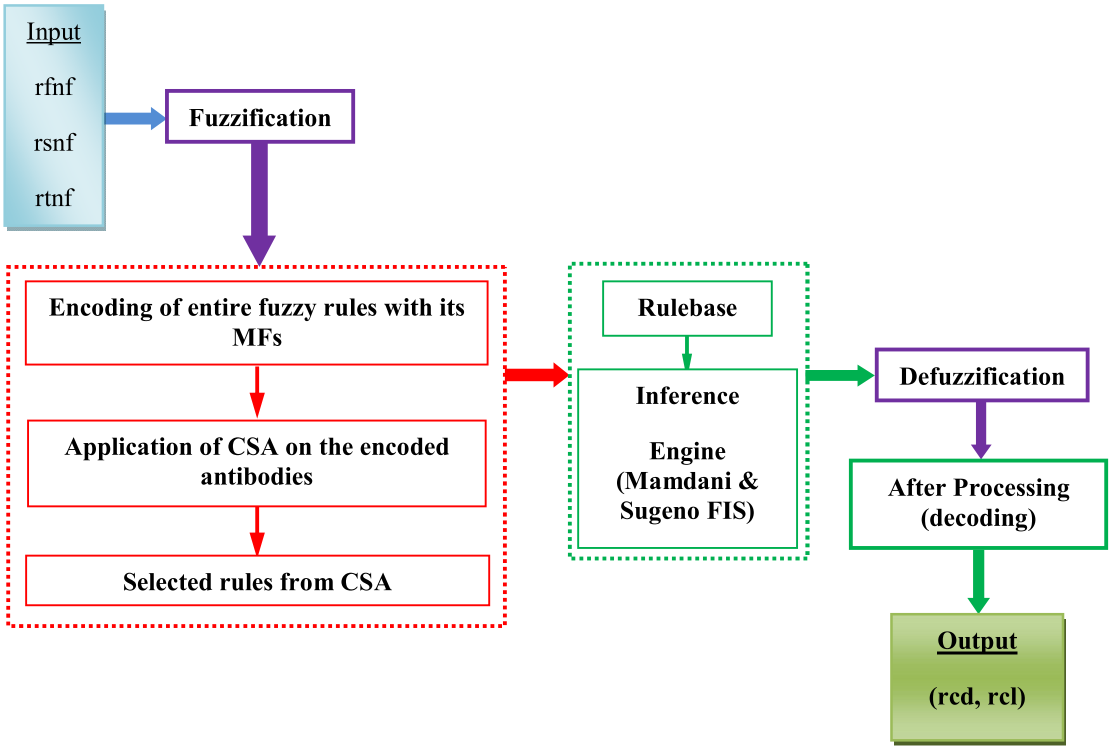


Figure 8.21: Pictorial presentation of CSA-FLS system

8.3.3 Result Table

Table 8.18: Comparison of the results of CSA-FLS (Mamdani FIS) with FEA of a cantilever beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the CSA-FLS technique	rcl using the CSA-FLS technique	percentage error rcd	percentage error rcl	Total Error in %
1	0.9923	0.9912	0.9966	0.325	0.21875	0.3109	0.2093	4.31	4.31	4.31
2	0.9931	0.9926	0.9978	0.3	0.20625	0.2871	0.1974	4.3	4.29	4.29
3	0.9946	0.9942	0.9972	0.2875	0.23125	0.2751	0.2212	4.31	4.32	4.31
4	0.9959	0.99772	0.999	0.125	0.21875	0.1195	0.2093	4.33	4.31	4.32
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2631	0.3468	4.31	4.32	4.31
Total Average Error in %									4.31	

Table 8.19: Comparison of the results of CSA-FLS (Mamdani FIS) with Exp. analysis of a cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the CSA-FLS technique	rcl using the CSA-FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3290	0.4485	4.27	4.31	4.29
2	0.9974	0.989	0.9999	0.375	0.5	0.3589	0.4786	4.29	4.28	4.28
3	0.99816	0.9982	0.9979	0.25	0.375	0.2393	0.3589	4.28	4.28	4.28
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2093	0.3887	4.31	4.3	4.30
5	0.9892	0.9996	0.9981	0.35	0.1875	0.3349	0.1794	4.29	4.29	4.29
Total Average Error in %										4.29

Table 8.20: Comparison of the results of CSA-FLS (Mamdani FIS) with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the CSA-FLS technique	rcl using the CSA-FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3648	0.3109	4.3	4.31	4.30
2	0.9966	0.9961	0.9978	0.3625	0.29375	0.3469	0.2811	4.3	4.3	4.3
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3409	0.2632	4.29	4.29	4.29
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3349	0.2751	4.3	4.31	4.30
5	0.9975	0.9991	0.9970	0.4	0.175	0.3827	0.1674	4.31	4.3	4.30
Total Average Error in %										4.3

Table 8.21: Comparison of the results of CSA-FLS (Mamdani FIS) with Exp. analysis of a fixed-fixed beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the CSA-FLS technique	rcl using the CSA-FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.3	0.18125	0.2871	0.1734	4.3	4.31	4.30
2	0.9981	0.9964	0.9977	0.33125	0.26875	0.3170	0.2572	4.28	4.27	4.27
3	0.9984	0.999	0.997	0.29375	0.1375	0.2811	0.1316	4.28	4.29	4.28
4	0.9985	0.9991	0.9975	0.31875	0.15625	0.3050	0.1495	4.29	4.27	4.28
5	0.9987	0.9999	0.9957	0.18125	0.2375	0.1734	0.2273	4.29	4.29	4.29
Total Average Error in %										4.28

Table 8.22: Comparison of the results of CSA-FLS (Sugeno FIS) with FEA of a cantilever beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the CSA-FLS technique	rcl using the CSA-FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9923	0.9912	0.9966	0.325	0.21875	0.3113	0.2095	4.21	4.21	4.21
2	0.9931	0.9926	0.9978	0.3	0.20625	0.2873	0.1975	4.21	4.21	4.21
3	0.9946	0.9942	0.9972	0.2875	0.23125	0.2754	0.2215	4.19	4.19	4.19
4	0.9959	0.99772	0.999	0.125	0.21875	0.1197	0.2095	4.18	4.21	4.19
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2634	0.3472	4.21	4.2	4.20
Total Average Error in %										4.2

Table 8.23: Comparison of the results of CSA-FLS (Sugeno FIS) with Exp. analysis of a cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the CSA-FLS technique	rcl using the CSA-FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3292	0.4490	4.21	4.2	4.20
2	0.9974	0.989	0.9999	0.375	0.5	0.3593	0.479	4.17	4.2	4.18
3	0.99816	0.9982	0.9979	0.25	0.375	0.2395	0.3592	4.19	4.19	4.19
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2095	0.3892	4.19	4.19	4.19
5	0.9892	0.9996	0.9981	0.35	0.1875	0.3353	0.1796	4.18	4.17	4.17
Total Average Error in %									4.18	

Table 8.24: Comparison of the results of CSA-FLS (Sugeno FIS) with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the CSA-FLS technique	rcl using the CSA-FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3651	0.3113	4.21	4.21	4.21
2	0.9966	0.9961	0.9978	0.3625	0.29375	0.3472	0.2814	4.22	4.2	4.21
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3412	0.2634	4.21	4.21	4.21
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3352	0.2753	4.21	4.21	4.21
5	0.9975	0.9991	0.9970	0.4	0.175	0.3831	0.1676	4.22	4.22	4.22
Total Average Error in %									4.21	

Table 8.25: Comparison of the results of CSA-FLS (Sugeno FIS) with Exp. analysis of a fixed-fixed beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the CSA-FLS technique	rcl using the CSA-FLS technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.3	0.18125	0.2874	0.1736	4.19	4.21	4.2
2	0.9981	0.9964	0.9977	0.33125	0.26875	0.3174	0.2574	4.18	4.19	4.18
3	0.9984	0.999	0.997	0.29375	0.1375	0.2814	0.1317	4.19	4.18	4.18
4	0.9985	0.9991	0.9975	0.31875	0.15625	0.3054	0.1497	4.17	4.17	4.17
5	0.9987	0.9999	0.9957	0.18125	0.2375	0.1736	0.2275	4.19	4.18	4.18
Total Average Error in %									4.18	

8.3.4 Results and Discussion

A strategy for crack prognosis in beam-like structures has been planned and created utilizing clonal determination calculation and fuzzy logic and is presented in this section. The FLS is designed using three triangular membership functions. To keep the encoding system simpler three number of triangular membership functions are used and the base values for each membership function is coded into six bit binary strings. The fitness function is given in equation 8.3. Figure 8.21 describes the steps used in the design of architecture of the CSA-FLS. Here the antibodies and antigens contain the fuzzy parameters (rules containing the fuzzy MFs) which undergo cloning and somatic hypermutation processes described in Chapter 6. The results from the method taking two types of beam constraints into consideration are given in Tables 8.18 to 8.25.

8.4 Analysis of Hybridized CSA-GA for Structural Damage Detection

Damage detection of systems represents an important research topic widely investigated. During the last two decades several researches have been conducted with reference to beams, trusses, plates, shells, bridges, offshore platforms, and other large civil structures, aerospace and composite structures to detect structural damages by monitoring the dynamic response of the system. The changes in the physical properties will cause changes in the modal properties. This work tries to derive a simple procedure for estimating the damage in structures based on changes in the modal parameters using AI techniques. Different natural AI techniques and vibration analysis can be used to detect the location, and the extent of damage in cracked beams. The main goal of this section is to integrate two evolution based (Genetic Algorithm) and immune based (Clonal Selection Algorithm) algorithms for damage detection. The pros and cons of both the algorithms have already been described in previous chapters.

This has been proved by different researchers that the hybrid methods give better results as compared to the original AI techniques. Many works has also been proposed by several researchers improve the quality of result produced by Clonal Selection Algorithm following paragraph lists some of them. Different algorithms based on combination with CSA such as adaptive mutation working on weighted aggregation function [203], population based Clonal Selection Algorithm combined with the elitist learning mechanism of Particle Swarm Optimization [204], integrated Clonal Selection Algorithm with biogeography based optimization [205] have been proposed by different researchers.

Though many works have been proposed for the hybridization of CSA with other algorithms but no work has been proposed for the optimization of fuzzy MF using CSA. So this work aims at incorporating Clonal Selection Algorithm and Genetic Algorithm for damage detection.

8.4.1 Analysis of the CSA-GA method for damage detection

As described in Chapter 6, in the standard CSA the population of antibodies evolves rapidly to match the antigen which gives better results as compared to other evolutionary algorithms. But CSA is devoid of crossover/recombination operation. It has been observed that, in some cases crossover can provide a higher level of genetic recombination than mutation. In the proposed hybrid method the recombination operation is borrowed from GA, so that there would be introduction of some cross action between the antibodies that can improve the diversity in antibodies after hypermutation.

The fusion can be described in two steps. In the first step, a data pool (initial population) of antibodies evolves rapidly to match the antigens. Both the antigens and antibodies are encoded using binary strings (bits). After the affinity measurement (evaluation of the antibodies according to their fitness values), the selected antibodies undergo proliferation (cloning).

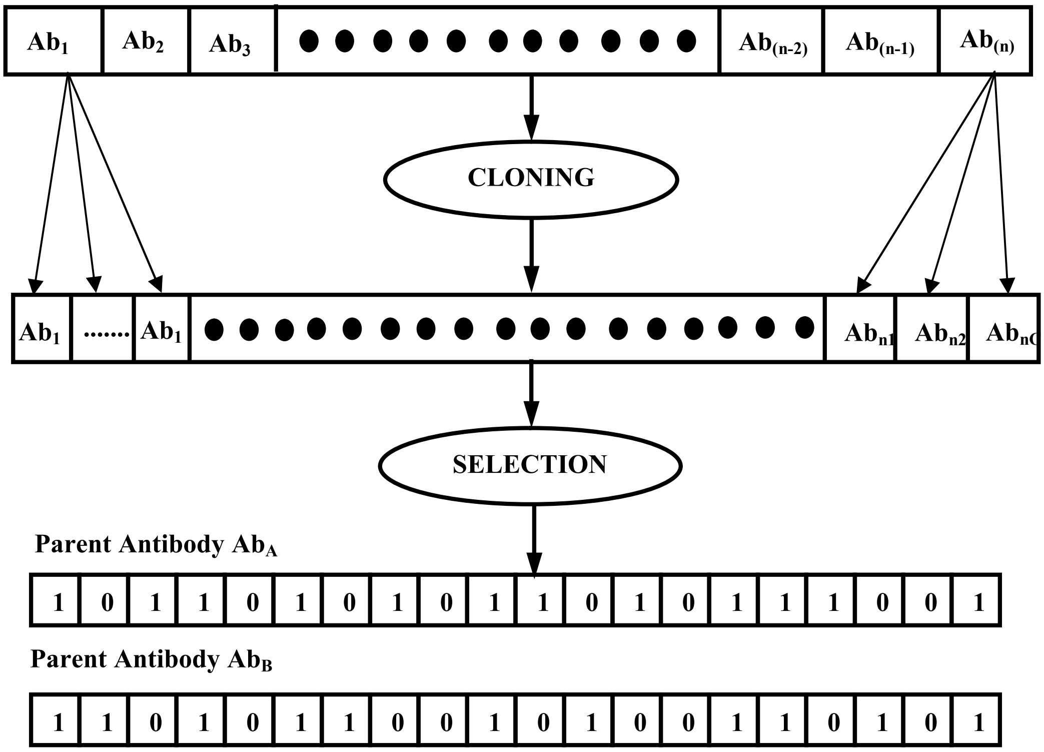
After this point of development of the algorithm, GA is introduced to the sequences of the CSA. Two of the cloned antibodies are selected as the parents for crossover based on the affinity value towards the antigens. Then the two selected antibodies as parents undergo crossover to produce two child/offspring antibodies. After crossover, mutation is implemented on all the individuals (chromosomes). As the population of clones is fed to the crossover operation of the Genetic Algorithm, it gives better result as the antibodies are already improved.

