Structural Damage Detection And Monitoring Using Vibration Signatures And Smart Techniques

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Abstract-**Early detection of damage is of special concern for engineering structures. The traditional methods of damage detection include visual inspection or instrumental evaluation. A crack in a structural member introduces local flexibility that would affect vibration response of the structure. The presence of damage leads to changes in some of the lower natural frequencies and mode shapes. Damage detection is one of the important aspects in structural engineering for safety reasons. Main problem is to detect existence of a crack together with its location and depth in the structural member. Proposed method based on some set of fuzzy rules obtained from the information supplemented by Experimental FFT Analysis, and Finite Element Analysis. The Fuzzy controller use comprises of three input variables (FNF, SNF, and TNF) and two output variables (RCD, RCL) are generated with Gaussian and Triangular MF. Experiment analysis can be for total 10 models of crack and uncracked beam having rectangular cross section, crack location and crack depth and it generates natural frequency for 3 modes of vibration. The proposed system used to detect existence of a crack together with its location and depth in the structural member Fuzzy controller here used comprises of three input variables (fnf, snf, tnf) and two output variables (rcl, rcd) with Gaussian and Triangular membership function. The proposed approach has been verified by comparing results obtained from fuzzy logic technique and Curve Fitting.**

Keywords — Rectangular Beam, Transverse Cracks, Free Vibrations, Natural Frequencies, Curve Fitting, Vibration Analysis.

I. INTRODUCTION

Beams are widely used as structural element in civil, mechanical, naval, and aeronautical engineering. Damage is none of the important aspects in structural analysis and Engineering. Damage analysis is done to promise the safety as well as economic growth of the industries. During operation all structures are subjected to degenerative effects that may cause initiation of structural defects such as cracks which, as time progresses, lead to the catastrophic failure or breakdown of the structure. To avoid the unexpected or sudden failure, earlier crack detection is essential. Taking this ideology into consideration crack detection is one of the most important domains for many researchers. Many researchers to develop various techniques for early detection of crack location, depth, size and pattern of damage in a structure.. Many researchers have been carried out in an attempt to find methods for non-destructive crack detection in structural members. Vibration-based methods have been proved as a fast and inexpensive means for crack identification. A crack in a structure induces a local flexibility which affects the dynamic behavior of the whole structure to a considerable degree. It results in reduction of natural frequencies and changes in mode shapes. An analysis of these changes makes it possible to determine the position and depth of cracks. Most of theresearches used in their studies are open crack models, that is, they assume that a crack remains always open during vibration

II. MATERIALS AND METHODS

Structural steel beams have been considered for making specimens. The specimens were cut to size from ready-made rectangular bars. Total 10 specimens were cut to the size as length 700 mm and cross section area is 32mm X 5mm. The modulus of elasticity and densities of beams have been measured to be 210GPa and 7850 Kg/m^3.

Table1. Different Beam models and their dimensions.

Beam No.	Material	C/S Dim. (m	Cracked / Uncracked	Position And Location of Crack			
				Crack	RCD	Crack	RCL
1	Structural Steel E= 210×10^3 N/m^2, ρ = 7850 Kg/m^3,length = 0.7m.	32×	Uncracke	0	0	0	0
2		32×	Cracked	1	0.2	175	0.25
3		32×	Cracked	2	0.4	175	0.25
4		32×	Cracked	3	0.6	175	0.25
5		32×	Cracked	1	0.2	350	0.5
6		32×	Cracked	2	0.4	350	0.5
7		32×	Cracked	3	0.6	350	0.5
8		32×	Cracked	1	0.2	525	0.75
9		32×	Cracked	2	0.4	525	0.75
10		32×	Cracked	3	0.6	525	0.75

A. Finite Element Modal Analysis of A Beam Models

Finite element analysis has been carried out by ANSYS15.0 software. ANSYS is a general-purpose finite element modeling package for numerically solving a wide variety of mechanical problems.

Following steps show the guidelines for carrying out Modal analysis.

