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Application of Hybrid Fuzzy Technique for Damage Estimation in Structural Member

Sasmita Sahu[1], Shakti P. Jena[2*]

[1]*School of Mechanical Engineering, KIIT University, Bhubaneswar, India*
[2]*Vardhaman College of Engineering, Hyderabad, India.*

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Abstract

Structural health monitoring has become an important research area from last two decades. This research area works on sensing and actuation and reasoning to find the exact location and amount of damage in a structure. The amount of damage must be quantified as to avoid serious catastrophic failure. For the above-mentioned purpose, the current method has been proposed. There are conventional and unconventional methods of damage detection. In the conventional methods, regular NDT methods are used. Among various Artificial Intelligent (AI) based methods, Fuzzy Logic System (FLS) is the one that can code and recode numerical inputs into semantic points, but the procedure of designing the fuzzy rule is troublesome and can turn out to be extremely confounded if the number of input and output parameters are increased. The combination of Fuzzy Logic with Genetic Algorithm (GA) provides an advanced hybrid intelligent algorithm called the automatic generation fuzzy rules, which generates the fuzzy rules automatically from the data. Here, a methodology is proposed for the automatic optimization of the fuzzy rules for the crack assessment in structure. At first, both FLS and GA approaches are implemented to present problem and obtain the results. In this analogy (hybrid-fuzzy), fuzzy rules are optimized with the fuzzy membership functions (MFs) and as rules of fuzzy comprises of fuzzy MFs also. Different GA operators like selection, crossover and mutation are implemented to optimize the fuzzy rules. A special type of objective function has been developed using absoluteness and factor of rules for the novel method and the results are obtained. A numerical model is formed for the entire analyses. The proposed method requires data collection. So, for this, the Finite Element Analysis (FEA) has been used. The data were collected from the FEA and Experimental analysis and then converted to normalized form. The data are normalized so, that the application in the given algorithm will be easier. The acquired results from the current analogy are validated with those of Finite Element Analysis (FEA) method. The same results are also compared with FLS and GA separately. From the results, it was obtained that the method convergence well and will be suitable for condition monitoring structures.

Keywords: Crack, FLS, GA, Natural Frequencies.

Nomenclature

L=Length of the beam.
L_1=Location of the crack from the fixed end.
a=Depth of the crack.
w=Width of the beam.
B=Thickness of the beam.
E=Elasticity of the material.
S=Stiffness of the material.
γ=Poisson's ratio.
u=Strain energy.
C_{ij}=flexibility influence co-efficient.
n=number of iterations.
μ=a/w=Relative crack depth.
υ=L_1/L=Relative crack location.
fnf, snf, tnf =These are the relative natural frequencies of the at first, second, and third modes of the beam in FEA respectively.
Fnf_{ds}, snf_{ds} and tnf_{ds} are the first, second and third relative modal frequencies extracted from data space at first, second
Fnf_{cr}, snf_{cr} and tnf_{cr} are the first, second and third relative modal frequencies extracted from field, second and third modes respectively.
S=Stiffness matrix.

1. Introduction

One of the most important aspects of health monitoring of structural systems and ensuring damage free operation can be achieved by structural damage detection. Large and complex structures like bridges, buildings and machineries must be continuously monitored to detect possible damages such as cracks. Even very small hairline crack(s) in a structure can deteriorate the act of the structure, for that crack detection in early stage of the deteriorated structure is required for structural health monitoring. There are many approaches that are already developed and implemented by researchers for damage exposure in structures. These methods are either conventional or Artificial Intelligence (AI) based techniques.

* Corresponding author e-mail: shaktipjena@gmail.com.

Beams are the essential part of any structures [1-2].Cantilever beam elements are mainly applicable in the sphere of Civil, Mechanical as well as Aerospace engineering. So the design of the best durable cantilever beams, the designer must know the effects of the damage or crack on a cantilever beam. Cracks can cause serious damage to any of the existing and working structures. So detection of damage in early stage is must. It is always very difficult to detect fine cracks through visual inspection techniques. Because of the occurrence of crack(s), the structure produces local flexibility which is caused due to the stress concentration at the vicinity of the crack tip. So the change in flexibility induces the alteration in the dynamic responses of the beam element [3-4].The alterations in the natural frequencies and the mode shapes may be treated as the damage indices which could be used for the detection of very fine and small crack. Therefore, Vibration based methods for structural condition supervising is a great potential tool. But the analytical determination of the vibration parameters is time consuming and the consequences are error prone. So computational approaches, such as Finite Element Method that acts as an imperative part in damage detection in structural elements.

The main advantage of current health monitoring methods is their ability to perform automatic vibration signal analysis and damage detection, significantly reducing the human factor. For this purpose, soft computing methods could be used. In this research work Fuzzy Logic [5-7] and Genetic Algorithm [8-9] are used. Both the methods are used to hybridize with each other for the self-regulating creation of the fuzzy associative rules [10-15] To the best of the authors' knowledge, the combination of both FLS and GA with the development of special type of algorithm is scanty for the crack assessment of structure. The relative values of the natural frequencies along with the relative crack depth and crack locations are considered as the input parameters for the proposed algorithm. The relative values of the natural frequencies along with the relative crack depth (μ) and locations (υ) are calculated by considering both the cracked and uncracked beam. In the proposed methodology, an algorithm has been developed to train the data generated from analytical and finite element method. The methodology describes about how the fuzzy logic rules with fuzzy MFs can be optimized using Genetic Algorithm (GA). The results or consequences from this methodology are compared with the individual methods (FLs, GA and FEA).