The rest of the algorithm steps follow the Clonal Selection Algorithm procedures. The stopping criteria for the algorithm are i) treatment of all the antigens to the antibody population, ii) number of iterations (100), and iii) time elapse (3minutes). The algorithm terminates if it faces any one of the stopping conditions first. Figure 8.25 describes the flowchart for the development of hybridization of CSA and GA.

Following are the steps used in the integration of Clonal Selection Algorithm and Genetic Algorithm.

1. A population of candidates is generated and fitness function is defined.
2. Antibodies and antigens are encoded using binary strings.
3. The populations of candidate solutions are evaluated using the fitness function.
4. The evaluated individuals are arranged according to their fitness values from the fitness function.

5. Then ‘n’ best individuals are selected for cloning to form a population of clones (C).



Parent Antibody Ab_A

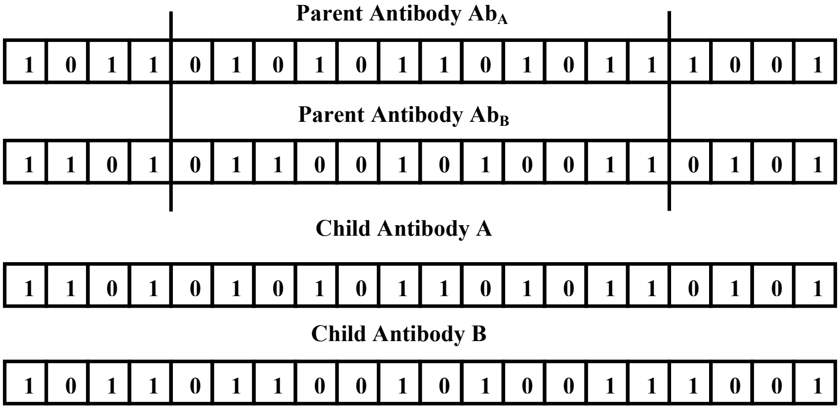
1 0 1 1 0 1 0 1 0 1 1 0 1 0 1 1 1 0 0 1

Parent Antibody Ab_B

1 1 0 1 0 1 1 0 0 1 0 1 0 0 1 1 0 1 0 1

Figure 8.22: Cloning process and selection of antibodies as parents for crossover in CSA-GA

6. Again the populations of candidates are trained in the fitness function and two best candidates are selected as the parents for crossover operation.



Parent Antibody Ab_A

1 0 1 1 0 1 0 1 0 1 1 0 1 0 1 1 1 0 0 1

Parent Antibody Ab_B

1 1 0 1 0 1 1 0 0 1 0 1 0 0 1 1 0 1 0 1

Child Antibody A

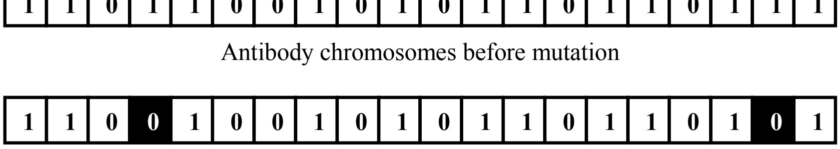
1 1 0 1 0 1 0 1 0 1 1 0 1 0 1 1 0 1 0 1

Child Antibody B

1 0 1 1 0 1 1 0 0 1 0 1 0 0 1 1 1 0 0 1

Figure 8.23: Two point crossover of antibodies as parents in CSA-GA

7. Then mutation is performed on parents and offsprings.



1 1 0 1 1 0 0 1 0 1 0 1 1 0 1 1 0 1 1 1

Antibody chromosomes before mutation

1 1 0 0 1 0 0 1 0 1 0 1 1 0 1 1 0 1 0 1

Antibody chromosomes after mutation

Figure 8.24: Representation of mutation of antibody chromosomes in CSA-GA

8. The parents and offsprings are again evaluated and the best antibody (chromosome) is added to the population. This population forms the initial population in the next generation.
9. The algorithm is repeated till it meets the stopping criteria.
10. If the stopping criteria are met, then the antibody which produces best affinity value is chosen as the current best body.

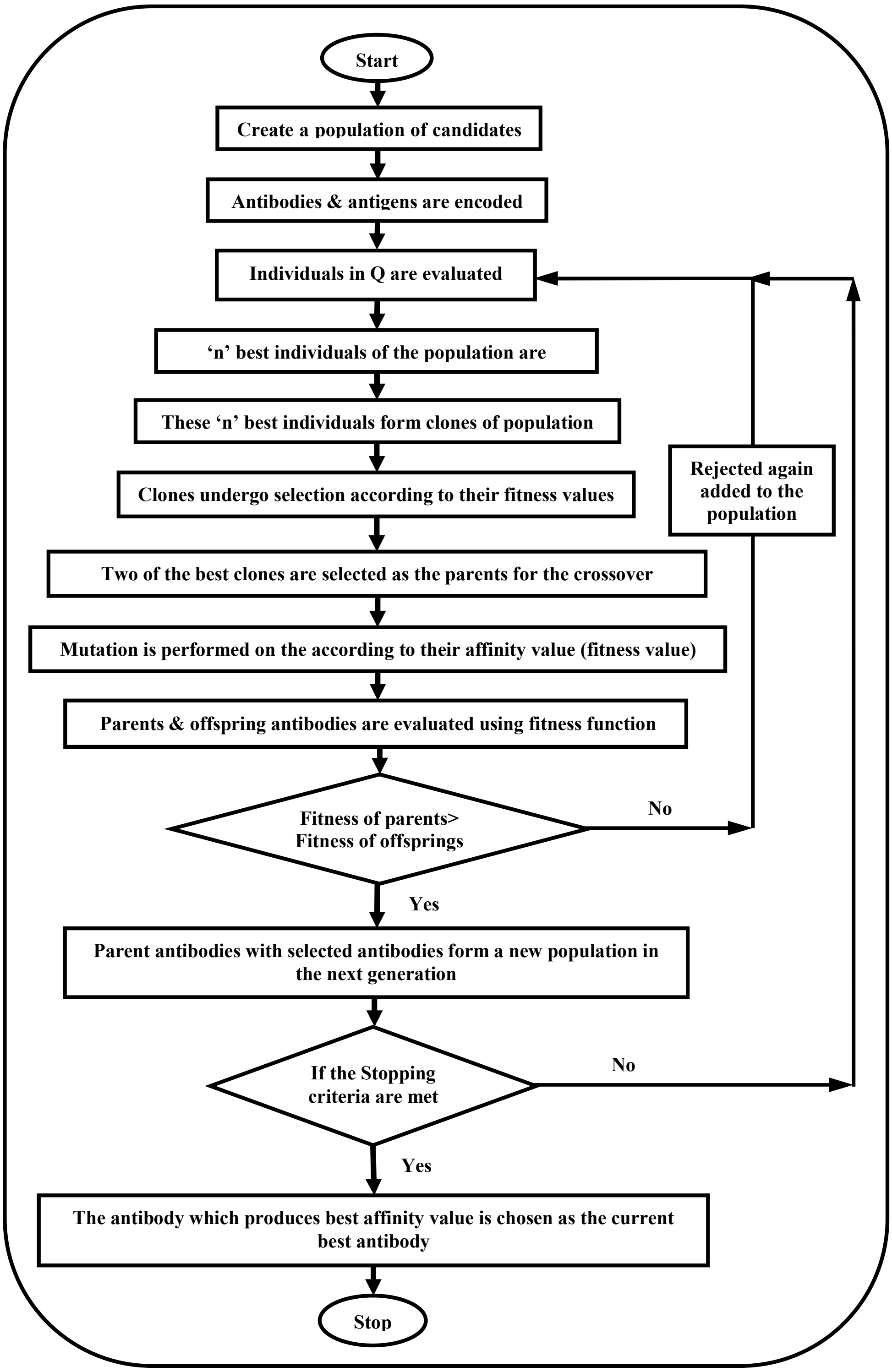


Figure 8.25: Flow chart for CSA-GA

8.4.2 Result Tables

Table 8.26: Comparison of the results of CSA-GA with FEA of a cantilever beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the CSA-GA technique	rcl using the CSA-GA technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9923	0.9912	0.9966	0.325	0.21875	0.3114	0.2096	4.16	4.18	4.17
2	0.9931	0.9926	0.9978	0.3	0.20625	0.2874	0.1976	4.17	4.16	4.16
3	0.9946	0.9942	0.9972	0.2875	0.23125	0.2755	0.2216	4.15	4.17	4.16
4	0.9959	0.99772	0.999	0.125	0.21875	0.1198	0.2096	4.16	4.15	4.15
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2635	0.3474	4.17	4.16	4.16
Total Average Error in %									4.16	

Table 8.27: Comparison of the results of CSA-GA with Exp. analysis of a cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the CSA-GA technique	rcl using the CSA-GA technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3295	0.4493	4.12	4.13	4.12
2	0.9974	0.989	0.9999	0.375	0.5	0.3594	0.4794	4.14	4.12	4.13
3	0.99816	0.9982	0.9979	0.25	0.375	0.2397	0.3594	4.12	4.14	4.13
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2096	0.3894	4.15	4.14	4.14
5	0.9892	0.9996	0.9981	0.35	0.1875	0.3356	0.1797	4.1	4.12	4.11
Total Average Error in %									4.12	

Table 8.28: Comparison of the results of CSA-GA with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the CSA-GA technique	rcl using the CSA-GA technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3653	0.3115	4.17	4.15	4.16
2	0.9966	0.9961	0.9978	0.3625	0.29375	0.3474	0.2815	4.15	4.15	4.15
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3414	0.2635	4.16	4.16	4.16
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3354	0.2755	4.15	4.15	4.15
5	0.9975	0.9991	0.9970	0.4	0.175	0.3834	0.1677	4.14	4.14	4.14
Total Average Error in %									4.15	

Table 8.29: Comparison of the results of CSA-GA with Exp. analysis of a fixed-fixed beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the CSA-GA technique	rcl using the CSA-GA technique	percentage error rcd	percentage error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.3	0.18125	0.2875	0.1737	4.15	4.15	4.15
2	0.9981	0.9964	0.9977	0.33125	0.26875	0.3176	0.2576	4.1	4.12	4.11
3	0.9984	0.999	0.997	0.29375	0.1375	0.2815	0.1318	4.15	4.14	4.14
4	0.9985	0.9991	0.9975	0.31875	0.15625	0.3055	0.1497	4.14	4.14	4.14
5	0.9987	0.9999	0.9957	0.18125	0.2375	0.1737	0.2276	4.14	4.14	4.14
Total Average Error in %									4.13	

8.4.3 Results and Discussion

The proposed algorithm is developed hybridizing the Clonal Selection Algorithm and Genetic Algorithm to derive the crack position (location and depth). Then by running the algorithm within the search space (data set) helps us to find if not exact but the near exact location of the crack which helps us to predict the damage severity. The portions of CSA and GA are borrowed from chapter 6 and chapter 5. The algorithm starts by encoding the antibodies antigens using binary encoding scheme. The same numbers of bits are used to encode the input (rfnf, rsnf, rtnf) and output (rcd, rcl) as in Genetic Algorithm chapter. The combined operators like cloning, crossover and mutation are described in Figures 8.22, 8.23 and 8.24 respectively. The flowchart for the integrated algorithm is shown in Figure 8.25. The results from the method taking two types of beam constraints into consideration are given in Tables 8.26 to 8.29.

8.5 Analysis of Hybridized CSA-DEA for Structural Damage Detection

The dynamic characteristics are important factors which should be taken into consideration during design of structures subjected to vibration. The change in the dynamic properties of the structures shows the changes in the system. This can be used for the identification of fault in structural elements. So the fault detection of the structures is being the research topic for decades. The majority of the procedures created for approaching this problem are based on the modal analysis of the vibrating structures. There have been extensive endeavors to comprehend and model the dynamics of a vibrating cracked beam. All models emerging from hypothetical have a large number of suppositions to be made. Therefore there is a need to utilize other vibration based intelligent strategies. Recent years have witnessed a major evolution in the field of fault diagnosis in structural elements and rotating machine parts using artificial intelligence techniques.

For the last two decades, global optimization methods have received much attention. Among these methods stochastic population based methods give a number of advantages. The advantages include freedom from derivative constraints, enhanced efficiency and utilization of large search space. Due to the above stated reasons studies in these fields are increased. However, when a single method is applied, sometimes it becomes restrictive for certain problems. This is due to the fact that every technique has certain limitations like convergence speed and searching accuracy. Some of the researchers have initiated studies on hybridization of different methods. Hence this provides a promising opportunity to improve the searching capability, enhancement of accuracy and speed of performance.

This section of Chapter 8 makes an attempt to hybridize Clonal Selection Algorithm and Differential Evolution Algorithm.

Recently many researchers have proposed methods to overcome these limitations incurred in individual methods. They include, attribute weighted CSA [206], chaos based mutation strategy [207], combination of improved hypermutation operator and receptor editing operator [208] etc. Some of the authors have also tried to improve the performance of DEA by introducing different mutation and crossover strategies [209], adding Negative Selection Algorithm to DEA [210], and combining Gene Expression Engineering [211].

This has been observed that less work has been done to integrate immune based CSA with DEA. All these hybridized techniques have not yet been applied for damage detection. So an attempt is made to hybridize CSA and DEA and apply it to predict the severity of damage.

In this section, the evolutionary operations of the DEA method are used for improving the exploration capability of the standard CSA. The proposed method has been designed hybridizing CSA and DEA techniques. In this hybrid method (CSA-DEA), the crossover and mutation are applied to exploit the information regarding different antibodies in the population. This strategy can proficiently enhance the searching quality compared to standard CSA and DEA method. This methodology has been adapted for finding out the crack depth and crack positions from the natural frequencies of the vibrating system.

8.5.1 Analysis of the CSA-DEA method for damage detection

Like other hybridized methods, these two nature inspired algorithms are incorporated to overcome one another's limitations. As they are integrated together, so they retain some part of their original algorithms features. Like general CSA the population of antibodies in the hybridized system (CSA-DEA) is initialized randomly. Then similarity measurement is done to find the affinity of the antibodies for the antigens. There is no change in the antibody and antigen definition and representation. Then on the basis of affinity measurement, some of the antibodies are selected for cloning process. The mutation and crossover is done using DEA on the clones and a new generation of antibodies is produced. After mutation and crossover, a selection operator of DEA is applied on the original and offspring antibodies. The antibodies with poor affinity values undergo randomization according to DEA. These selected improved antibodies form a new population. The antibody which produces best affinity value is chosen as the current best antibody and the algorithm is repeated till it meets the stopping criteria of the algorithm.