1. Set material preferences. (Structural steel).
2. Define constants & material properties. (Density, Young's modulus, Poisson's ratio).
3. Follow bottom up modelling and create/import the geometry.
4. Define element type. (Default mesh of element size 2mm.
5. Mesh the area.

6. Apply constraints to the model. (Fixed support at the end of beam).
7. Specify analysis types and options
8. Solve.

The ANSYS 15 finite element program was used for free vibration of the cracked beams. For this purpose, the total 10 models are created at various crack positions in CAD software (Creo) and imported in ANSYS (.igs file). The beam model was discretised into no. of elements with N nodes. Cantilever boundary conditions can also be modelled by constraining all degrees of freedoms of the nodes located on the left end of the beam. The subspace mode extraction method was used to calculate the natural frequencies of the beam.

Table.2 Natural frequencies by FEM

Beam Model No.	RCD	RCL	First Natural Frequency (fnf)	Second Natural Frequency (snf)	Third Natural Frequency (tnf)
1	0	0	8.5601	53.632	150.14
2	0.2	0.25	8.528	53.591	149.72
3	0.4	0.25	8.4532	53.576	148.76
4	0.6	0.25	8.2037	53.52	145.61
5	0.2	0.5	8.5475	53.421	150.03
6	0.4	0.5	8.526	52.844	150.02
7	0.6	0.75	8.4536	51.044	150.02
8	0.2	0.75	8.5553	53.526	149.5
9	0.4	0.75	8.5562	53.337	147.95
10	0.6	0.75	8.5515	52.612	142.45

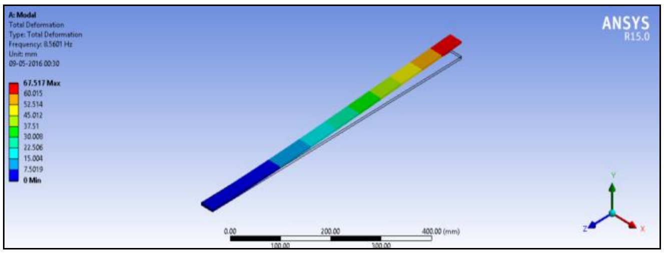

Fig.1 First natural frequency of beam model 1.

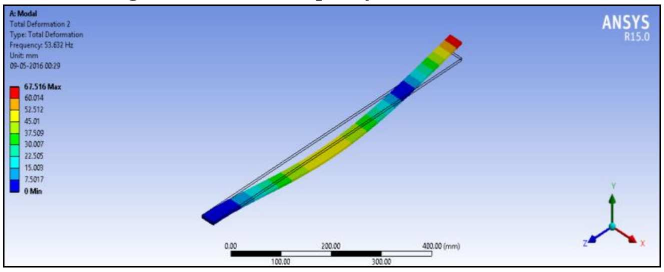

Fig.2. Second natural frequency of beam model 1.

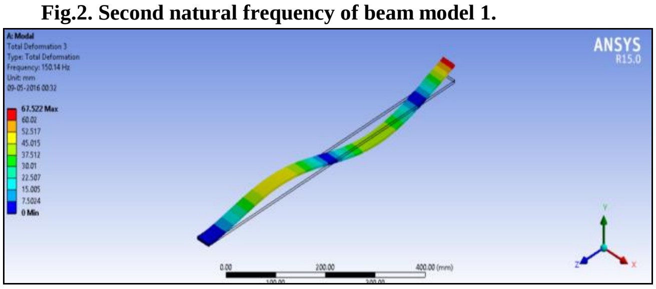

Fig.3. Third natural frequency of beam model 1.

B.Experimental Modal Analysis

Experimental analysis was performed to find out the three modal transverse natural frequencies of a cracked cantilever beam.

C. FFT Analyzer with data handling unit

It consists of function generator ,data processing unit, A/D converter, memory unit together called as FFT analyzer.. The analyzer for experimentation is four channel spectrum analyzer data collector and balance with software along with acceleration sensor sensitivity 100 m V/g (g=9.81 m/s^2).