Jena and Parhi [16] have developed a fault detection method based on Elman's Recurrent Neural Networks method. The particular method was verified with a moving load dynamics problem and found to be good convergent. This method also can be very useful to identify the cracks and their severities in the area of transportation and structural dynamics problem. An imperialist competitive algorithm has been developed by Shahrouzi and Salehi [17] for the analysis of structural design problem in an optimal manner. They have also compared their method with other methods like genetic algorithm, differential evolution, particle swarm optimization and other rule-based techniques and found to be improved technique. The technique was also verified with various engineering and structural sizing problem. Baburao and Mallikarjuna [18] have explored a fault detection approach using the concepts of discrete wavelet neural networks mechanism. They have first implemented this method to a rotating stepped shaft with multiple discs having open grooves. Here, the coefficients of discrete wavelet transforms are considered as the input for the NNs model.

Darian and Onchis [19] developed a methodology for the condition monitoring of a beam (cantilever) with deep learning approach using the time frequency response data or signatures. The deep learning classifier concept was introduced by them to distinguish the beam with and without crack. The proposed content was also verified with laboratory test method. Asigbi et al. [20] proposed an intelligent approach based on fuzzy inference system to foresee the locations and severities of cracks in vibrating structures. The first natural frequencies of healthy and unhealthy cracked structures and the kurtosis of vibration response signal obtained from experimental analysis are considered as the input data to the fuzzy model. The fuzzy model was trained implemented with varieties of membership functions. The method was so good that it can be useful for online condition monitoring of structures. Bagherahmadi and Seyedpoor [21] also conducted crack detection procedures using frequency response concepts. Chasalevris and Papadopolos [22] developed a multi crack detection method using the concepts of bending vibration.

Asmael et al. [23] applied the machine learning approach to predict the behavior of spring back (SB) in a Vee bending process of aluminum sheet. To check the consequence of process parameters on the SB behavior, they have also implemented ANOVA, ANN and multi regress analysis (MRL) to optimize the SB behavior of the process parameter. They have observed that the ANN approach yields better results as comparison to others. Liang [24] used the visual inspection system to discover the position of work piece of mechanical parts in the process of transportation. He has developed the orientated fast and rotated brief (ORB) key frame algorithms to detect the position of the work piece.

Cui [25] proposed a parallel computing based dynamic model approach to object moving targets. The application of this model is to particularly detect the position of tennis ball moving target.

Gaikwad and Chinchanikar [26] implemented the Adaptive Neuro Fuzzy Inference System (ANFIS) to estimate the mechanical properties in friction stir welded joints. They have also carried out experiments to check the ultimate strength of the joint for the validation purpose of the proposed model. To monitor the fault status of large complex electromechanical system, a fault state informatization approach was developed by Wei and Jiao [27]. The characteristic values of the fault signal were determined from the conventional communication theory. This monitoring approach was designed on concepts of support vector machine and can decrease redundant losses. Alazzam and Tashtoush [28] also applied the ANFIS method to develop a lead free solder reliability model for the purpose of electronic components manufacturing. Abdelsalam et al. [29] developed a model based on Magnetic Flux Leakage (MFL) along with experimentation to check and discover the corrosion formation in cables of a cable stay bridge. Want et al. [30] approached the modified Particle Swarm Optimization (PSO) method for the fault diagnosis of gears transmission system.

It has been noticed by various researchers that, there are some insufficiencies in terms of different applications. So, in this research paper, an idea of eliminating the shortcomings of Fuzzy Logic has been created and developed. The proposed method can automatically tune the shapes of the membership functions and at the same time can create new effective fuzzy associative rules using Genetic Algorithm. The type of presentation scheme of the variables used in the proposed method reduces the length of the search space as a smaller number of linguistic terms is used. The objective function is so developed that the distance between the field chromosome (with the variables) and the chromosome taken from the solution space will be less, in such a way that error during evaluation can be lessened.

As for the literatures concerned; many methods are developed based on FLs, genetic algorithm (GA), and neural networks for crack detection in structural members. With the advent of many AI techniques, they have been successfully used in various engineering or other fields. It has been observed that these techniques have various shortcomings which hinder the ability of the algorithm of producing good results. So, the algorithms or the methods can be combined or hybridized to overcome the shortcomings of each other. There are many methods of hybridizing the different AI methods. The proposed method can be considered as one such method. The above mentioned shows the novelty of the research works.

The techniques based on the knowledge based or rule based FLs (hybrid-fuzzy) are scanty for the crack assessment of structures. In this problem, both the FLS and GA are jointly applied in a rule-based manner for crack or damage exposure in vibrating structures. Again, the authentication of hybrid-fuzzy technique results with FEA is also scanty. A beam (cantilever) with a single hair line crack is considered for the proposed analysis. For the proposed method, a numerical model is formed. The results acquired from the projected approach are compared with those of Finite Element Analysis (FEA) as an authentication method and also compared with those of FLS and GA separately to check accuracy of the technique.