By the employment of the evolutionary operations of DEA method in the mutation and crossover operation of the standalone Clonal Selection Algorithm, the fitness values of different clones are enhanced. In the modified version of CSA by the use of mutation and crossover operations from DEA, the information of neighboring clones is included against the standard mutation operation which considers only the single clone and its original antibody in the standard CSA method. The stopping criteria for the algorithm are i) treatment of all the antigens to the antibody population, ii) number of iterations (50), and iii) time elapse (3minutes). The algorithm terminates if it faces any one of the stopping conditions. Figure 8.27 describes the flow chart for the CSA-DEA hybridization technique.

Before proceeding towards the algorithm an initial population is created using the data from the data pool (Tables 6.1 and 6.2) of chapter 6. In this algorithm the individual solutions (vectors) are represented as antibodies. Following are the steps used in the hybridization of Clonal Selection Algorithm and Differential Evolution Algorithm.

1. Initial population and fitness function are defined. Antibodies and antigens are encoded.
2. Individuals in the initial population are evaluated using affinity measurement function using equation 6.3 of chapter 6 and ranked according to their fitness values.
3. Individuals (n) according to their fitness values are selected.
4. The antibodies according to their affinity values undergo proliferation to create clones (C) according to equation (6.2). The number of clones is directly proportional to the affinity values or fitness values. Figure 8.26 describes the cloning process in CSA-DEA hybridized method.

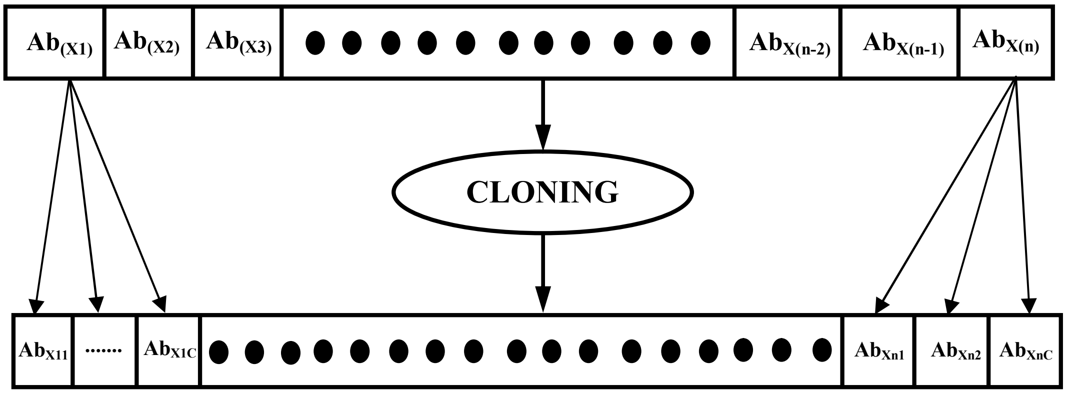


Figure 8.26: Cloning process applied to DEA individuals in CSA-DEA

5. The clones generated by proliferation undergo mutation using equation (7.4) of DEA.
6. The mutated clones undergo crossover using equation (7.5) of DEA.
7. After crossover, selection operation is applied on all the antibodies using equation (7.6) of DEA.
8. Then antibodies with poor affinity values are randomized using equation (7.3) of DEA.
9. These antibodies with selected antibodies create a new population in the next generation.
10. If the stopping criteria are met then the antibody with highest affinity is chosen as the current best antibody, otherwise the algorithm is repeated.

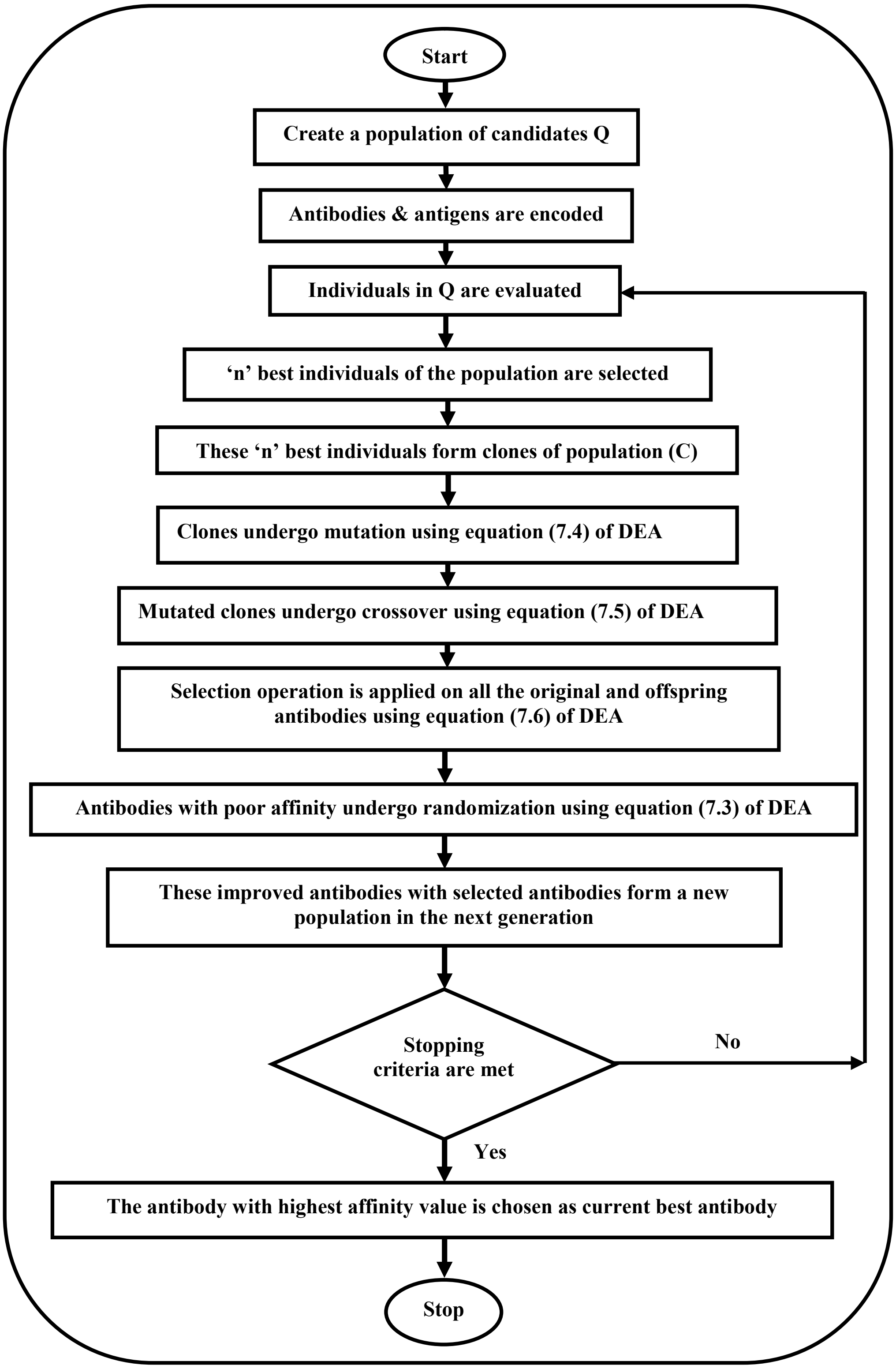


Figure 8.27: Flow chart of the CSA-DEA algorithm

8.5.2 Result Tables

Table 8.30: Comparison of the results of CSA-DEA with FEA of a cantilever beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the CSA-DEA method	rcl using the CSA-DEA method	percentage error rcd	percentage error rcl	Total error in %
1	0.9923	0.9912	0.9966	0.325	0.21875	0.3120	0.2100	3.98	3.96	3.97
2	0.9931	0.9926	0.9978	0.3	0.20625	0.288	0.1980	4	3.98	3.99
3	0.9946	0.9942	0.9972	0.2875	0.23125	0.2760	0.2220	3.99	3.99	3.99
4	0.9959	0.99772	0.999	0.125	0.21875	0.1200	0.2100	3.99	3.99	3.99
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2640	0.3476	3.97	4.1	4.03
Total Average Error in %									3.99	

Table 8.31: Comparison of the results of CSA-DEA with Exp. analysis of a cantilever beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the CSA-DEA method	rcl using the CSA-DEA method	percentage error rcd	percentage error rcl	Total error in %
1	0.9973	0.9914	0.9995	0.34375	0.46875	0.3301	0.4500	3.97	3.98	3.975
2	0.9974	0.989	0.9999	0.375	0.5	0.3601	0.4803	3.96	3.94	3.95
3	0.99816	0.9982	0.9979	0.25	0.375	0.2401	0.3601	3.95	3.95	3.95
4	0.9988	0.9981	0.9989	0.21875	0.40625	0.2101	0.3902	3.95	3.93	3.94
5	0.9892	0.9996	0.9981	0.35	0.1875	0.3361	0.1800	3.96	3.96	3.96
Total Average Error in %									3.95	

Table 8.32: Comparison of the results of CSA-DEA with FEA of a fixed-fixed beam

Sl. No	rfnf from FEA	rsnf from FEA	rtnf from FEA	rcd from FEA	rcl from FEA	rcd using the CSA-DEA method	rcl using the CSA-DEA method	percentage error rcd	percentage error rcl	Total error in %
1	0.9949	0.9953	0.9968	0.38125	0.325	0.3656	0.312	4.1	4	4.05
2	0.9966	0.9961	0.9978	0.3625	0.29375	0.348	0.2820	4	3.99	3.99
3	0.9969	0.9968	0.9968	0.35625	0.275	0.3420	0.2640	3.99	3.99	3.99
4	0.9970	0.9958	0.9977	0.35	0.2875	0.3360	0.2759	3.99	4.01	4
5	0.9975	0.9991	0.9970	0.4	0.175	0.3836	0.168	4.1	4	4.05
Total Average Error in %									4.01	

Table 8.33: Comparison of the results of CSA-DEA with Exp. analysis of a fixed-fixed beam

Sl. No	rfnf from exp. analysis	rsnf from exp. analysis	rtnf from exp. analysis	rcd from exp. analysis	rcl from exp. analysis	rcd using the CSA-DEA method	rcl using the CSA-DEA method	percentage error rcd	percentage error rcl	Total error in %
1	0.9982	0.9982	0.9967	0.3	0.18125	0.2881	0.1740	3.94	3.96	3.95
2	0.9981	0.9964	0.9977	0.33125	0.26875	0.3181	0.2581	3.95	3.95	3.95
3	0.9984	0.999	0.997	0.29375	0.1375	0.2821	0.1320	3.96	3.95	3.95
4	0.9985	0.9991	0.9975	0.31875	0.15625	0.3060	0.1500	3.97	3.97	3.97
5	0.9987	0.9999	0.9957	0.18125	0.2375	0.1740	0.2280	3.99	3.99	3.99
Total Average Error in %									3.96	

8.5.3 Results and Discussion

In spite of the advantages of finding out great results in multimodal problems, the main shortcoming of the CSA method consists of comprises of untimely and moderate convergence. Due to these limitations in the Clonal Selection Algorithm (CSA), the evolutionary algorithm such as Differential Evolution Algorithm (DEA) method has been utilized to enhance the seeking capacity of the CSA technique. The hybridized method employs evolutionary operations to the antibodies that yield potentially good fitness values. Figure 8.26 describes the cloning process of the antibodies containing the vector presentation of the individuals. The flowchart for the combined algorithm is given in Figure 8.27.The results are provided in Tables 8.30 to 8.33.

8.6 Summary

Different hybridized techniques which are designed integrating standalone methods are described in this chapter. The results from the proposed methods are compared with the FEA and test results simultaneously. Same set of data is considered for all the proposed methods, so that there will be fair comparison.

Section 8.1 of the Chapter 8 presents optimization of fuzzy MF using Genetic Algorithm. In this approach, GA has been used to design the architecture of the Fuzzy Logic System for fault detection in cracked structural elements. The method is well capable to learn and adopt the vibration parameters of the cracked structure which are used as the decision variables for the FLS. The Genetic Algorithm based approach optimizes the membership functions associated with the attributes with less error as they require fewer support parameters for the optimization.

The total average error from this method (ADFMF) using Mamdani FIS for cantilever beam and fixed-fixed beam is found to be within 5% when compared with the results of Finite Element Analysis and Experimental Analysis respectively. Similarly the total average error in Sugeno FIS for cantilever beam and fixed-fixed beam is found to be around 4.8% when compared with the results of Finite Element Analysis and Experimental Analysis respectively.

Although FLS has been depicted as the effective control method in various applications, but it lacks many innovative techniques in terms of applications. So in Section 8.2 of Chapter 8, a method has been presented for adjusting the membership function shapes as well as generation of fuzzy associative rules using GA. The fitness function is so designed that it can incorporate the problem variables and the rule factors, to lessen the evaluation error. The proposed ATFRBS operations modify the rules by manipulating the linguistic variables. This approach mainly emphasizes on the use of Genetic Algorithm to model the control processes of the Fuzzy Logic System.

The total average error from this method (ATFRBS) using Mamdani FIS for cantilever beam and fixed-fixed beam is found to be within 4.8% when compared with the results of finite element analysis and experimental analysis respectively. Similarly the total average error in Sugeno FIS for cantilever beam and fixed-fixed beam is found to be around 4.7% when compared with the results of finite element analysis and experimental analysis respectively.

This has already been stated in previous chapters that the appropriate placing of the membership functions (MFs) in the rule table is very difficult. So parameters of the FLS must be optimized using global methods. The current section presents optimization of the membership function shape using an artificial immune system based method. The Section 8.3 may look alike Section 8.1of Chapter 8, where GA is used to optimize the MF shape, but the operations and algorithm are quite different from ADFMF. Here the immune based Clonal Selection Algorithm has been used for the membership function shape optimization.