1. Impact Hammer

It has Measuring range up to 2000N with cable and other accessories and sensitivity at 100 Hz=2mV/N. the overload capacity is 500N with Resonance frequency = 27 KHz, hammer mass=100 gm, Rigidity=0.8 KN/Micron, temperature range = - 20 to 70 ^{0}c.

2. Accelerometer with cable arrangement

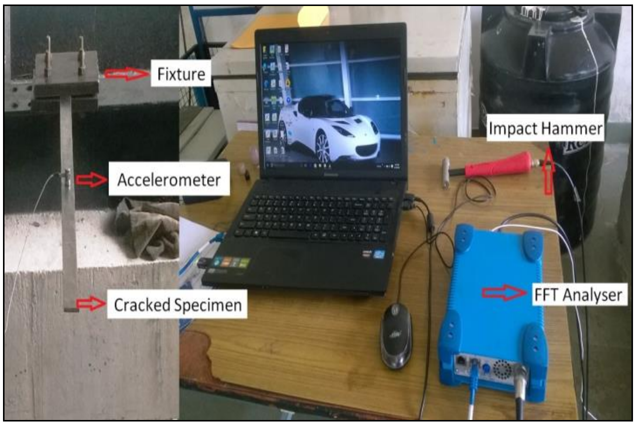

Fig.4. Experimental setup for measuring Natural Frequency.

3. FFT Analyser

Specifications of the FFT Analyser:

Model - OR34(4Channel)

Power- <15VA

External Power Supply- 100 to 240VAC

Frequency- 47 to 63 Hz

UPS-Internal NiMH Battery

Table.3. Experimental natural frequencies for the beam

Beam Model No.	RCD	RCL	First Natural Frequency (fnf)	Second Natural Frequency (snf)	Third Natural Frequency (tnf)
1	0	0	8.6	55.75	151.25
2	0.2	0.25	8.5	55	146
3	0.4	0.25	12.5	53.75	145.25
4	0.6	0.25	8.5	53.5	141.5
5	0.2	0.5	8.75	57.5	155
6	0.4	0.5	8.5	52.5	146.25
7	0.6	0.75	7.5	50	140
8	0.2	0.75	10	55	157.5
9	0.4	0.75	8.75	46.25	148.75
10	0.6	0.75	6.25	45	147.5

C. Identification of Crack by Fuzzy Logic

The input for the defuzification process is a fuzzy set (the aggregated output fuzzy set), and the output of the defuzzification process is a crisp value obtained by using some defuzzification method such as the centroid, height, or maximum.

Steps For Creating Fuzzy Model

Step 1: Fuzzy Inputs

The first step is to take inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions.

Step 2: Apply Fuzzy Operators

Once the inputs have been fuzzified, we know the degree to which each part of the antecedent has been satisfied for each rule.

Step 3: Apply the Implication Method

The implication method is defined as the shaping of the output membership functions on the basis of the firing strength of the rule.

Step 4: Aggregate all Outputs

Aggregation is a process whereby the outputs of each rule are unified. Aggregation occurs only once for each output variable.

Step 5: Defuzzify

The input for the defuzzification process is a fuzzy set (the aggregated output fuzzy set), and the output of the defuzzification process is a crisp value obtained by using some defuzzification method such as the centroid, height, or maximum. The natural frequencies have been used as input for fuzzy model creation and by using these values of natural frequencies the RCD and RCL have been found out. This is an approach to find out the RCD and RCL values by fuzzy logic.