2. Mathematical Formulation of the Problem:

Because of the development of the crack, quantity of strain energy is released at the cracked, which is a kind of potential energy. According to Tada et al. [5], the strain energy released rate at the cracked fragment is specified below. In this research work a v-notch type of crack is considered. This is a known fact that geometry of the hairline crack cannot be perfectly imagined, so here for the ease of calculation a v-notch with defined crack location (depth and length) is taken. The geometrical model of the cracked cantilever beam is revealed in Fig 1. The crack width is taken as 1mm.

Where L=Length of the beam, L_1=Location of the crack from the fixed end, a=Depth of the crack, w=Width of the beam, B=Thickness of the beam.

$$E_R = \frac{1}{E'}(S_{11}+S_{12})^2 \quad (1)$$

Where $\frac{1}{E'} = \frac{1-\gamma^2}{E}$ (plain strain condition)

$= \frac{1}{E}$ (plain stress condition) (2)

S_{11}, S_{12} are the stress intensity factors for crack opening mode (mode I) for load W_1 and W_2 respectively. From earlier research, the values of SIF (stress intensity factors) are described as given below;

$$S_{11} = \frac{W_1}{BW}\sqrt{\pi a}\left(F_1\left(\frac{a}{w}\right)\right) \quad (3)$$

$$S_{12} = \frac{6W_2}{BW}\sqrt{\pi a}\left(F_2\left(\frac{a}{w}\right)\right) \quad (4)$$

Where,

$$F_1\left(\frac{a}{w}\right) = \left(\frac{2W}{\pi a}\tan\left(\frac{\pi a}{2w}\right)\right)^{0.5}\left\{\frac{0.752+2.02\left(\frac{a}{w}\right)+0.37\left(1-\sin\left(\frac{\pi a}{2w}\right)\right)^3}{\cos\left(\frac{\pi a}{2w}\right)}\right\} \quad (5)$$

$$F_2\left(\frac{a}{w}\right) = \left(\frac{2W}{\pi a}\tan\left(\frac{\pi a}{2w}\right)\right)^{0.5}\left\{\frac{0.923+0.199\left(1-\sin\left(\frac{\pi a}{2w}\right)\right)^4}{\cos\left(\frac{\pi a}{2w}\right)}\right\} \quad (6)$$

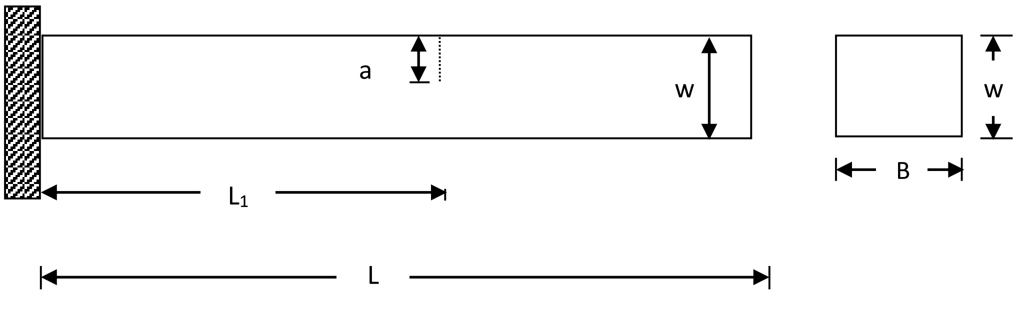


Figure 1. Schematic view of a cantilever beam with a hairline crack

Applying Castiglione's theorem

$$u_i = \frac{\partial E_E}{\partial P_i} \tag{7}$$

The strain energy can be the form of

$$E_E = \int_0^{a_1} \frac{\partial E_E}{\partial a} da = \int_0^{a_1} E_R da \tag{8}$$

Where, $E_R = \frac{\partial E_E}{\partial a}$ the density functions of strain energy.

From the equations (7) and (8), the additional displacement can be expressed as:

$$q_i = \frac{\partial}{\partial P_i}\left[\int_0^{a_1} E_R(a)da\right] \tag{9}$$

The flexibility influence co-efficient (C_{ij}) is expressed like:

$$C_{ij} = \frac{\partial q_i}{\partial P_j} = \frac{\partial^2}{\partial P_i \partial P_j}\int_0^{a_1} J(a)da \tag{10}$$

The flexibility influence co-efficient can be determined by integrating the equation (10) over the breadth.

$$C_{ij} = \frac{\partial q_i}{\partial P_j} = \frac{\partial^2}{\partial P_i \partial P_j}\int_{-B/2}^{+B/2}\int_0^{a_1} J(a)dadz \tag{11}$$

The equation (11) can be modified with the inclusion of strain energy release rate; i.e.