The total average error from this method (CSA-FLS) using Mamdani FIS for cantilever beam and fixed-fixed beam is found to be within 4.3% when compared with the results of finite element analysis and experimental analysis respectively. Similarly the total average error in Sugeno FIS for cantilever beam and fixed-fixed beam is found to be around 4.2% when compared with the results of finite element analysis and experimental analysis respectively.

Section 8.4 of chapter 8 proposes the introduction and addition of GA to CSA while being applied for damage detection. Clonal Selection Algorithm contains no crossover and contains only proliferation and hypermutation. During cloning good and efficient traits of the antibodies (solutions) are replicated but there is no addition of extra informations which can improve the solution efficiency. So by adding GA's crossover higher level of genetic recombination is added to the offspring antibodies. There are drawbacks of GA like slow convergence rate and prematurity which are taken care by the cloning and mutation mechanisms of CSA. The above stated benefits can be well visualized from the results of the proposed algorithm. The total average error in CSA-GA for cantilever beam and fixed-fixed beam is found to be within 4.15% when compared with the results of finite element analysis and experimental analysis respectively.

In Section 8.5 of Chapter 8, a new hybridized method is proposed for fault detection in cracked structural elements using an evolutionary algorithm and an artificial immune based algorithm. Global optimization methods are required to deal with the uncertainties and nonlinearities of the in damage detection problems. But there are limitations like huge computational time and getting trapped into the local solutions. So to get rid of all these limitations CSA and DEA are combined to make a universal approach for damage detection. In this algorithm DEA behaves similar to that of GA but it begins from an initial point and generates new candidate solutions by adding the difference between the two referred solutions. Clonal Selection Algorithm helps the proposed algorithm to get out of the local solutions. The efficiency can be confirmed from the results of the hybrid technique. The total average error in CSA-DEA for cantilever beam and fixed-fixed beam is found to be within 4% when compared with the results of finite element analysis and experimental analysis respectively.

From the analysis of the results from all the proposed hybrid methods, it could be noticed that, the total average error is well within a tolerance limit and convergent results could be achieved from these methods. All the proposed hybrid methods, give better results than their respective individual methods. The hybrid methods could be used as online health monitoring devices for large complex structures considering other application conditions. Among all the proposed hybrid methods, CSA-DEA gives best result with 4% of error and is well capable of attaining global solution.

Chapter 9

Results and Discussion

9.1 Introduction

The problem definition and the feasibility of the required investigations for the research work have been described systematically in detail in the thesis. The objectives and the framework of the research work have been described in Chapter 1. The strategies utilized depend on the dynamic reaction (frequency response) of the damaged structure. The frequency response measurement is one of the effortless methods to obtain in real-time as it only requires a small number of sensors. This method avoids the use of a validated reference model. Different Artificial intelligence techniques have been proposed with their hybrid models for identification and location of the cracks. The analytical models have been developed using strain energy release method and the finite element analysis. All these direct and inverse methods of crack detection are described in detail in Chapters 3 to 9.

9.2 Analysis of Results

This research work proposes the methods of crack detection in a cantilever and a fixed-fixed beam. The first chapter gives the introductory idea about the research work and the methodologies used in the current investigation. A thorough literature analysis has been done on the Analytical and the Artificial Intelligence techniques part in the second chapter. The third and fourth chapters of the thesis describe the direct method to find the vibration response of the cracked structure. Chapters 5 to 8 outline the different AI techniques and their hybrid methods used for crack location and used as inverse approaches for fault diagnosis.

To solve complex and intricate nonlinear problems a diversity of intelligent properties are required comprising traditional methods. There is an array of AI techniques available, but each technique has some strengths and limitations. So the combination of the two techniques allows taking advantage of their respective strengths and compensates individual's weakness. Hybrid intelligent system gives the flexibility of representing different types and structures of data and knowledge which may come from different sources. However the design and development is difficult for a particular problem. The intelligent techniques are developed keeping in mind the problem parameters and expertise knowledge. The following section discusses formulation and results of the hybrid intelligent techniques. The hybrid intelligent methods designed and developed are also narrated in different sections of the Chapters 5 to 8.

Model required for the dynamic examination of the cracked cantilever beam and fixed-fixed beam is shown in Figures 3.1 and 3.3. Figures 3.2 and 3.4 describe the amplitudes of longitudinal and bending vibration for the two sections generated due to the presence of the crack. The changes in the first three natural frequencies are obtained by analyzing different crack configurations for two end conditions. Table 3.1 describes the influence of boundary conditions on the natural frequencies. The results from the dynamic analysis of the beam are compared with the results of experimental analysis. The results are given in Tables 3.2 and 3.3. The schematic diagram for the experimental analysis is presented in Figures 3.5(a) and 3.5(b). This method is used for mathematical modeling of the transverse hairline crack and the results are used to make the database that is used in other chapters of the thesis.

In the fourth chapter, Finite Element Analysis of the damaged structure has been studied to get the dynamic responses by numerical simulation. The results are then compared with the results of the Experimental Analysis. The results are given in Tables 4.1 and 4.2. From the comparison of the results from the three methods, it can be observed that all the results are in close agreement with each other.

Chapter five describes the details of the Mamdani-Adaptive Genetic-Sugeno model. Before analyzing the methodology, one must be clear on the concept of Fuzzy Logic System and Genetic Algorithm. The details of the Fuzzy Logic System and the parameters which are used in the design of various types of Fuzzy Inference Engines are narrated in Section 5.1of Chapter 5. Both, Mamdani FIS and Sugeno FIS are used in the development of the proposed methodology. The Fuzzy Inference System used in this Section 5.1.2.1 is a Mamdani FIS whose output fuzzy sets need defuzzification operation to give the crisp output. In the next section, Sugeno FIS is described. The main difference in the two Inference Engines lies in their defuzzification and output determination techniques. The Mamdani FIS for damage detection is designed using triangular and Gaussian membership functions. The Mamdani FIS for damage detection is narrated in Figure 5.5. The results from the Mamdani FIS and Sugeno FIS are given in Tables 5.3 to 5.10. Some of the fuzzy rules which are generated using expertise knowledge base (the deviation of natural frequencies with the change in crack configuration) are given in Table 5.2 and the various linguistic terms used are described in Table 5.1. From the results it can be observed Mamdani FIS gives better result as compared to Sugeno FIS.

Section 5.2 of Chapter 5 describes the formulation of the problem using natural selection based evolutionary algorithm known as Adaptive Genetic Algorithm. The representation scheme plays a vital role in finding an optimized global solution in evolutionary algorithms. The representation scheme adopted for GA is the binary encoding system. Like encoding the fitness function/objective function is required for the process of natural selection. The objective function is given in equation (5.22). The fundamental operators used in describing the methodology are same as the simple Genetic Algorithm. The genetic operators like crossover and mutation are described in Figures 5.7 and 5.8 respectively. The results are provided in Tables 5.13 to 5.16. For the running of the algorithm a set of initial population of chromosomes are required, these chromosomes are selected from the data pool given in Tables 5.11 to 5.12. In this portion the Regression Analysis has been incorporated with GA. The adaptive nature of the proposed method is derived from the data mining process of the data pool, which is used to generate the solution space for the algorithm. The data mining process using Regression Analysis is depicted in Section 5.2.2 of the chapter.

Section 5.3 of Chapter 5 describes the methodology for determination of damage location using Mamdani-Adaptive Genetic -Sugeno model. Section 5.3.2 describes the framework of Mamdani-Adaptive Genetic-Sugeno model. The results from the methodology are compared with the FEA and Experimental analysis as well as with the individual methods.

An artificial immune based, AI technique has been proposed for fault detection in cracked structural elements in Chapter 6. The immune algorithm is based on the clonal selection principle. This algorithm requires an encoding strategy and a data pool like the Genetic Algorithm. The encoding scheme used for this algorithm is the binary encoding for both antibodies and antigens. The data pool is supplied in Tables 6.1 and 6.2. The affinity distance and the number of clones are given in equations 6.1 and 6.2 respectively. The immunity process is described in Figure 6.1. Figure 6.2 shows the representation of the antibodies and antigens. The results from the analysis of Clonal Selection Algorithm for damage detection are produced in Tables 6.3 to 6.6. From the results, it is noticed that

CSA gives better results as compared to the GA and FLS due to the simplicity of the operations. In the later chapters of the thesis, the CSA is combined with FLS, GA and DEA to give a hybridized algorithm for fault detection.

Table 9.1: Comparison of the results of the standalone algorithms in terms of percentage error

Comparison of the standalone algorithms (FLS, AGA, CSA, DEA) for cantilever beam

Sl. No	rfnf	rsnf	rtnf	rcd	rcl	rcd from FLS (Sugeno FIS)	rcl from FLS(Sugeno FIS)	rcd from AGA	rcl from AGA	rcd from CSA	rcl from CSA	rcd from DEA	rcl from DEA
1	0.9923	0.9912	0.9966	0.325	0.21875	0.307	0.2071	0.3081	0.207	0.3087	0.2075	0.3082	0.2074
2	0.9931	0.9926	0.9978	0.3	0.20625	0.2841	0.1952	0.2844	0.195	0.2850	0.1959	0.2845	0.1956
3	0.9946	0.9942	0.9972	0.2875	0.23125	0.2722	0.219	0.2725	0.219	0.2732	0.2196	0.2726	0.2193
4	0.9959	0.9977	0.999	0.125	0.21875	0.118	0.2071	0.1185	0.207	0.1187	0.2078	0.1185	0.2074
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2602	0.3433	0.2607	0.343	0.2612	0.3444	0.2608	0.3438
Percentage Error						5.31	5.29	5.19	5.200	4.99	5.01	5.14	5.15

Comparison of the standalone algorithms (FLS, AGA, CSA, DEA) for fixed-fixed beam

Sl. No	rfnf	rsnf	rtnf	rcd	rcl	rcd from FLS (Sugeno FIS)	rcl from FLS(Sugeno FIS)	rcd from AGA	rcl from AGA	rcd from CSA	rcl from CSA	rcd from DEA	rcl from DEA
1	0.9952	0.9992	0.9944	0.2812	0.5625	0.266	0.532	0.2666	0.533	0.266	0.5337	0.2667	0.5334
2	0.9958	0.9998	0.9940	0.25	0.4687	0.236	0.443	0.2369	0.444	0.237	0.4452	0.2371	0.4444
3	0.9960	0.9999	0.9987	0.25	0.25	0.236	0.236	0.2369	0.237	0.237	0.2372	0.2371	0.2371
4	0.9969	0.9969	0.9952	0.1875	0.5	0.177	0.473	0.1777	0.474	0.178	0.4752	0.1778	0.4742
5	0.9705	0.9703	0.9700	0.2166	0.5	0.205	0.473	0.2052	0.474	0.205	0.4757	0.2054	0.4741
Percentage Error						5.29	5.31	5.21	5.19	4.99	5.00	5.14	5.16

In Chapter 7, a hybridization of Differential Evolution Algorithm and Fuzzy Logic has been designed and developed for the training of the vibration responses from the cracked structural elements to predict the damage position. The first section of the chapter addresses the fundamental DEA which is a type of evolutionary algorithm but begins with a starting point initialization. The algorithm starts with the definition of initial vector with upper and lower limitations which is described in Figure 7.3. The evolutionary procedures followed by the algorithm are described in the flowchart (Figure 7.6).

Table 9.2: Comparison of the results of the hybrid algorithms with FLS (using Mamdani FIS) in terms of percentage error

Comparison of the hybrid algorithms with FLS (using Mamdani FIS) for cantilever beam

Sl. No	rfnf	rsnf	rtnf	rcd	rcl	rcd from ADMF	rcl from FLS-ADMF	rcd from FLS-ATFRBS	rcl from FLS-ATFRBS	rcd from DEA-FLS	rcl from DEA-FLS	rcd from CSA-FLS	rcl from CSA-FLS
1	0.9973	0.9914	0.9995	0.3437	0.4687	0.326	0.444	0.327	0.446	0.328	0.447	0.328	0.448
2	0.9974	0.989	0.9999	0.375	0.5	0.355	0.475	0.357	0.476	0.358	0.477	0.358	0.478
3	0.9981	0.9982	0.9979	0.25	0.375	0.237	0.356	0.238	0.357	0.238	0.358	0.239	0.358
4	0.9988	0.9981	0.9989	0.2187	0.4062	0.207	0.386	0.208	0.386	0.208	0.387	0.209	0.388
5	0.9892	0.9996	0.9981	0.35	0.1875	0.333	0.178	0.333	0.178	0.334	0.179	0.334	0.179
Percentage Error						5.03	4.98	4.79	4.79	4.49	4.51	4.29	4.30

Comparison of the hybrid algorithms with FLS (using Mamdani FIS) for fixed-fixed beam

Sl. No	rfnf	rsnf	rtnf	rcd	rcl	rcd from ADMF	rcl from FLS-ADMF	rcd from FLS-ATFRBS	rcl from FLS-ATFRBS	rcd from DEA-FLS	rcl from DEA-FLS	rcd from CSA-FLS	rcl from CSA-FLS
1	0.9988	0.9993	0.9976	0.1562	0.3125	0.148	0.296	0.1487	0.297	0.149	0.2985	0.149	0.299
2	0.9997	0.9960	0.9996	0.333	0.3125	0.316	0.296	0.3170	0.297	0.318	0.2984	0.318	0.299
3	0.9552	0.9551	0.9549	0.2833	0.375	0.269	0.356	0.2697	0.356	0.270	0.3580	0.271	0.358
4	0.9211	0.9219	0.9218	0.4	0.25	0.380	0.237	0.3808	0.237	0.381	0.2387	0.382	0.239
5	0.9463	0.9460	0.9458	0.367	0.3125	0.348	0.296	0.3493	0.297	0.35	0.2984	0.351	0.299
Percentage Error						4.99	5.00	4.79	4.81	4.51	4.49	4.29	4.29

In this case after fitness evaluation of the initial vectors, they undergo mutation (equation 7.4) and after the generation of mutant vectors, the algorithm proceeds towards the crossover operation (equation 7.5). The results from the DEA analysis for damage detection are produced in Tables 7.1 to 7.4. If we analyze the results from the individual methods, then it can be observed that DEA gives better result than GA but inferior than CSA. In the next section of the chapter, DEA is integrated with FLS. Table 9.1 gives the overall comparison of the standalone algorithms (FLS, GA, CSA and DEA) for cantilever and fixed-fixed beams.