1. ***Analysis of the Fuzzy Controller (FIS Editor)***

The fuzzy controller developed has got three input parameters and two output parameters. The fuzzy controller developed has got three input parameters and two output parameters. The linguistic term used for the inputs are as follows;

- First natural frequency = "FNF';
- Second natural frequency = "SNF";
- Third natural frequency = "TNF";
- The linguistic term used for the outputs are as follows;
- Relative crack location = "RCL"
- Relative crack depth = "RCD"

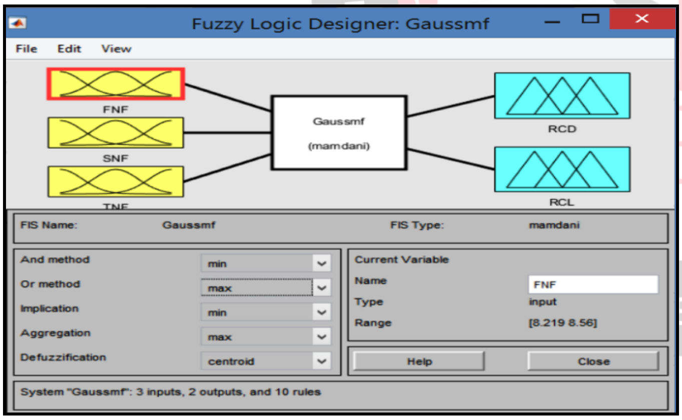

Fig.5. Input and Output variables.

GAUSSIAN MF is used for inputs(fnf, snf, tnf) and GAUSSIAN MF is used for outputs(rcd, rcl).The process of specifying the membership functions is as follows,

1. Select the variable (input/output) by double-clicking on it. Set both the Range and the Display.
2. Select Add MFs... from the Edit menu. The window below opens

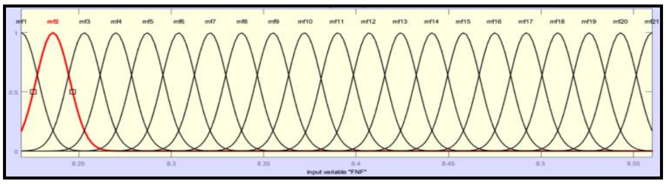

Fig.6. MF for natural frequency for 1st mode.(FNF).

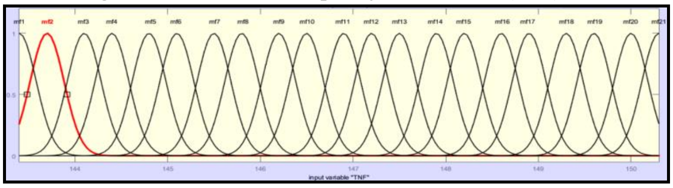

Fig.7. MF for natural frequency for 2nd mode.(SNF).

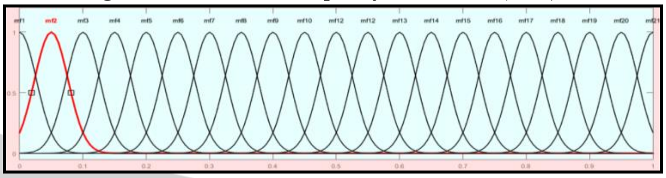

Fig.8. MF for natural frequency of 3rd mode.(TNF).

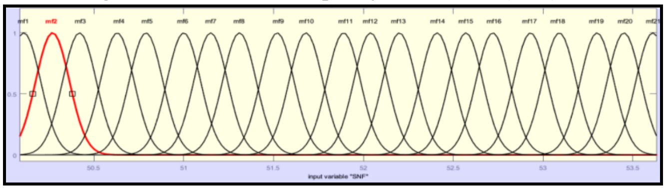

Fig.9. MF for relative crack depth (RCD) and (RCL).

2. Rules Editor

To insert the first rule in the Rule Editor, select the following:

- H1F4 under the variable fnf
- L2F1 under the variable snf
- L3F4 under the variable tnf
- The AND radio button, in the Connection block
- MD under the output variable, rcd
- SL14.under the output variable rcl

3. Rules Viewer

The Rule Viewer allows you to interpret the entire fuzzy inference process at once. The Rule Viewer also shows how the shape of certain membership functions influences the overall result. The defuzzified output value is shown by the thick line passing through the aggregate fuzzy set. Since it plots every part of every rule, it can become unwieldy for particularly large systems, but, for a relatively small number of inputs and outputs, it performs .