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

If $\mu=(\frac{a}{w}), d\mu=\frac{da}{w}, da=Wd\mu$, then at $a=0, \mu=0; a=a_1, \mu=\frac{a_1}{w}=\mu_1$

Incorporating the above condition, equation (12) is renewed as:

$$C_{ij} = \frac{BW}{E'}\frac{\partial^2}{\partial P_i \partial P_j}\int_0^{\xi_1}(S_{11}+S_{12})^2 d\xi \tag{13}$$

$$C_{11} = \frac{Bw}{E'}\int_0^{\xi_1}\frac{\pi a}{B^2 w^2}(F_1(\xi_1))^2 d\xi = \frac{2\pi}{E'}\int_0^{\xi_1}\xi(F_1(\xi))^2 d\xi \tag{14}$$

$$C_{12} = C_{21} = \frac{12\pi}{E'Bw}\int_0^{\xi_1}\xi F_1(\xi)F_2(\xi)d\xi \tag{15}$$

$$C_{22} = \frac{72\pi}{E'Bw}\int_0^{\xi_1}\xi F_1(\xi)F_2(\xi)d\xi \tag{16}$$

3. Investigation of Parameters of Cracked Beam (cantilever) with a Hairline Crack

Let $P_1(x, t)$ and $P_2(x, t)$ are the amplitudes in longitudinal directions for the sections on both sides of the crack and $Q_1(x, t)$, $Q_2(x, t)$ are the amplitudes in transverse directions for the same segments of the crack.

The normal functions for the structure can be expressed like:

$$\overline{P_1}(\overline{x}) = A_1\cos(\overline{S_P}\,\overline{x}) + A_2\sin(\overline{S_P}\,\overline{x}) \tag{19}$$

$$\overline{P_2}(\overline{x}) = A_3\cos(\overline{S_P}\,\overline{x}) + A_4\sin(\overline{S_P}\,\overline{x}) \tag{20}$$

$$\overline{Q_1}(\overline{x}) = A_5\cosh(\overline{S_Q}\,\overline{x}) + A_6\sinh(\overline{S_Q}\,\overline{x}) + A_7\cos(\overline{S_Q}\,\overline{x}) + A_8\sin(\overline{S_Q}\,\overline{x}) \tag{21}$$

$$\overline{Q_2}(\overline{x}) = A_9\cosh(\overline{S_Q}\,\overline{x}) + A_{10}\sinh(\overline{S_Q}\,\overline{x}) + A_{11}\cos(\overline{S_Q}\,\overline{x}) + A_{12}\sin(\overline{S_Q}\,\overline{x}) \tag{22}$$

Where $\overline{x} = \frac{x}{L}, \overline{u} = \frac{u}{L}, \overline{y} = \frac{y}{L}, \upsilon = \frac{L_1}{L}$ (23)

$$\overline{S_u} = \frac{\omega L}{C_u}, C_u = (\frac{E}{\rho})^{1/2}, \overline{S_u} = (\frac{\omega L^2}{C_y})^{1/2}, C_y = (\frac{EI}{\mu})^{1/2}, m = A\rho \tag{24}$$

A_i, (i=1, 12), the different constants which are to be calculated from the supporting conditions. The supporting conditions of the beam are as follows:

$$\overline{P_1}(0)=0; \overline{Q_1}(0)=0, \overline{Q_1}'(0)=0; \overline{P_2}'(0)=(0); \overline{Q_2}''(1)=0; \overline{Q_2}'''(1)=0 \tag{25}$$

At the fixed end: $\overline{P_1}(\mu)=\overline{P_2}(\mu); \overline{Q_1}(\mu)=\overline{Q_2}(\mu); \overline{Q_1}''(\mu)=\overline{Q_2}''(\mu); \overline{Q_1}'''(\mu)=\overline{Q_2}'''(\mu)$ (26)

At the free end, $AE\frac{dP_1(L_1)}{dx} = S_{11}(P_2(L_1)-P_1(L_1)) + S_{12}(\frac{dQ_2(L_1)}{dx} - \frac{dQ_1(L_1)}{dx})$ (27)

On multiplication of $\frac{AE}{LS_{22}S_{21}}$ on both sides of equation (17):

$$M_1M_2\overline{P}'(\alpha) = M_2(\overline{P_2}(\alpha)-\overline{P_1}(\alpha)) + M_1(\overline{Q_2}'(\alpha)-\overline{Q_1}'(\alpha)) \tag{28}$$

In the same way, $EI\frac{d^2Y_1(L_1)}{dx^2} = S_{21}(u_2(L_1)-u_1(L_1)) + S_{22}(\frac{dY_2(L_1)}{dx} - \frac{dY_1(L_1)}{dx})$ (29)

On multiplication of $\frac{EI}{LS_{22}S_{21}}$ on both sides equation (29);

$$M_3M_4\overline{Q_1}''(\alpha) = M_3(\overline{P_2}(\alpha)-\overline{P_1}(\alpha)) + M_4(\overline{Q_2}'(\alpha)-\overline{Q_1}'(\alpha)) \tag{30}$$

Where, $M_1 = \frac{AE}{LS_{11}}, M_2 = \frac{AE}{S_{12}}, M_3 = \frac{EI}{LS_{22}}, M_4 = \frac{EI}{L^2S_{21}}$ (31)

4. Implementation of Fuzzy Logic System (FLS) for Damage Detection

Fuzzy logic control has been come out as most significant areas of research for several years now. The theory of this logic is based on fuzzy set. This logic imitates human thinking and natural language which makes it different from traditional logical system. This logic system provides a method of using imprecise, in exact character of the physical world. The main part of the FLS is a set of linguistic fuzzy rules related to the mechanism of fuzzy implication and inference fuzzy associative rules. From different literatures, it is examined that FLS provides superior results as compared to the conventional logical theory. It is noticed that FLS gives more significant results when the data from the sources are inexact and uncertain. The general structure of the fuzzy inference system with Gaussian membership function is represented in Fig 2.