In Section 7.4 of Chapter 7, the Fuzzy Logic System (Mamdani FIS and Sugeno FIS) has been integrated with the DEA. It has already been discussed that the parameters of FLS are difficult to decide. So for the performance enhancement of the FLS, an optimization method must be integrated with the FLS. The Fuzzy Inference System (Mamdani FIS) has been designed using Gaussian MF and is described in Figure 7.8. The Gaussian MFs are specified by their center and width as shown in Figure 7.7. In this method each variable contains nine Gaussian MFs and the linguistic variables used for the description is same as that of Chapter 5. The procedure followed by this hybrid technique is narrated in Figure 7.9. This method uses no encoding strategy as used by other evolutionary algorithms. Due to the absence of encoding system, the algorithm becomes simpler and much of the computational error is lessened. The Figures 7.10(a) and 7.10(b) report the shape of the fuzzy Gaussian MFs before and after the optimization operation. The results are supplied in Tables 7.5 to 7.12. From the results it can be noticed that DEA gives better optimization performance as compared to Genetic Algorithm.

Chapter 8 describes different hybrid methods using Fuzzy Logic (Mamdani FIS and Sugeno FIS), Genetic Algorithm, Clonal Selection Algorithm and Differential Evolution Algorithm.

The combination of GA and FLS is newer and less explored as compared to the integration of Fuzzy Logic and Neural Networks. These two technologies have some features in common and some complement each other. Both the techniques are well equipped to deal with nonlinear systems and data. However, sometimes for complicated systems, Fuzzy Logic System becomes difficult to design relying on manual methods. The array of rules which describe the relationship between the cause and effect become unmanageable and the specifications needed to describe the membership functions can be tough to fix. So in these types of approaches GA can be used to improve the performance of the Fuzzy Logic Controllers. Sections 8.1 and 8.2 of Chapter 8 propose two different method of hybridizing Fuzzy Logic System and Genetic Algorithm for Automatic Design of Fuzzy Mf and Automatic Tuning of Fuzzy Rules Base System respectively. All the hybridized methods which involve fuzzy logic are made using both Mamdani FIS and Sugeno FIS and the results are given separately. Table 9.2 compares the result of the hybrid algorithms with FLS (Mamdani FIS).

Section 8.1of Chapter 8 proposes a hybrid intelligent system using Fuzzy Logic System (Mamdani FIS and Sugeno FIS) and Genetic Algorithm to optimize the membership function parameters for automatic design of the fuzzy membership function. The block diagram narrating the steps used in this method is shown in Figure 8.1. In these types of hybrid methods where evolutionary algorithms require representing scheme, is very difficult design, but once designed it gives fine results. So to keep the encoding scheme simple, the numbers of MFs used are kept small. The triangular MFs with their parameters are presented in Figure 8.2. Here three triangular MFs are used to describe the range of each input and output variables in Mamdani FIS and for input variables in Sugeno FIS are described in Figure 8.3. The detail representation scheme is outlined in Section 8.1.1.1. The rules are formed according to the linguistic terms used and are supplied in Table 8.1. The encoded fuzzy rule containing the fuzzy MFs is presented in Figure 8.4. The fitness function is given in equation 8.1. The results are in Tables 8.2 to 8.9 for both the inference systems (Mamdani and Sugeno). From the results it can be said that the proposed method gives more accurate results with less percentage of error. The shape change of the triangular MFs after optimization is given in Figure 8.7.

It is found that the use of GA to design the shape of the fuzzy MF by optimizing the MF parameters still needs human intervention to form fuzzy rules. So to make the system automatic the fuzzy rules must be optimized. For the above stated reasons the Automatic Tuning of Fuzzy Rules Base System using Genetic Algorithm in Section 8.2 of Chapter 8. In this method a rule set with MFs is presented as a chromosome. The encoding strategy is narrated in Section 8.2.1.1. The algorithm is described in Section 8.2.1.2. For doing crossover four crossover points are chosen within the rule set and within the membership function which is described in Figure 8.14. Two different types of mutation are used for rule set and membership function set as two different types of encoding is used for these two parts. Figure 8.16 presents the chromosome after two part mutation. The objective function described in equation 8.2, is developed keeping in mind, the problem variables and fuzzy logic parameters. The results from the method taking two types of beams (cantilever beam and fixed-fixed beam) into consideration are given in Tables 8.10 to 8.17 for both the inference systems. From the results it could be visualized that the proposed method gives better result as compared to the method narrated in Section 8.1 of Chapter 8.

In the next section of Chapter 8, the Fuzzy Logic System (Mamdani FIS and Sugeno FIS) parameters are optimized using artificial immune based Clonal Selection Algorithm to be applied in the field of damage detection. Here each rule is considered as an antibody, all the fundamental parameters (base values of MFs) within the fuzzy rule are encoded using binary encoding method. In this algorithm the coding system is similar to that of GA but the operations used are different. The representations of both the type of fuzzy rules are described in Figures 8.19 and 8.20. The results are stated in Tables 8.18 to 8.25. From the results obtained it can be observed that CSA is easier to handle gives better results as compared to GA and DEA. CSA operators are flexible and do not comprise selection, cross over rate and mutation rate as in case of GA and DEA which are difficult to decide.

It is well known that Clonal Selection Algorithm does not include crossover which can add diversity to the population and that leads to the evolution of population. So in Sections 8.4 and 8.5 of Chapter 8, Clonal Selection Algorithm has been integrated with Genetic Algorithm and Differential Evolution Algorithm respectively.

In Section 8.4 of Chapter 8 Clonal Selection Algorithm has been combined with Genetic Algorithm. In this method after cloning the improved antibodies undergo crossover and mutation. Figure 8.22 outlines the cloning and selection process of the hybrid intelligent technique. The crossover operation which is described in Figure 8.23 provides recombination of more improved genetic information as the selected antibodies are the clones of the improved antibodies. Then all the antibodies undergo mutation which adds diversity to the population and helps the algorithm to avoid get trapped in local optimum. The mutation operation is sketched in Figure 8.24. Figure 8.25 presents the flowchart of the algorithm. The results from the combined algorithm supplied in Tables 8.26 to 8.29. The results produced by this method give less error as compared to other hybrid techniques narrated in the research work.

Table 9.3: Comparison of the results of the hybrid evolutionary algorithms in terms of percentage error

Comparison of the hybrid evolutionary algorithms for cantilever beam

Sl. No	rfnf	rsnf	rtnf	rcd	rcl	rcd from CSA-DEA	rcl from CSA-DEA	rcd from CSA-GA	rcl from CSA-GA
1	0.9982	0.999	0.9976	0.225	0.33125	0.2159	0.318	0.2155	0.3173
2	0.9989	0.9992	0.9981	0.2125	0.3375	0.2038	0.3239	0.2035	0.3232
3	0.9996	0.9996	0.999	0.1625	0.35	0.1559	0.3361	0.1556	0.3352
4	0.9985	0.999	0.998	0.2	0.34375	0.1920	0.3300	0.1916	0.3292
5	0.9974	0.9977	0.9965	0.275	0.3625	0.2640	0.3479	0.2634	0.3472
Percentage Error						4.01	3.99	4.19	4.21

Comparison of the hybrid evolutionary algorithms for fixed-fixed beam

Sl. No	rfnf	rsnf	rtnf	rcd	rcl	rcd from CSA-DEA	rcl from CSA-DEA	rcd from CSA-GA	rcl from CSA-GA
1	0.9211	0.9219	0.9218	0.4	0.25	0.3835	0.2397	0.3832	0.2394
2	0.9463	0.9460	0.9458	0.367	0.3125	0.3523	0.2995	0.3516	0.2994
3	0.9552	0.9551	0.9549	0.2833	0.375	0.2720	0.3595	0.2714	0.3591
4	0.9621	0.9618	0.9616	0.25	0.4375	0.2397	0.4195	0.2395	0.4191
5	0.9705	0.9703	0.9700	0.2166	0.5	0.2079	0.4791	0.2075	0.4788
Percentage Error						4.03	4.13	4.19	4.20

Section 8.5 of Chapter 8, delineates the fusion of Clonal Selection Algorithm and Differential Evolution Algorithm. Due to the facts stated in Section 8.4, the combination of CSA and DEA is proposed. The cloning process of encoded vectors is shown in Figure 8.26. After the cloning process the cloned antibodies undergo mutation and crossover, this is the reverse of the processes used in Genetic Algorithm. The proliferated antibodies endure mutation and crossover using equations (7.4) and (7.5) of DEA respectively. After application of these operations a selection operation is implemented between the parent and offspring antibodies using equation (7.6) of DEA. Then the antibodies with poor affinity undergo randomization process using (7.3). The flowchart portraying the detail of the procedure used in the combined method is given in Figure 8.27. The results are stated in Tables 8.30 to 8.33. From the analysis of the results it could be observed that the errors found to be lower as compared to the other hybrid methods. Clonal Selection Algorithm gives better result when integrated with DEA than the combination with GA. Table 9.3 gives the comparison of hybrid algorithms using evolutionary algorithms.

For the validation of the results from the different methods used in the research work, Experimental Analysis is done using different crack configurations. Two different experimental set-ups are developed for cantilever beam and fixed-fixed beam and are depicted in Appendix 1. The results of the Theoretical and Finite Element Analyses are compared with the results of Experimental Analysis and are found to be in close agreement with each other. The schematic diagrams of the experimental set-ups are narrated in Figures 3.5(a) and 3.5(b).The photographic description of the experimental set-ups is given in Figures A1 and A2. The specifications of the different instruments used are described in Section A1.2.

The contribution of the work in the field of damage detection, conclusion extracted from the research work and the approaches which can be carried out in future for fault detection is outlined in the next chapter.

Chapter 10

Conclusion and Future Scope

The current chapter narrates the conclusions drawn from the analysis and during the formulation of the problem. This chapter discusses the provision of scope in this field for research work in future. Prior to that, the contribution of the current work for damage diagnosis and detection is described in the following section.

10.1 Contributions of the research work

This work is devoted for proposing online damage detection and localization methods using non destructive methods. Following section depicts the contributions of the research work.

- The problem is formulated considering a single transverse hairline crack on a beam with two end conditions i.e., fixed-free and fixed-fixed conditions. First the theoretical analysis is performed using strain energy release rate. Strain energy release rate is used to find flexibility coefficients. The analysis process is performed to study the changes in dynamic characteristics of cracked and uncracked beams.
- Next a Finite Element Analysis is done on the cracked and uncracked beams to find out the change in the first three natural frequencies. The Finite Element Analysis is applied to a structure having crack. There is an appreciable amount of change in the local stiffness of the structure at the cracked section which changes the dynamic response of the structural element. This theory has been exploited to find the changes in the natural frequencies. This method can also be used for the identification of crack.
- The vibration parameters (natural frequencies) for the first three modes of vibration are extracted for the cantilever and fixed-fixed beam from the analytical and numerical method, and then they are converted to dimensionless relative values (equations 1.1 to 1.3) which are used to make a database.

- ★ After the generation of a strong data base, it is treated in various artificial intelligence (Fuzzy Logic, Adaptive Genetic Algorithm, Clonal Selection Algorithm and Differential Evolution Algorithm) and their hybrid techniques (3-stage Mamdani-Adaptive Genetic-Sugeno model, ADFMF, ATFRBS, DEA-FLS, CSA-FLS, CSA-GA, and CSA-DEA) to locate the crack in the beam.
- ★ The variation of the natural frequency with crack position forms the basis for Fuzzy Logic (Mamdani FIS and Sugeno FIS) design and the fuzzy rules are formed accordingly. The fuzzification process in the fuzzy model (Mamdani FIS and Sugeno FIS) is designed using triangular and Gaussian membership function. Triangular MF presents a piecewise linear type of MF and the Gaussian MF presents a piecewise nonlinear type of MF. The uncertainty handling capacity of Gaussian MF is more than the triangular MF.
- ★ An Adaptive Genetic Algorithm approach has been presented in this work. The Adaptive Genetic Algorithm is a combination of simple Genetic Algorithm and a data mining process. The data mining is done using Regression Analysis.
- ★ In the fifth chapter, Mamdani-Adaptive Genetic -Sugeno model has been designed using Fuzzy Logic System and Adaptive Genetic Algorithm for the crack detection purpose. The results from the proposed method are also compared with the results from the Fuzzy Inference Systems and the Adaptive Genetic Algorithm method. From the correlation it can be presumed that the proposed strategy gives better result when compared with the individual techniques. The proposed method produces more converging results while compared with the finite element and experimental analyses.
- ★ The next approach in this work is based on the artificial immune system of vertebrates. Here the possible solutions are presented as antibodies. The antigens presented contain dynamic responses from the field. The affinity is found out using fitness function (equation 6.3).
- ★ A Differential Evolution Algorithm has been developed for the crack detection problem. The algorithm creates an initial population of vectors containing the real valued individual vectors. Then an initial vector known as target vector is decided so that it could cover the solution space. Then the target vector comprises of the input and output variables of the problem. Then it is initialized within the lower and upper boundary value of each variable. This type of evolutionary algorithm

undergoes first mutation and then through crossover unlike other evolutionary algorithms.

- ★ Though the AI techniques used give good approximate results as compared to the conventional methods, the proposed algorithms have certain limitations that are faced during the conduction of the work. The limitations must be overcome to produce appreciable results that could make the algorithm a robust tool for damage detection. This work also presents hybridization of the AI techniques described.
- ★ A set up to get the natural frequencies experimentally is designed and developed. The experimental process is carried out for both cantilever and fixed-fixed beam. The natural frequencies of cracked and uncracked beams of different crack configurations are found out. The Experimental test is used to affirm the results from different AI techniques and their hybrid methods. The results of the experimental analysis are also used to make the database and to compare the results of theoretical analysis and finite element analysis.

The following are some of the applications of the research work.