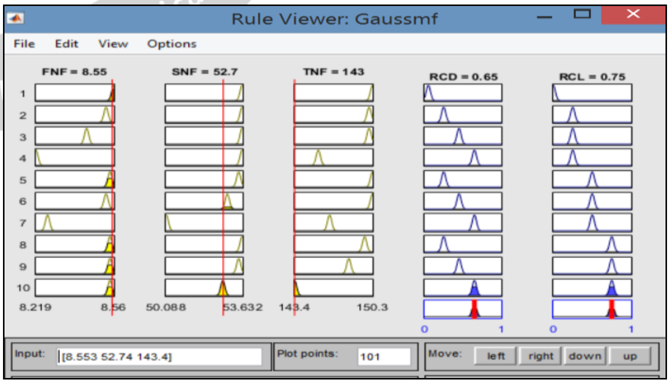

Fig.10. FIS Rules Viewer for beam model 10.

Table.4. Comparison of Fuzzy Logic parameters with Theoretical parameters

Beam model no.	Relative Crack Depth			Relative Crack Location		
	Fuzzy Logic	Actual depth	Relative error	Fuzzy Logic	Actual depth	Relative error
1	0.097	0	-0.0975	0.018	0	-0.0185
2	0.2	0.2	0	0.25	0.25	0
3	0.45	0.4	-0.05	0.25	0.25	0
4	0.6	0.6	0	0.25	0.25	0

5	0.173	0.2	0.027	0.452	0.5	0.048
6	0.45	0.4	-0.05	0.5	0.5	0
7	0.65	0.6	-0.05	0.5	0.5	0
8	0.24	0.2	-0.04	0.744	0.75	0.006
9	0.45	0.4	-0.05	0.75	0.75	0
10	0.65	0.6	-0.05	0.75	0.75	0

III. DETECTION OF CRACK BY USING CURVE FITTING

Curve Fitting Toolbox software is a collection of graphical user interfaces (GUIs) and functions for curve and surface fitting that operate in the MATLAB® technical computing environment. For a beam with a single crack with unknown parameters, the following steps are required to predict the crack location, and depth, as follows:

A. Measurements of the first three natural frequencies

Natural frequencies of beams with varying crack depth and varying location are found out by Finite Element Modal Analysis and tabulated.

B. Plotting of three dimensional surface plot of frequencies vs RCD,RCL

Load crack depth data matrix in the MATLAB command line. Load crack depth data matrix in the MATLAB command line. Load First natural frequency data matrix in the MATLAB command line.

C. Plotting of Contour of Natural Frequency vs RCD,RCL

Load crack depth data matrix in the MATLAB command line. Load crack depth data matrix in the MATLAB command line. Load First natural frequency data matrix in the MATLAB command line.

D. Extraction of Coordinate Matrix of Calculated Natural Frequency

By using Matlab Program the x and y coordinates of particular contour line are extracted. The same procedure is repeated second natural frequency and third natural frequency to plot surface plot, Contour plot and to extract coordinate data matrix.

E. Plotting of contour lines from different modes on the same axes

By using Minitab 17.0 extracted data matrix for particular beam model natural frequencies X and Y data matrices are selected and contour lines for all three modes are plotted on same X and Y axes The point of intersection, common to all the three modes, indicate the crack location, and crack depth. This intersection will be unique due to the fact that any natural frequency can be represented by a governing equation that is dependent on crack depth, crack location. Therefore a minimum of three curves is required to identify the two unknown parameters of crack location and crack depth.The point of intersection, common to all the three modes, indicate the crack location, and crack depth.

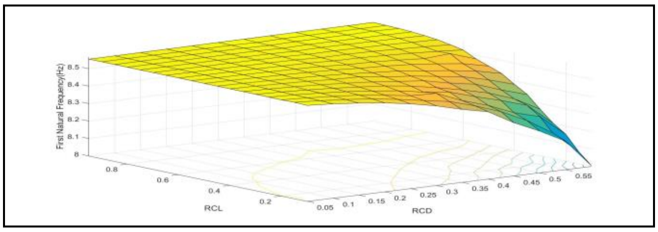

Fig.11. Surface Plot with Contour Plot of RCD,RCL vs FNF.