This logic gives a way to produce better results as compared to conventional precise mathematical control and human like decision making methods. In this suggested methodology MAMDANI fuzzy inference scheme has been personalized to locate the crack. The schematic diagram showing MAMDANI fuzzy inference system has been depicted in Figure3. Here different fuzzy MFs have been used. But in the proposed methodology for the fuzzy inference system only Gaussian or Bell shaped MF has been exercised to make the fuzzy linguistic rules.

As described earlier in the “Introduction section”, the first three natural frequencies relative values are taken as the three inputs to the MAMDANI fuzzy inference system and the relative crack depth, and relative crack location are considered as the outputs from the fuzzy inference structure. The results achieved from the fuzzy inference structure are given in Table 2.

5. Implementation of Genetic Algorithm (GA) for Damage Detection

In the last two decades, the problem of damage detection has gained considerable attention in different engineering. The presence of the crack introduces deviations in the dynamic properties of the structure. These changes can be used for health monitoring of the structures. GA works on the principle of natural selection developed by Charles Darwin. GA applies virtually by selecting the best solution from the data-pool created or generated by the developer. In the initial step, different data are created using direct methods like dynamic analysis and FEA.

Genetic Algorithms (GAs) are developed using the concept of natural evolution and genetics. The theory of survival of the best is used to find out the best solution for the given data. To find the best solution, the natural selection process is used. In natural selection process some characters are developed in individual’s overtime. Likewise, in GA during search process, some good solutions are also added to the data pool. Due to the selection operation, GA makes it easy to search a larger data pool. In this problem, it is required to find the relative crack depth and relative crack location to a corresponding set of relative natural frequencies from the field signals. For this, first a database is prepared from the results of Numerical, FEA and experimental analyses. Then rest of the steps is done according to the Genetic Algorithm.

The subsequent steps are used in the genetic algorithm:

1. A data pool of some selected solutions is generated.
2. Prior to the fitness evaluation, each individual solution is coded using binary coding method. Then each individual is treated in the objective/fitness function.
3. The fitness values of each of the solutions (which are counted as individuals) are calculated using objective/fitness function.
   The fitness function to be minimized is defined as
   Fitness function=
   $$\sqrt{(fnf_{cr}-fnf_{da})^2+(snf_{cr}-snf_{da})^2+(tnf_{cr}-tnf_{da})^2}$$
   fnf_{cr} = First modal natural frequency of the field
   fnf_{da} = Relative first modal natural frequency from the data space.
   snf_{cr} =Second modal natural frequency of the field
   snf_{da} = Relative second modal natural frequency from the data space.
   tnf_{cr} =Third modal natural frequency of the field
   tnf_{da} = Relative third modal natural frequency from the data space.
   n =number of iterations
4. Then the values for each individual from the objective/fitness function are compared among themselves and the best two individuals are selected as the parents.
5. Next crossover is applied on the two selected parents. There are different types of crossover operations which can be used for different types of problems. Selection of these types of crossover operations depends on the type of problem to be solved and the encoding method used in the problem. In the present paper, two-point crossover has been acclimatized to solve the problem.
   As the chromosomes contain five features, and each feature contains six bits, so the chromosome contains thirty bits. The crossover points are chosen five bits left of the chromosome and five bits right of the chromosome.

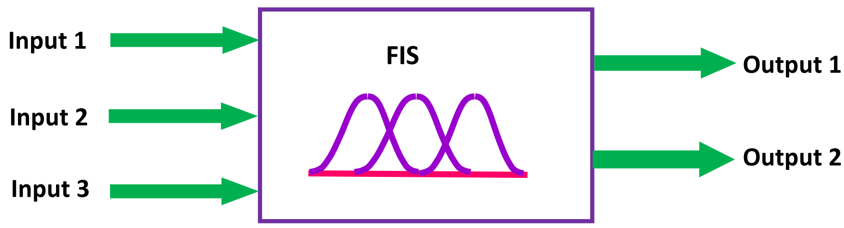


Figure 2. Fuzzy inference system using input and output Gaussian membership functions

6. With the application of crossover, two offspring are generated from the two parents. So there will be two new individuals are generated from the crossover operation. Now, the fitness values of the newly created individuals (offspring) are calculated using the objective/fitness function. Then the fitness values are compared with the parent's fitness values. Then any two fit or selected individuals with better fitness values are added to the data pool to create a new and better data pool.
7. It is noticed that sometimes, the evolutionary algorithms shall be due to vigorous search process in the solution space. So to reduce number of times of stalling, mutation is added in the algorithm like nature. Usually the mutation percentile is kept small. Otherwise, the solution may totally change.
   Here 1% of changes are allowed. A flip type of mutation is used. The total number of bits used in each individual/solution is twenty-five bits. So the 1% of twenty-five bits will be 2.5bits, here we have to take whole number. So three bits will be altered.
8. After the implementation of crossover and mutation, fitness values of all the individuals are calculated including the newly generated offspring.
9. If the offspring becomes fittest, then it is added to the data-pool, and if the parent becomes best fit then it's crack depth and location is considered as the final solution.
10. After the above step, steps from 2-10 are repeated in each iteration, till the algorithm meets the threshold values. The threshold value for this algorithm is set as maximum time spent (running time of the algorithm, i.e., one minute). The results from the GA are given in Table 3.