- ♣ The problem can be used to find cracks in complex structures.
- ♣ The proposed systems and the hybrid methods created utilizing different computerized reasoning methods can be used to forecast faults in turbo machinery, nuclear plants, ship structures, marine structures etc.
- ♣ The AI techniques can be used to detect multiple cracks in complex structures.

10.2 Conclusions extracted from the research work

The following section of the chapter features the various conclusions drawn from the results achieved during the application of various methods for crack localization and detection.

- ◈ Analytical and Numerical methods have been used to identify the cracks. The crack can be diagnosed using these methods. While performing the Theoretical and Finite Element analyses, the variation in the natural frequencies are observed and this seemed to be very dominant in cracked structural elements.
- ◈ After the analysis of dynamic responses of the cracked structures, the results of the Theoretical and Finite Element analyses are compared with the results of the Experimental Analysis (Figures 3.5(a) and 3.5(b)) and are found to be in good agreement with each other. The total average error is found to be 2%, when the

results of the Theoretical and Experimental analyses are compared. Similarly, when the results of the Finite Element and Experimental analyses are compared, the total average error is found to be 3%.

- From the Theoretical analysis of the cracked beam, it has been noticed that, the change in the first three natural frequencies are predominant and the change in the natural frequencies is indirectly proportional to the crack depth. It has also been observed from the Theoretical and Finite Element analyses for the same crack configuration; the reduction in natural frequency occurs more in location away from the support, this occurs due to the change in stiffness which is elaborate at those locations.
- Any dynamic system can be defined using the stiffness and mass. Mass induces inertia due to kinetic energy and stiffness introduces from potential energy. The potential energy is a function of boundary condition. The reactions at different end conditions present different reactions (moments and forces) at the support, accordingly the stiffness of the dynamic system changes, for the same mass. The changes in the natural frequencies are inevitable which can be analyzed from the Theoretical analysis of the cracked beams for two different end conditions.
- During the investigation of the outcomes from the different Fuzzy Inference Systems, the Sugeno FIS is found to be more efficient than the Mamdani FIS. The results from the Sugeno FIS are more converging with total average percentage error of 5.3%. But in case of Mamdani FIS the total average percentage error is slightly higher than the Sugeno FIS. The total average percentage error for Mamdani FIS is found to be 5.5%.
- The Adaptive Genetic Algorithm gives an average percentage error of 5.2% and is capable of achieving global solution. When the results of the AGA Algorithm are compared with the results of the FLS, it is found the AGA gives better result as compared to the results from both the Fuzzy Inference Systems.
- In 3-stage Mamdani-Adaptive Genetic -Sugeno model which is combination of AI techniques, the error is found to be within 4.6% and is capable of attending global solution. The error found in 3-stage Mamdani-Adaptive Genetic -Sugeno model is much lesser than the individual methods exploited to design the algorithm. The results of the Mamdani-Adaptive Genetic Algorithm-Sugeno model are more coinciding than the results of AGA and FLS.

- The error evaluated in case of clonal selection algorithm is around 5%. From the analysis of the results of Clonal Selection Algorithm, it can be observed that the results are better from AGA, FLS and DEA.
- From the results of the Differential Evolution Algorithm, it is noticed that DEA gives better result when compared with GA and FLS, however gives less great results when compared with CSA. The error determined in this case is around 5.15%. When DEA is combined with FLS for the optimization of the MF parameters, there occurs a remarkable change in the error. The error is found to be around 4.5% for Mamdani FIS and around 4.3% for Sugeno FIS.
- The last segment of the research work comprises of various hybrid methods developed using individual methods described. The hybrid methods using GA for optimization of FLS parameters like ADFMF and ATFRBS are simple and easier to handle as the operators involved with GA are simpler. From the comparison of the results of both the method, it has been found that ATFRBS gives better result than ADFMF. The total average error in case of ADFMF is found to be around 5% for Mamdani FIS and 4.8% for Sugeno FIS. Similarly, for ATFRBS, the total average error is found to be around 4.8% for Mamdani FIS and 4.7% for Sugeno FIS.
- From the analysis of the results, it has been noticed that among the hybrid methods used to optimize the fuzzy parameters CSA-FLS gives the best result with a percentage error of 4.3%(Mamdani) and 4.2% (Sugeno). But it has been observed that DEA-FLS can get a global solution, due to the presence of initial point in the search space.
- When results of all the hybrid methods are compared, it is noticed that CSA-GA (4.15%) and CSA-DEA (4%) gives better results as compared to other methods and are relatively simple. By comparing all the methods, it is observed that CSA-DEA gives the best and more convergent result.

10.3 Future scope for the research work

As research never ends, following section outlines some of the future scopes of research for damage identification, detection and localization.

- The present analysis can be reached out, to be applied for plate like structures.
- In the present analysis undamped vibration analysis is done, this can be extended to analyze damped vibration condition using viscous material.

- In the present work, the beams under consideration have uniform cross section but this method can be extended to components with varying cross section, different geometry of any boundary condition.
- In the present work FLS, GA, CSA and DEA and their hybrid methods have been used, but AI technique field is vast and a number of hybrid methods can be designed. Other AI techniques and their hybrid methods can be explored for the same purpose as described in this work in future.

Appendix 1

Experimental Analysis of Cracked Beam

In the above described chapters different Artificial Intelligence Techniques and their hybrid methods have been proposed. The outcomes from the proposed strategies have been contrasted with the outcomes of the Finite Element Analysis. For further validation of the results, it is necessary to compare the results obtained from the proposed methods with experimental results. The results from the experimental analysis are used to affirm the results obtained from theoretical, finite element, artificial intelligent techniques and their hybridized methodologies used for damage detection. The procedures employed in the experimental inspection have been systematically organized in this segment. Two Different experimental set-ups are developed for the analysis.

A1.1 Description of the experimental procedure

The experimental set up developed for the two different end conditions of the beam element have been shown in Figures A1 and A2. Several tests are performed on the test pieces using these set-ups and the natural frequencies of the 1st, 2nd and 3rd mode of vibration are noted down. For the experiments aluminum alloy beam of 800x38x8 mm^3 has been used. Here free vibration analysis of the beam element is performed. As the experiment is done at free vibration mode, so the beam element is excited using an impact hammer. Then the vibration responses from the whole length of the beam element are picked up by the accelerometer or vibration pick-up. The vibration responses from the accelerometer which contains information about the modal frequencies are fed to the vibration analyzer for further analysis. Then the results from the analyzer are shown in vibration indicator. The transverse hairline cracks on the aluminum alloy beam are generated using electrical discharge machining. The natural frequencies are obtained both for cracked and uncracked beam element.

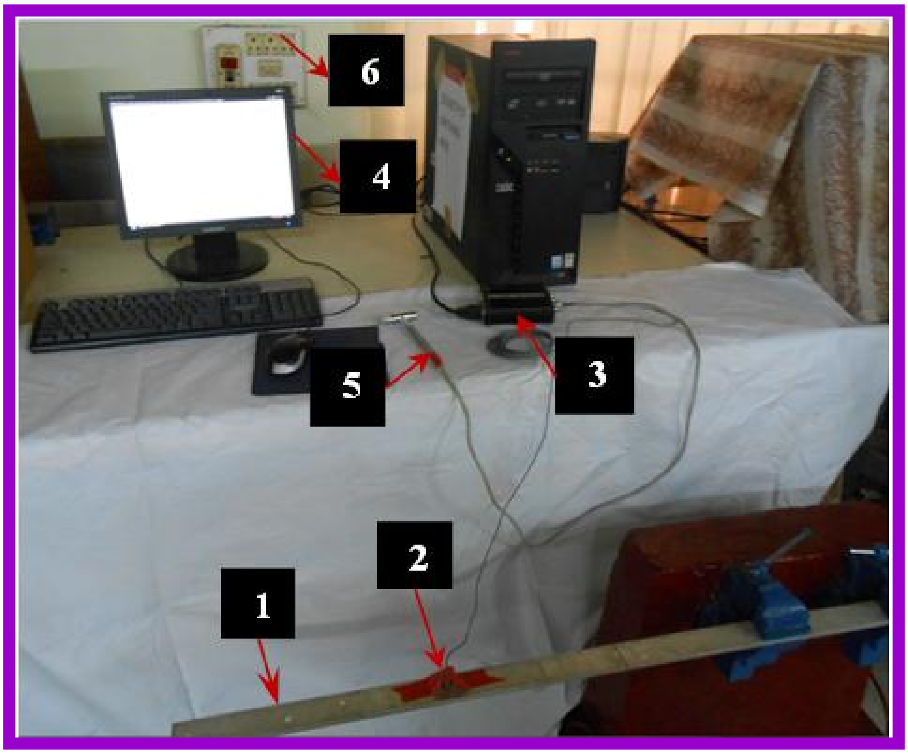


Figure A1: Experimental set-up for cantilever beam with a single crack

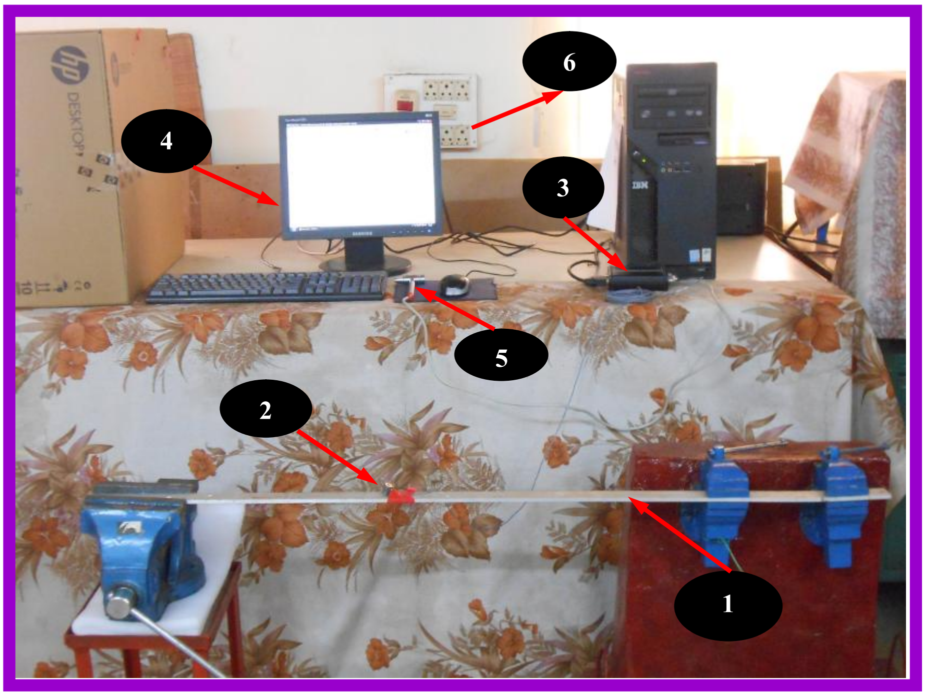
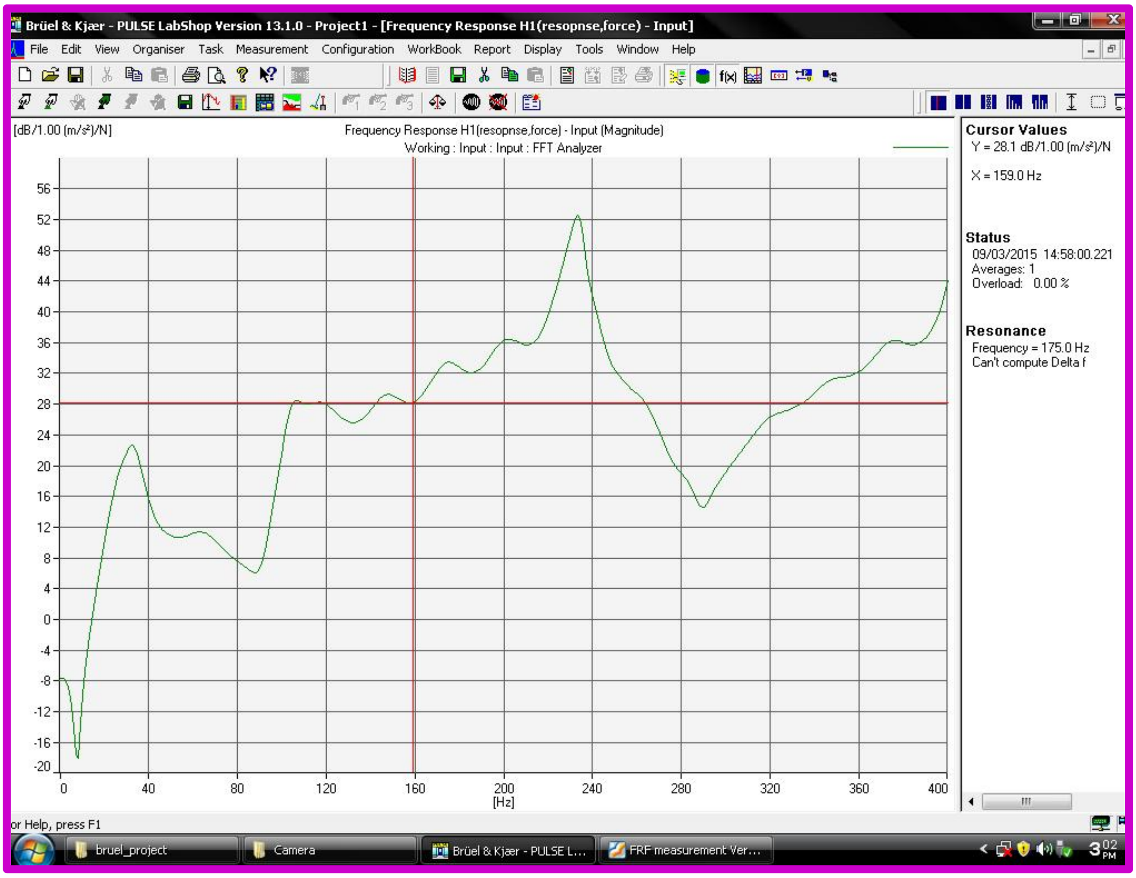


Figure A2: Experimental set-up for fixed-fixed beam with a single crack

To comprehend a structure's behavior, we have to analyze the way it responds to forces and moments. By exciting the structure with power hammer or shaker and measuring its reaction with accelerometers, its modes and natural frequencies. Methods like Techniques like operational modal analysis (OMA) and operating deflection shapes analysis (ODS) work while the structure is in operation, allowing you to get a realistic picture without having to artificially excite the structure. But during the experimental investigation the structural element is excited using a power hammer (Figure A4). Here the FFT spectrum analysis on live data that is measured with transducer connected via data acquisition hardware to a PC is done using PULSE LabShop software (Figure A3).