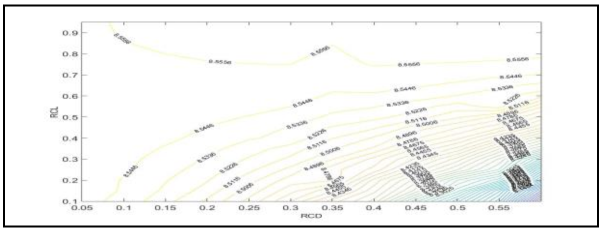

Fig.12. Contour Plot of First Natural frequency RCD vs RCL.

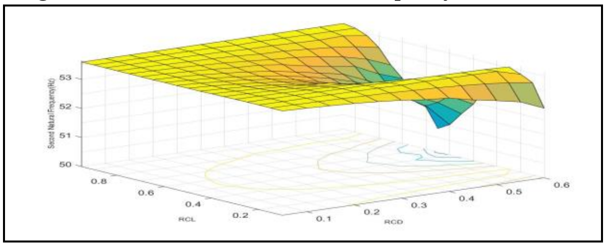

Fig.13. Surface Plot with Contour Plot of RCD,RCL vs SNF.

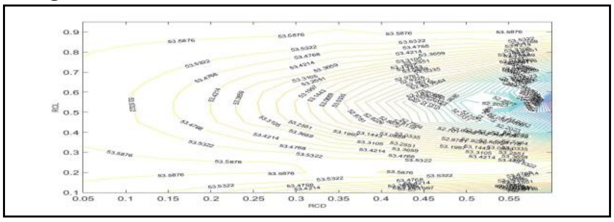

Fig.14. Contour Plot of Second Natural frequency RCD vs RCL.

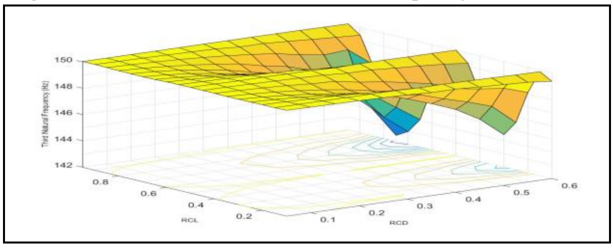

Fig.15. Surface Plot with Contour Plot of RCD,RCL vs TNF.

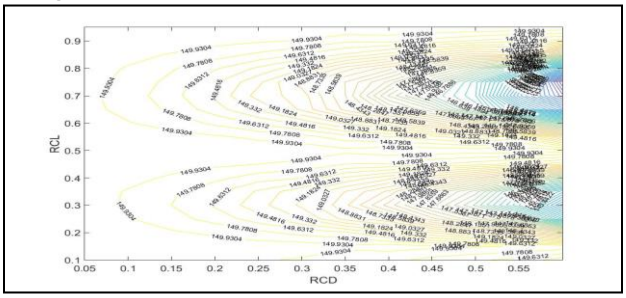

Fig.16. Contour Plot of Third Natural frequency RCD vs RCL.

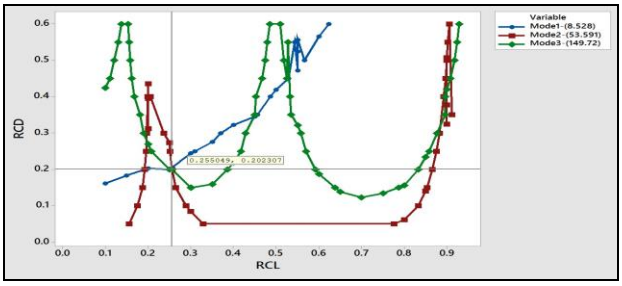

Fig.17. Curve Fitting Result for Beam Model 2.