6. Algorithm for Hybrid Fuzzy Rule based System for Crack Assessment

The conventional types of fault detection methods use alterations in the dynamic changes in the physical responses of the structural and machine elements, such as natural frequencies and mode shapes. For calculation of these parameters, experimental modal analysis and transfer function measurements are needed which is not easy and especially expedient for online assessment of structural damage. The standard methods have disadvantages like experimental dependence which is time consuming as well as expensive. It is extremely complicated to establish a global method because size, shape and material of different structures vary from one another. The conventional type of damage detection methods cannot respond to the occurrence of small cracks within the structures whose propagation leads to a sudden catastrophic failure of the structure. So these tiny cracks must be detected from the infant stage.

In today's world everything is needed to be done effectively and efficiently. So nowadays, damage detection methods are usually incorporated with various types of AI techniques and vibration analysis. There are some major advantages of new damage detection methods over standard health monitoring methods. These methods are very efficient in detecting small hairline cracks at its initiation, so serious catastrophic failures can be checked. These methods do not require physical experiments that need time and money. As these modern types of damage detection methods use AI techniques so they are more convenient to be used for online damage exposure method.

Fuzzy systems added many advantages in the development of AI systems. Among these are clear presentations of knowledge in the form of rules or concise mathematical expressions. In addition, the fuzzy system introduced parameterization through the concept of fuzzy membership function. These membership functions contribute to flexibility of representation of high degrees of complexity in a convenient way. Genetic Algorithms also operate well in environments similar to that of fuzzy logic systems. These are also applied to situations involving nonlinearities. This nature inspired algorithm, also it has the ability to optimize the presentation of the fuzzy systems. So to get the best score in performance, levels of these two methods are combined or hybridized. The use of genetic algorithm markedly enhances the performance of the FLS, which are receiving considerable attention in the field of control system. A promising application of fuzzy logic system and genetic algorithm is to use them as alternatives to traditional treatments in the data analysis.

1. The population size and initial population is specified
2. Objective Function is generated according to the objective.

$$\text{Absoluteness} = \text{features matched} / \text{total features} \quad (32)$$

Total number of features taken here is fifteen.

$$\text{Factor of rule} = \text{rules present in the initial iteration} / \text{number of fuzzy rules} \quad (33)$$

For the present problem initial iteration consists of 3 rule sets and there are 4 rules in each rule set. So the starting iteration consists of 12 numbers of fuzzy rules.

3. Fuzzy rules are designated by the data from the data pool which is made from expertise and historical records. The fitness function decides which chromosomes will stay in the next iteration to generate initial population. When the closeness of the chromosomes from the field and from the population is more, the result produced will be better.
   The fitness of each individual can be calculated using the following function (objective function)

$$O_{(x)} = \text{exactness} / \text{factor of rule} \quad (34)$$

4. The initial population which comprises of the initial rule sets with their respective membership functions is created. The rule sets are initiated using the expertise knowledge from the field which tells how the input and output variables are related to each other.
5. Every chromosome represents a rule set which is encoded using binary coding. The linguistic term used in a rule is coded using 'one' and 'zero'. The membership functions used in the fuzzy rules are coded by using real numbers.
6. The point for doing crossover is designated as cpmf(ii) for the other parent must be chosen six units to the left of MF(ii), cpd(i) and cpd(ii) are chosen at the boundaries between membership function sets and the rule set. cprs(i) and cprs(ii) are crossover points for rule sets 1 and 2 respectively. These points are chosen randomly. Figure 3 describes the chromosome string before crossover.
7. Crossover is a type of reproduction operator. In case of crossover two offspring are generated interchanging the two substrings between cprs, cpd, cpmf and the end points of both parents. The substring from cpr(i) to cpd(i) is exchanged with that sub-string from cpr(ii) to

cpd(ii) and the substring from cpmf1 to cpe1 is exchanged with that from cpmf(ii) to cpe(ii). The chromosomes strings generated after crossover is explained in figure 4.

8. Once the crossover operation is over two offspring are generated and order of the membership functions of the new offspring will be changed. So the orders are rearranged according to the central values of the membership functions.
9. The algorithm comprises of two types of coding methods for which two types of mutations are used. A bit inversion type of mutation is used for fuzzy rule set and for the membership function small value is either added or subtracted.
10. To find the best candidate for the next iteration, the values of the objective function of parents and children are compared. Among the parents and offspring, best candidate is selected and added to the data pool to create a new dataset.
11. As the iterations of the algorithm could not be continued for infinite time, stopping criteria are provided. The stopping criteria for this algorithm are either, the number of generations (20) or the time lapse (3mins) whichever is less.
12. Once the discontinuity (stopping criteria) is set, then the algorithm is run till the threshold values are achieved.
13. By following above mentioned procedures, strong fuzzy rules are created. Then these fuzzy rules are added to the data pool.
14. Then by using COG method of Mamdani Fuzzy inference System to all the new formed strong fuzzy rules to find out the defuzzified real values of the output variables.

7. Finite Element Analysis Approach

To authenticate the proposed approach, the FEA has been carried out in commercial ANSYS 2020 software for both the cracked and uncracked beam. The FEA is a direct approach to find out the vibration parameters (natural frequency and mode shapes) which are also used as input parameters for the developed method. A structural steel cantilever beam of size 800×40×6 mm is considered here for the analysis. The cracks with various crack depth are made at various locations to carry forward the solution analysis. The relative natural frequency at a particular mode is the ratio of natural frequency of cracked to that of uncracked at this particular mode.