Cursor Values
Y = 28.1 dB/1.00 (m/s²)/N
X = 159.0 Hz

Status
09/03/2015 14:58:00.221
Averages: 1
Overload: 0.00 %

Resonance
Frequency = 175.0 Hz
Can't compute Delta f

Figure A3: FFT Analyzer of PULSE LabShop software

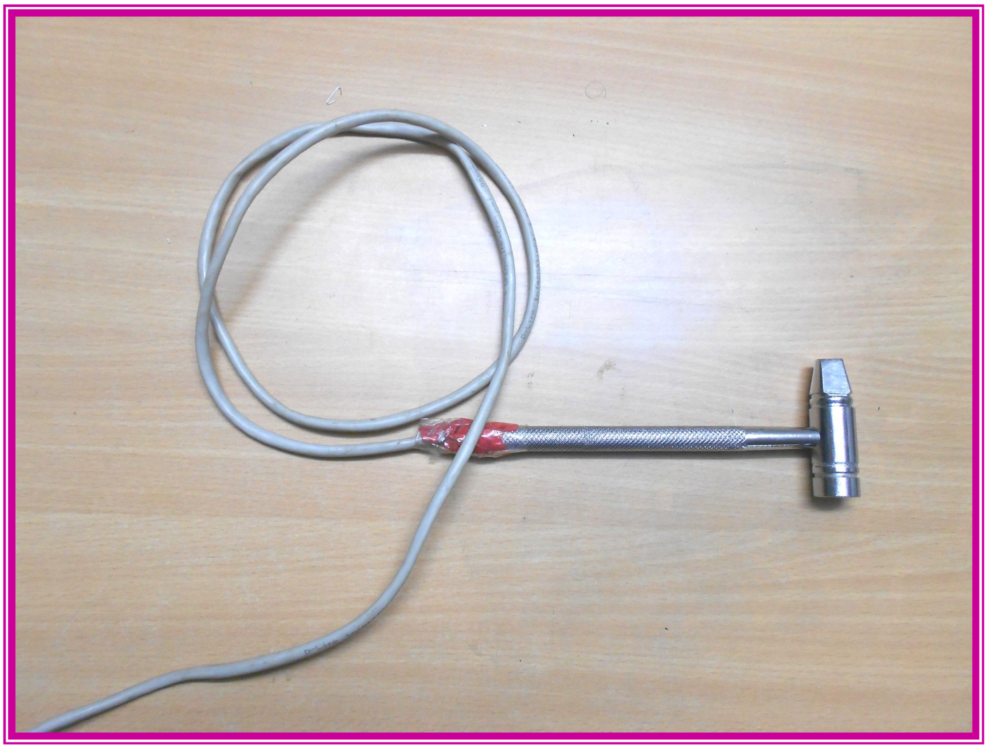


Figure A4: Impact Hammer

Figure A5: Vibration Pick-Up

Figure A6: Vibration Analyzer

Figure A7: Vibration Indicator

Figure A8: Cracked (Single crack) beam made from Aluminum Alloy

A1.2 Specifications of the vibration measuring instruments

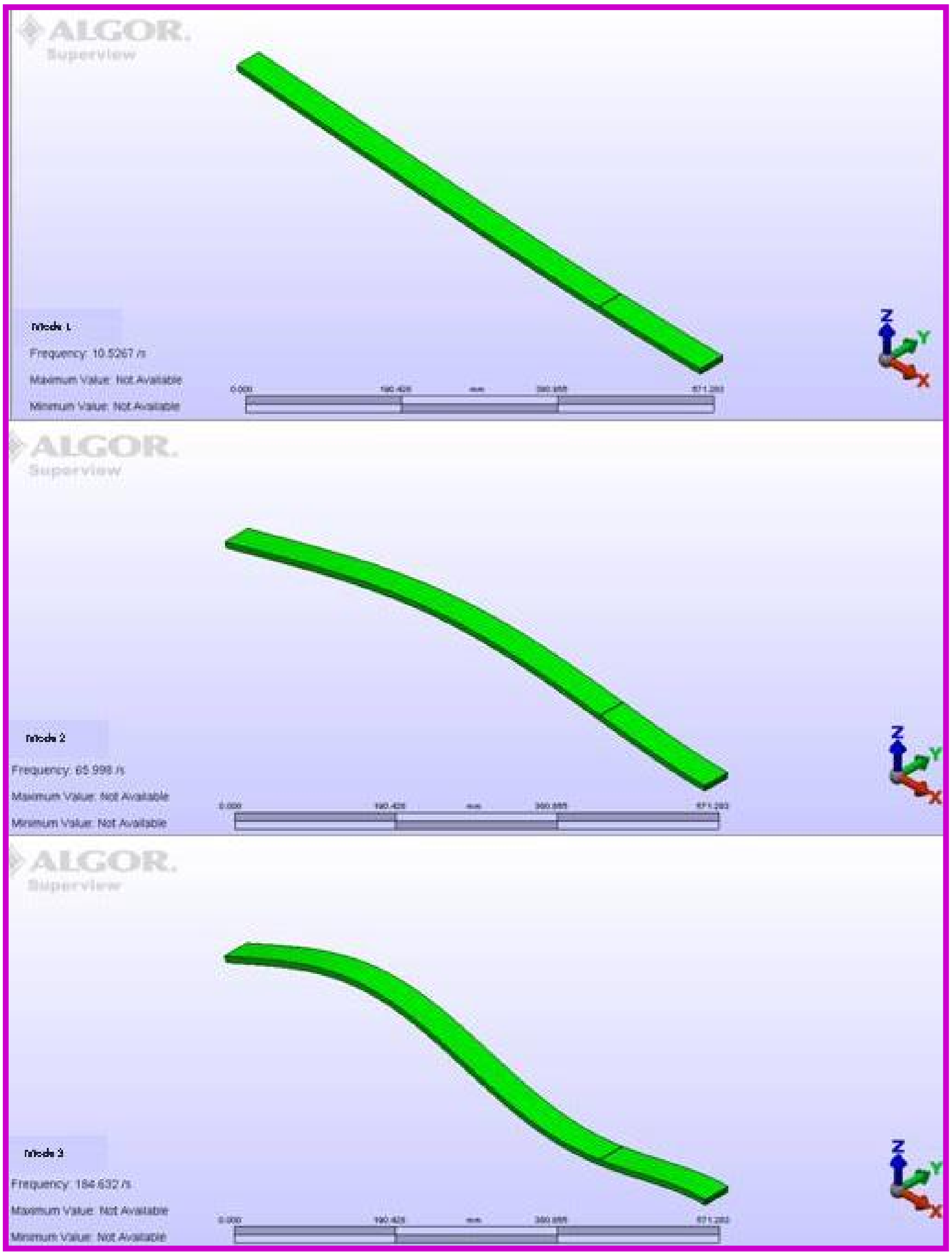
Table A.1: Description and Specifications of the instruments used in the experimental set up

Sl.No	Name of the Instrument	Description
1	Beams	Cracked (Single crack) cantilever beams made from Aluminum Alloy with dimension 800mmx38mmx8mm
2	Vibration Pick-Up	Type : 4513-001 Make : Bruel & kjaer Sensitivity : 10mv/g-500mv/g Frequency Range : 1Hz-10KHz Supply voltage : 24volts Operating temperature Range : -50^{o}C to +100^{o}C
3	Vibration Analyzer	Type : 3560L Product Name : Pocket front end Make : Bruel & kjaer Frequency : 7 Hz to 20 Khz Range ADC Bits : 16 Simultaneous Channels : 2 Inputs, 2 Tachometer Input Type : Direct/CCLD
4	Vibration Indicator	PULSE LabShop Software Version 12 Make : Bruel & kjaer
5	Impact Hammer	Range :222N Maximum Force: 890N Frequency Range: 10KHz Overall Length: 122mm
6	Power Distribution	220V power supply, 50Hz

Appendix 2

Description of parameters and procedures for FEA using ALGOR

For vibration analysis of the damaged and the whole cantilever beam The ALGOR V 19.3 SP 2 Finite Element Program is used. First the beam element with different single crack is plotted using CATIA V5R15 software, and then they are treated in ALGOR environment. The uncracked and cracked beam model is then analyzed in ALGOR environment. First of all the mesh generation is performed. The mesh size is around 1.4529mm and approximately 33369 elements are created. Then the parameters such as element type (brick and isotropic), material name (Aluminium Alloy) are defined in the ALGOR environment. The model unit is then changed to S.I. standards. Then in the 'analysis window', the particular analysis type is selected (natural frequency i.e. modal analysis). Then the analysis is performed and the first three modes of natural frequencies at different crack locations and crack depths of the cantilever and fixed-fixed beam are recorded. Figures A8 and A9 shows modes of vibration Cracked beam after finite element analysis. 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 (ρ) is 2700 kg/m^3. In the finite element analysis of the cracked cantilever beam having V-shaped single crack is taken into account. The fixed-fixed beams are generated using CATIA software, and then converted into compatible files, to be treated in ALGOR environment.



Mode 1
Frequency: 10.5267 /s
Maximum Value: Not Available
Minimum Value: Not Available

Mode 2
Frequency: 65.998 /s
Maximum Value: Not Available
Minimum Value: Not Available

Mode 3
Frequency: 184.632 /s
Maximum Value: Not Available
Minimum Value: Not Available

Figure A9: First three modes of vibration of cracked cantilever beam

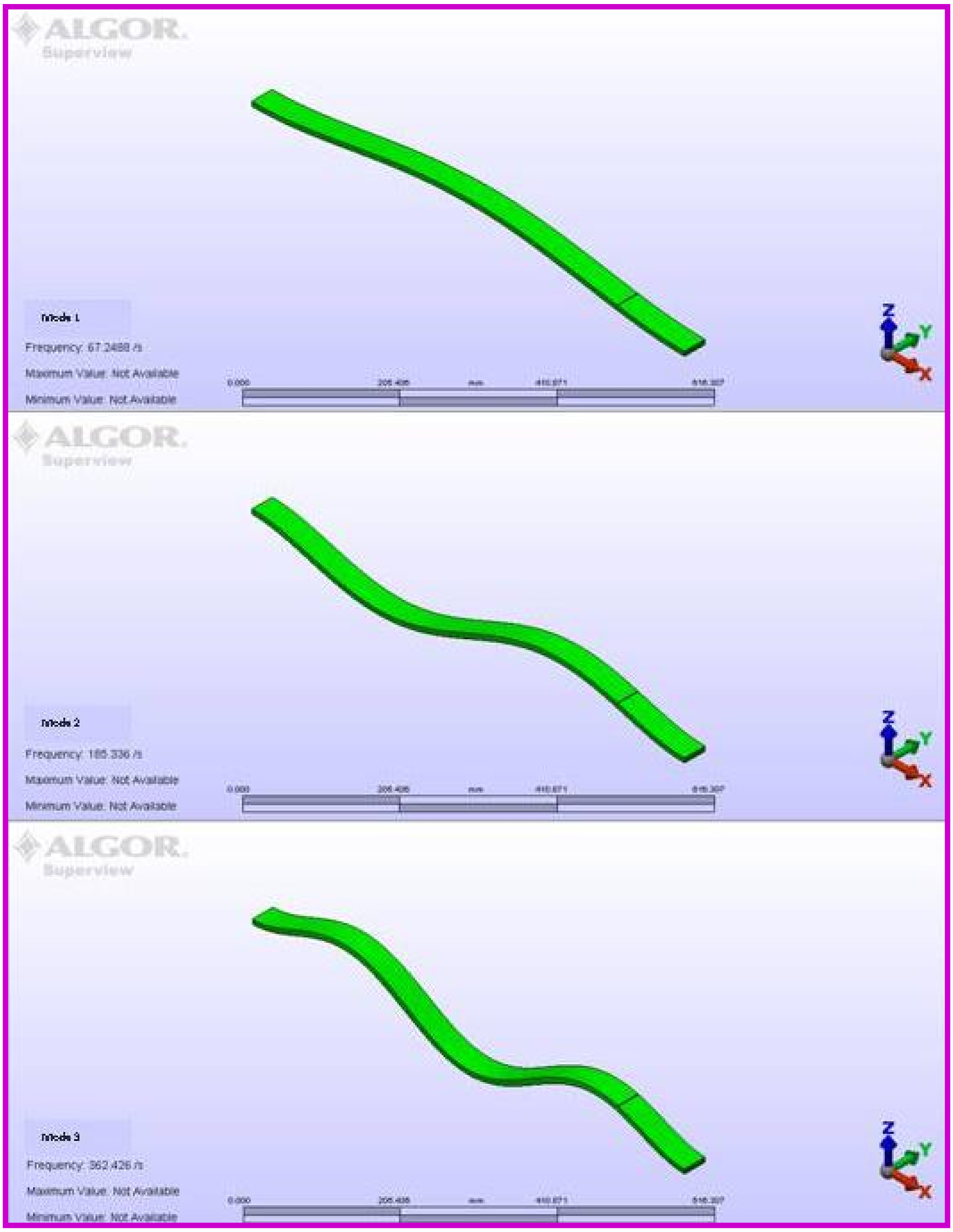
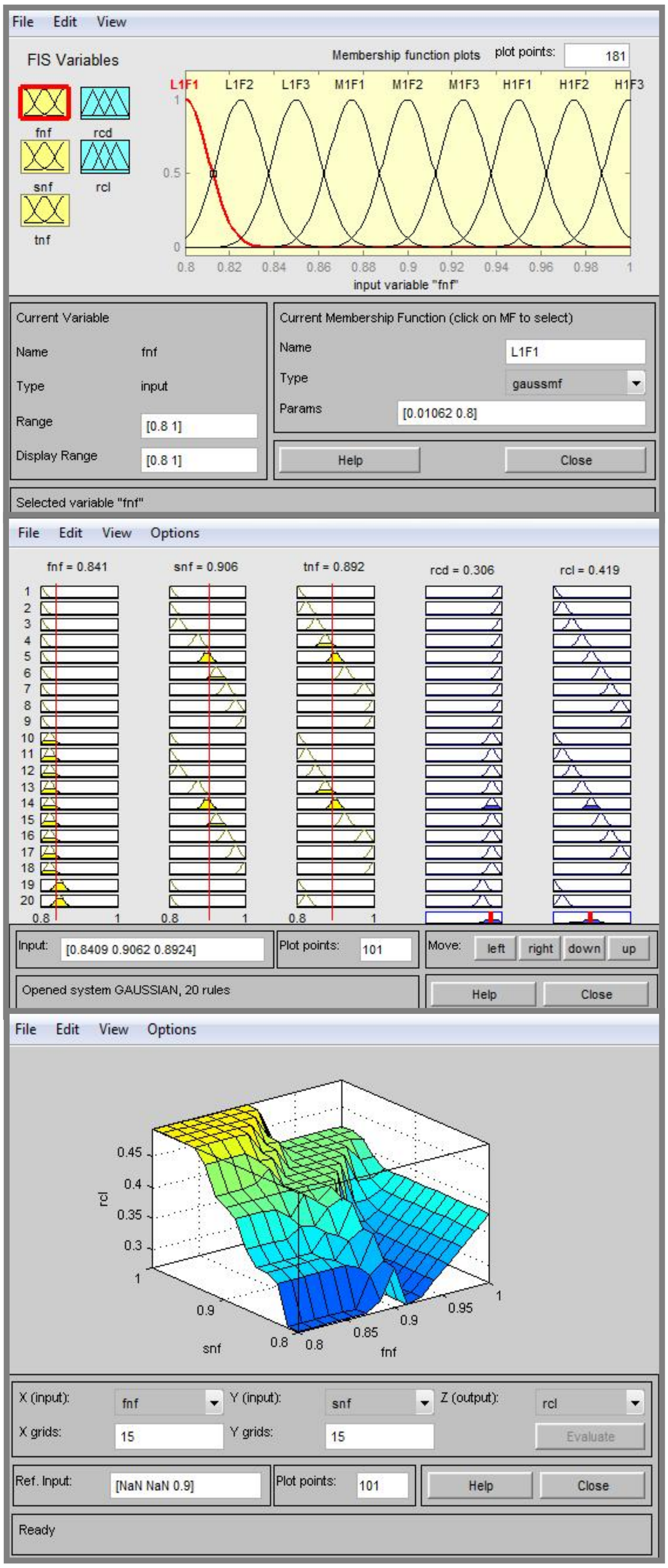