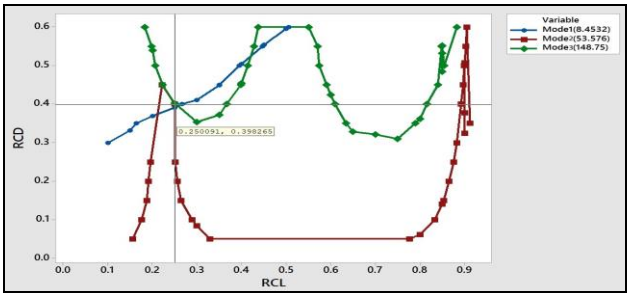

Fig.18. Curve Fitting Result for Beam Model 3.

Table.5 Comparison of results of Curve Fitting.

FNF	SNF	TNF	Theoretical		Curve Fitting		RCD	RCL
			RCD	RCL	RCD	RCL	Relative Error	Relative Error
8.5601	53.632	150.14	0	0	0.0271	0.0203	-0.0271	-0.0203
8.528	53.591	149.72	0.2	0.25	0.202307	0.255049	-0.0023	-0.0050
8.4532	53.576	148.76	0.4	0.25	0.398265	0.250091	0.0017	-0.0001
8.2037	53.52	145.61	0.6	0.25	0.600114	0.250797	-0.0001	-0.0008
8.5475	53.421	150.03	0.2	0.5	0.20219	0.453643	-0.0022	0.0464
8.526	52.844	150.02	0.4	0.5	0.35633	0.500787	0.0437	-0.0008
8.4536	51.044	150.02	0.6	0.5	0.600868	0.501827	-0.0009	-0.0018
8.5553	53.526	149.5	0.2	0.75	0.20276	0.756512	-0.0028	-0.0065
8.5562	53.337	147.95	0.4	0.75	0.393561	0.753373	0.0064	-0.0034
8.5515	52.612	142.45	0.6	0.75	0.593243	0.747066	0.0068	0.0029

IV. RESULT AND DISCUSSION

A comparison is made in between the Finite Element Modal Analysis values of natural frequencies and experimental values of natural frequencies. The result shows that all the values obtained by both the methods are closed to the agreement.

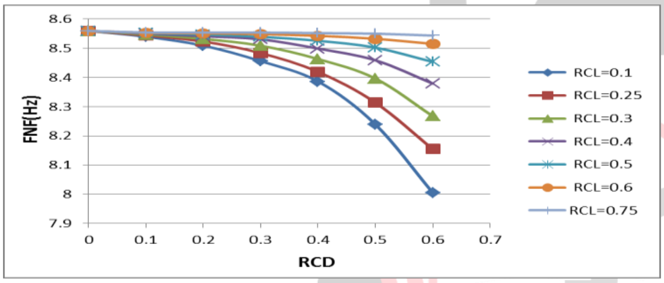

Fig.19. Variation of First Natural Frequency with Relative Crack depth with Varying Relative Crack Location.

With increase in crack depth (at a certain crack location) frequency of vibration decreases for first mode, second mode and third mode of vibration, whereas it is also observed that when the position of the crack moves from the fixed end towards the free end of the cantilever beam, the effect of the crack also decreases gradually.

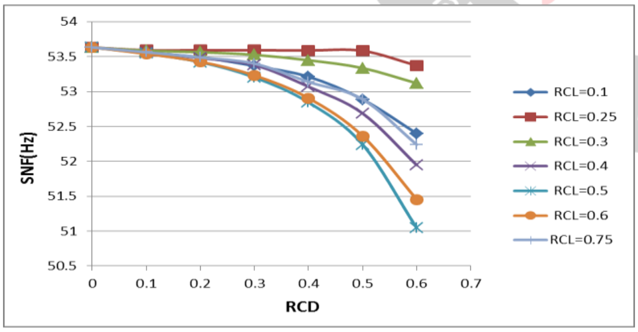

Fig.20. Variation of Second Natural Frequency with Relative Crack depth with Varying Relative Crack Location.