The current analogy is based on the assumptions of Euler-Bernoulli's and ignorance of the damping effect on the structure. So the governing equation of motion of the structure with free vibration condition will be given as:

$$M\left[\ddot{x}\right]+S[x]=0 \tag{35}$$

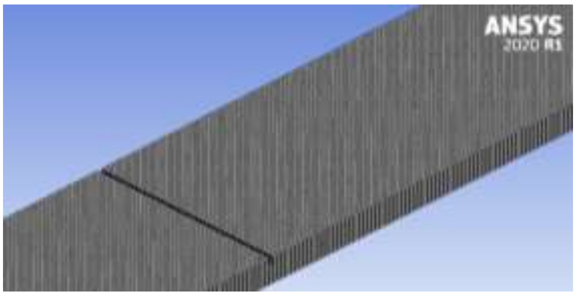


Figure 5. Modeling of crack at μ=0.325 and υ=0.360

$R_{1(i)}$ $R_{1(ii)}$ $R_{1(k)}$ MF_{fnf}……………………………………………….MF_{rcl}
R_1+MF_1 :101101…..010101….100101….0.8139,0.04417,….0.9912,0.04411,…….0.124,0.1095,…,0.5623,0.1095

$R_{2(i)}$ $R_{2(ii)}$ $R_{2(l)}$ MF_{fnf}……………………………………………….MF_{rcl}
R_2+MF_2 :101001…..…110111…011010…0.8141,0.04414,….0.9885,0.04411,…….0.125,0.1091,…,0.5522,0.1091

Figure 3. String presentation before crossover

$R_{1(i)}$ $R_{1(ii)}$ $R_{1(k)}$ MF_{fnf}……………………………………………….MF_{rcl}
$Offspring_1$:111001…..011001….110101….0.8141,0.04415,….0.9907,0.04415,…….0.125,0.1093,…,0.5625,0.1093

$R_{2(i)}$ $R_{2(ii)}$ $R_{2(l)}$
MF_{FNF}……………………………………………….MF_{rcl}
$Offspring_2$:101001…..…110101…010010…0.8143,0.04415,….0.9889,0.04415,…….0.128,0.1093,…,0.5525,0.1093

Figure 4. Two offsprings after crossover

The first or initial three modes of vibrations are allowed here to obtain the natural frequencies, mode shapes and amplitudes of both the cracked and uncracked beam. The numbers of coordinates are taken around 323 in this analysis. The mesh size for FEA is around 1mm with 13275 elements. The mesh generation and the number of element selection is a random method which is decided by performing different analyses. The modeling of the cracked beam with open transverse crack is represented in Fig 5. The first three mode shapes of the cracked beam are shown in Figures 6. The measurement or geometry of the uncracked beam has been taken as 800×40×6mm. Where, μ is the relative crack depth, where υ is the relative crack location. Mathematically $\mu=a/w$, $\upsilon=L_1/L$. The first five modes of natural frequency values for both the beam are presented in Table 1.

Table 1. Comparison of natural frequencies (Hz) between cracked and uncracked beam

Mode no	Uncracked Beam	Cracked Bam at μ=0.325 and υ=0.360
1	7.6681	7.5463
2	48.041	47.707
3	50.91	50.076
4	134.48	133.83
5	263.47	261.67

Then other parameters like material name (Aluminum Alloy) and element type (brick and isotropic) are also selected by the user for the training process. After this number of analyses are run to find the natural frequencies of different cracked cantilever beams.

8. Result and Discussions

In this analogy, a damage assessment method for a cracked beam (cantilever) with a single hair line crack has been performed. The mathematical analysis along with FEA is first carried out as direct method for quantification of the damage. Using these direct methods, data are collected which are used to build the search space for the proposed algorithm. A hybridized soft computing method, the hybridization of the fuzzy logic analysis along with GA is developed for the damage assessment of the structure. The proposed method can be treated as a reverse or indirect approach for damage assessment. This method is carried out in a supervised manner and later the results acquired from the soft computing analysis are compared with those of FEA.

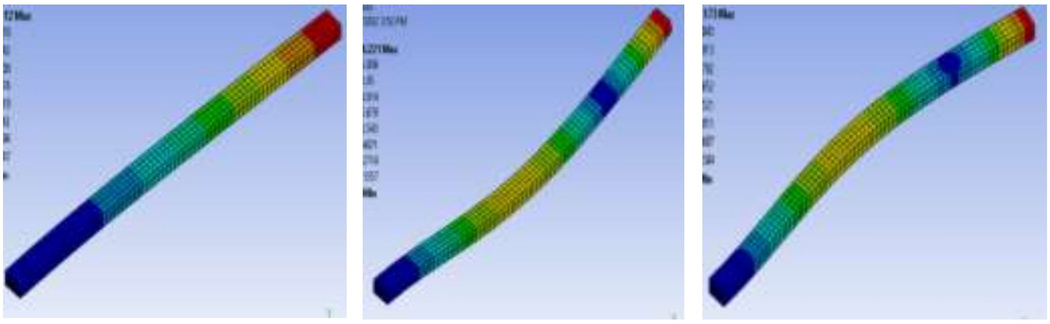
The results acquired from the present method are also compared with the results of FLS and GA separately. From the results, it was obtained that the method convergence well and will be suitable for condition monitoring structures.