Figure A10: First three modes of vibration of cracked fixed-fixed beam



plot points: 181

Current Variable
Name fnf
Type input
Range [0.8 1]
Display Range [0.8 1]

Current Membership Function (click on MF to select)
Name L1F1
Type gaussmf
Params [0.01062 0.8]

Selected variable "fnf"

fnf = 0.841
snf = 0.906
tnf = 0.892
rcd = 0.306
rcl = 0.419

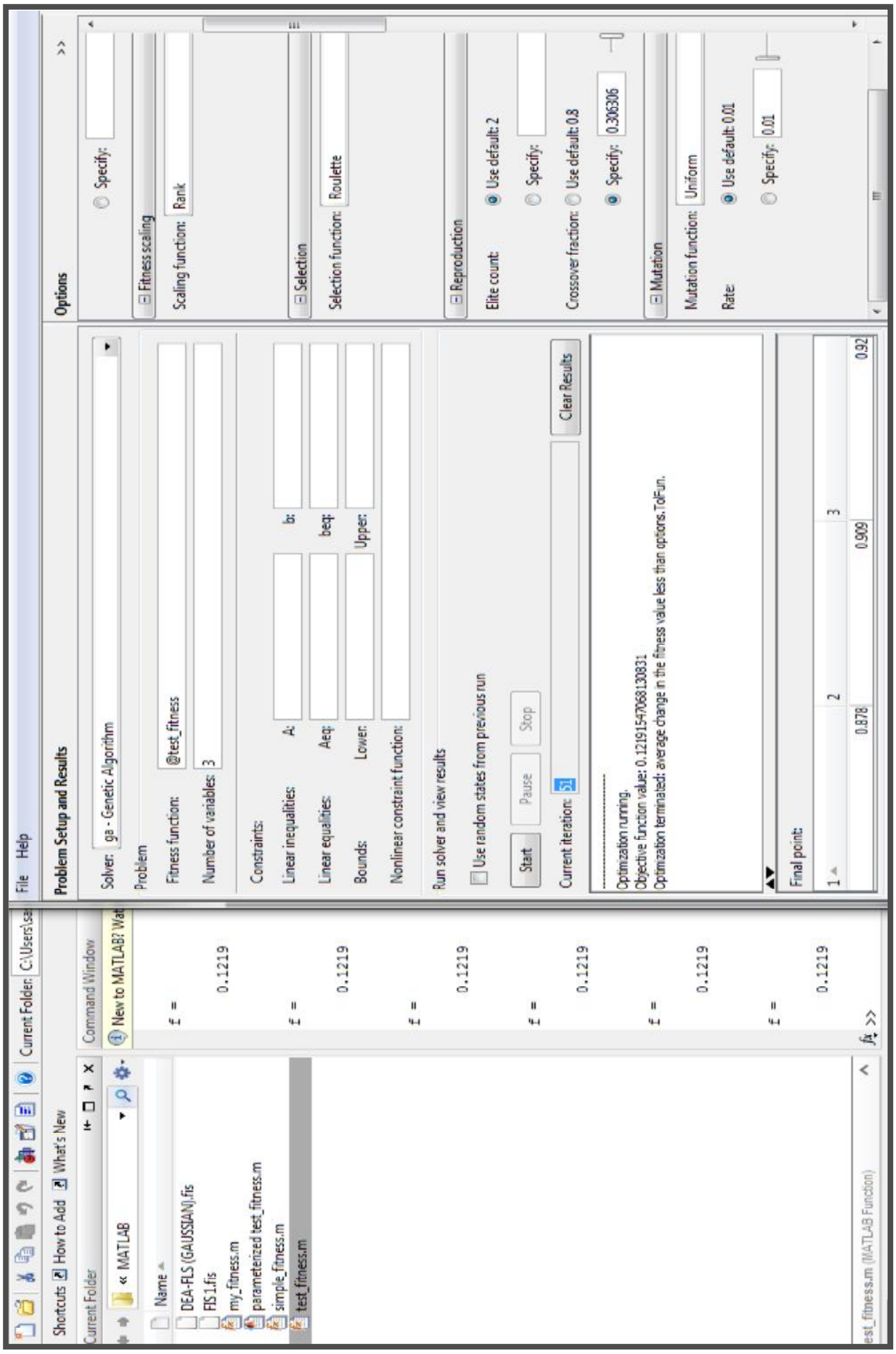
Input: [0.8409 0.9062 0.8924]
Plot points: 101

Opened system GAUSSIAN, 20 rules

X (input): fnf
Y (input): snf
Z (output): rcl
X grids: 15
Y grids: 15
Ref. Input: [NaN NaN 0.9]
Plot points: 101

Ready

Figure A11: Fuzzy Logic System (Mamdani FIS) for damage detection



```
f =

    0.1219

f =

    0.1219

f =

    0.1219

f =

    0.1219

f =

    0.1219

f =

    0.1219
```

Solver: ga - Genetic Algorithm

Problem

Fitness function: @test_fitness

Number of variables: 3

Constraints:

Linear inequalities: A: b:

Linear equalities: Aeq: beq:

Bounds: Lower: Upper:

Nonlinear constraint function:

Run solver and view results

☐ Use random states from previous run

Current iteration: 51

```
------------------------------
Optimization running.
Objective function value: 0.12191547068130831
Optimization terminated: average change in the fitness value less than options.TolFun.
```

Final point:

1	2	3
0.92	0.878	0.909

Options

○ Specify:

Fitness scaling

Scaling function: Rank

Selection

Selection function: Roulette

Reproduction

Elite count: ● Use default: 2

○ Specify:

Crossover fraction: ○ Use default: 0.8

● Specify: 0.306306

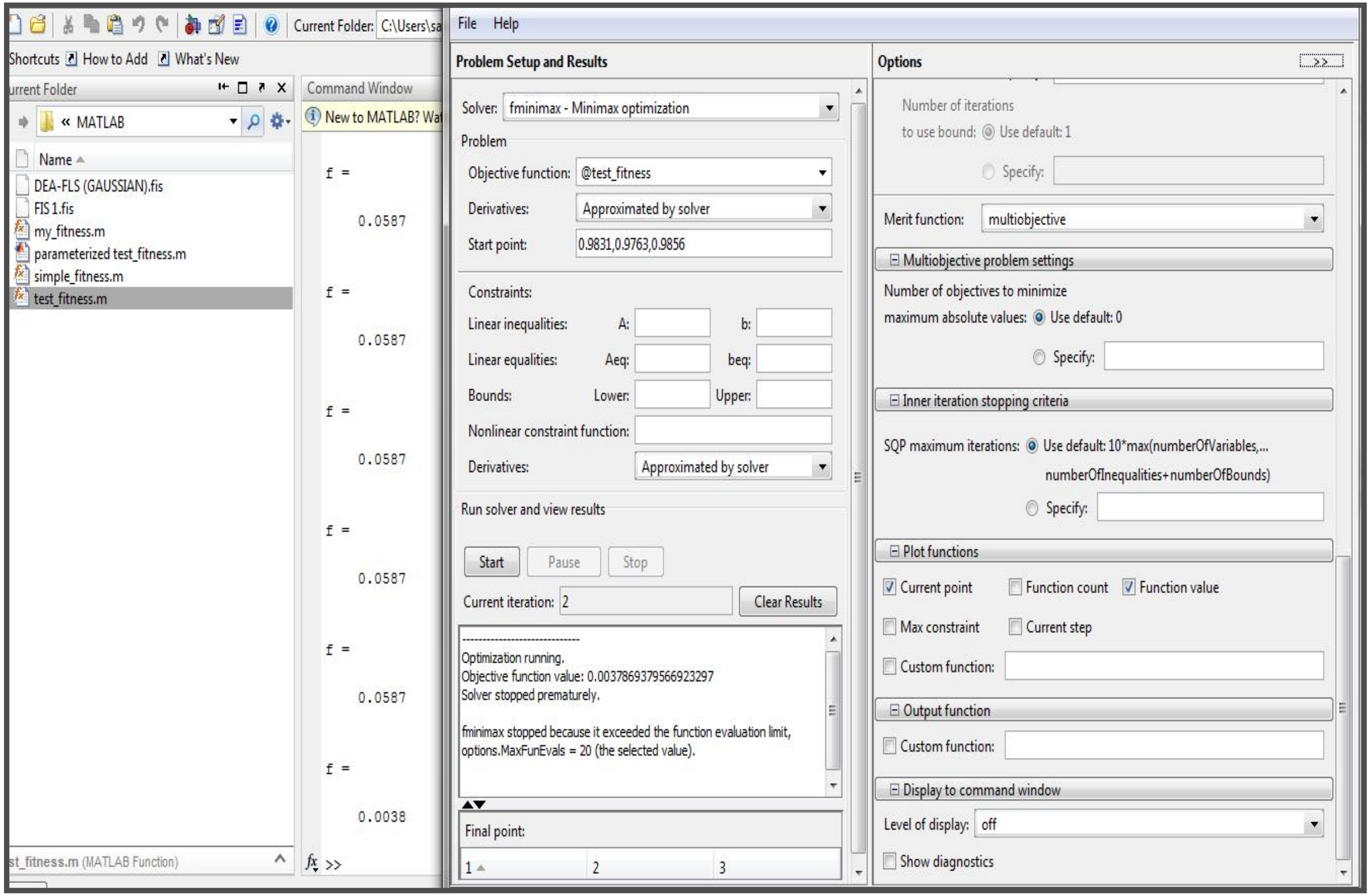
Mutation

Mutation function: Uniform

Rate: ● Use default: 0.01

○ Specify: 0.01

Figure A12: Quantification of the damage using Genetic Algorithm



Current Folder: C:\Users\sa

Name
- DEA-FLS (GAUSSIAN).fis
- FIS 1.fis
- my_fitness.m
- parameterized test_fitness.m
- simple_fitness.m
- test_fitness.m

Command Window

```
f =

    0.0587

f =

    0.0587

f =

    0.0587

f =

    0.0587

f =

    0.0587

f =

    0.0038
```

Problem Setup and Results

Solver: fminimax - Minimax optimization

Objective function: @test_fitness

Derivatives: Approximated by solver

Start point: 0.9831,0.9763,0.9856

Nonlinear constraint function: Derivatives: Approximated by solver

Current iteration: 2

```
------------------------------
Optimization running.
Objective function value: 0.0037869379566923297
Solver stopped prematurely.

fminimax stopped because it exceeded the function evaluation limit,
options.MaxFunEvals = 20 (the selected value).
```

Final point: 1 2 3

Options

Number of iterations to use bound: ● Use default: 1

Merit function: multiobjective

Multiobjective problem settings: Number of objectives to minimize maximum absolute values: ● Use default: 0

Inner iteration stopping criteria: SQP maximum iterations: ● Use default: 10*max(numberOfVariables,... numberOfInequalities+numberOfBounds)

Plot functions: ☑ Current point ☐ Function count ☑ Function value ☐ Max constraint ☐ Current step ☐ Custom function:

Output function: ☐ Custom function:

Display to command window: Level of display: off ☐ Show diagnostics

Figure A13: Quantification of the damage using Differential Evolution Algorithm

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Communicated Research Papers

1. Journal of Risk and Reliability (under review)
2. International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems (under review)
3. Damage mechanics
4. Journal of the Brazilian Society of Mechanical Sciences and Engineering
5. Journal of Theoretical and Applied Mechanics
6. International Journal of Fuzzy Systems
7. Perspectives in Science

Vitae

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