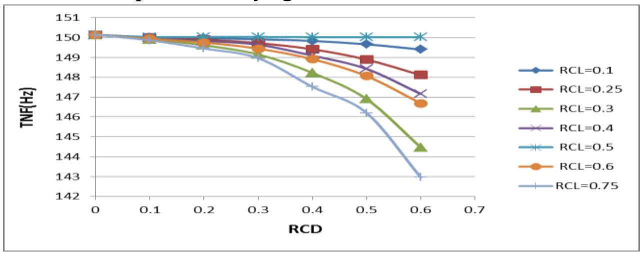

Fig.21. Variation of Third Natural Frequency with Relative Crack depth with Varying Relative Crack Location.

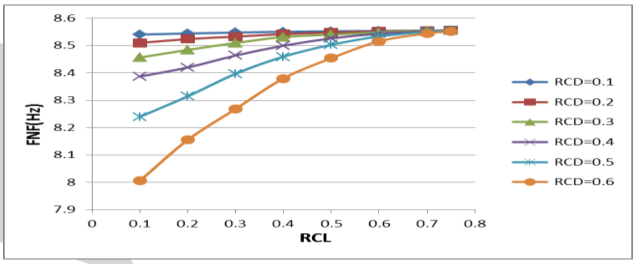

Fig.22. Variation of First Natural Frequency with Relative Crack Location with Varying Relative Crack Depth.

From the above figure it was found out that First natural frequency is increases with increase in crack location.

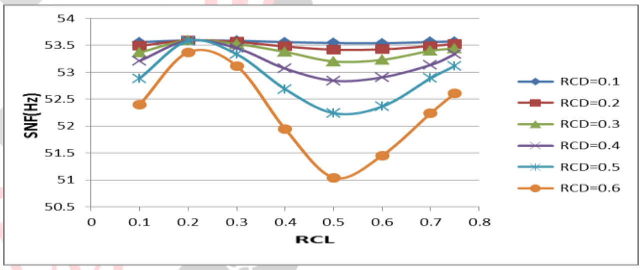

Fig.23. Variation of Second Natural Frequency with Relative Crack Location with Varying Relative Crack Depth.

From the figure below it was observed that the third natural frequency of the beam is not affected at the fixed end, free end and at the middle of the beam, whereas the frequency is very much reduced at 30% and 80% of the length of the beam.

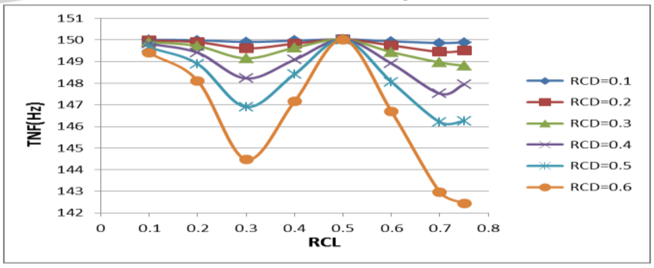

Fig.24. Variation of Third Natural Frequency with Relative Crack Location with Varying Relative Crack Depth.

V. CONCLUSIONS

The frequency of the cracked cantilever beam decreases with increase in the crack depth for the all modes of vibration. When the crack location shifts towards the fixed end of the cantilever beam the natural frequency decreases in first mode of vibration. But for second, third modes of vibrations the frequency of the cracked beams for the same crack depth varies as sinusoidal (approx). Hence it saves considerable amount of computation time. Significant changes in natural frequency observed at the vicinity of crack location. By Comparing the Fuzzy results with the theoretical results it is observed that the developed Fuzzy Controller can predict the relative crack depth and relative crack location in a very accurate manner. Result produced by Gaussian input and triangular output are in good correlation with actual RCD and RCL. Curve fitting also validates the results of fuzzy controller in a very accurate manner. Certain precision and skilled operating is required to develop Fuzzy controller. Results based on fuzzy techniques are not much accurate as it depends on some training pattern of fuzzy controller, whereas in ANSYS, it is much accurate as it is based on finite elements.

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