The percentage error is worked out by means of the subsequent prescription:

$$\frac{\text{Result from FEA-Result from AGA}}{\text{Result from FEA}}\times 100 \qquad (36)$$

To authenticate the proposed algorithm's convergence, a numerical problem has formulated. The different crack parameters (crack depth and locations) are calculated from the proposed algorithm and compared with those of FEA. The dimension of the uncracked beam has been taken as 800×40×6mm. Where, μ is the relative crack depth, where υ is the relative crack location. Mathematically $\mu=a/w$, $\upsilon=L_1/L$. The results obtained from the various analyses are represented in Tables 2, 3 and found be well convergent.

$$\text{Total percentage of error}=\frac{\text{Percentage error in '}\mu\text{'+Percentage error in '}\upsilon\text{'}}{2} \qquad (37)$$



(Mode-1) (Mode-2) (Mode-3)

Figure 6. First three mode shapes for the cracked cantilever beam

Table 2. The results of FLS compared with FEA

Sl. No	Input Parameters to Hybrid- Fuzzy model			Results from FEA		Results from FLS		error percentage		Total error
	fnf	snf	tnf	μ	υ	μ	υ	μ	υ	
1	0.9924	0.9915	0.9959	0.325	0.21875	0.30728	0.2066	5.45	5.52	5.48
2	0.9934	0.9923	0.9975	0.3	0.20625	0.2835	0.1948	5.48	5.5	5.49
3	0.9948	0.9946	0.9969	0.2875	0.23125	0.2715	0.2185	5.55	5.48	5.51
4	0.9955	0.99769	0.9988	0.125	0.21875	0.1180	0.2066	5.56	5.51	5.53
5	0.9978	0.9975	0.9968	0.275	0.3625	0.2599	0.34267	5.49	5.47	5.48

Table 3. The results of GA compared with FEA

Sl. No	Input Parameters to Hybrid-Fuzzy model			Results from FEA		Results from GA		error percentage		Total error
	fnf	snf	tnf	μ	υ	μ	υ	μ	υ	
1	0.9924	0.9915	0.9959	0.325	0.21875	0.3105	0.2087	4.46	4.55	4.5
2	0.9934	0.9923	0.9975	0.3	0.20625	0.2865	0.1970	4.49	4.45	4.47
3	0.9948	0.9946	0.9969	0.2875	0.23125	0.2744	0.2208	4.55	4.48	4.51
4	0.9955	0.99769	0.9988	0.125	0.21875	0.1193	0.2088	4.54	4.5	4.52
5	0.9978	0.9975	0.9968	0.275	0.3625	0.2626	0.3462	4.48	4.49	4.48

Table 4. The **results** of AGA compared with FEA

Sl. No	Input Parameters to Hybrid-Fuzzy model			Results from FEA		Results from AGA		error percentage		Total error
	fnf	snf	tnf	μ	υ	μ	υ	μ	υ	
1	0.9924	0.9915	0.9959	0.325	0.21875	0.3151	0.212	3.04	3.03	3.03
2	0.9934	0.9923	0.9975	0.3	0.20625	0.291	0.20	3	2.99	2.99
3	0.9948	0.9946	0.9969	0.2875	0.23125	0.2788	0.2242	3	3.01	3.02
4	0.9955	0.99769	0.9988	0.125	0.21875	0.1212	0.2121	3.01	2.99	3.001
5	0.9978	0.9975	0.9968	0.275	0.3625	0.2668	0.3516	2.95	2.98	2.96

Finding a global optimization method is a major challenge in engineering. For this number of optimization methods involve nonlinearity, so these problems also require global optimization methods to be solved. But sometimes, performances of these methods are hampered by some limitations which include huge computational time consumption. In this work an involuntary method to produce strong fuzzy rules has been proposed which strengthens the fuzzy inference system.

9. Conclusion

The Fuzzy Logic System has been applied to various fields very effectively and efficiently. But it has been noticed by various researchers that there are some insufficiencies in terms of for different applications. So, in this research paper, an idea of eliminating the shortcomings of Fuzzy Logic has been created and developed. The proposed method can automatically tune the shapes of the membership functions and at the same time can create new effective fuzzy associative rules using Genetic Algorithm. The type of presentation scheme of the variables used in the proposed method reduces the length of the search space as a smaller number of linguistic terms is used. The objective function is so developed that the distance between the field chromosome (with the variables) and the chromosome taken from the solution space will be less, in such a way that error during evaluation can be lessened. Application of different AI methods and their hybridization with each other is purely a hit and trial manner. So, these types of researches need deep analysis to decide hybridizing algorithms. In this method Genetic Algorithm has been used to develop better fuzzy rules by exploiting the linguistic variables. The Genetic Algorithm is mainly used to train and models the inference processes of the Fuzzy Logic System. This technique can be exploited as an online device to survey the structural health condition for large structures and machines. It can be observed that the results are converging towards the observations from the finite element method. The average total error achieved during the application is about 3%, which can be considered as a markable result within the tolerable range. If the results of AGA are compared with the results of FLS (5.5%) and GA (4.5%), then it can be noticed that AGA gives the better result as compared to other methods mentioned in the research work.

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