Damage Localization of Cantilever Beam Based on Normalized Natural Frequency Zones and Vibration Nodes

Siva Sankara Babu Chinka, Balakrishna Adavi, Srinivasa Rao Putti

Abstract: ***The damage of the mechanical structure causes the change in its behavior and variation in their modal parameters such as mode shapes and natural frequencies. Early stage identification of damage is very necessary to avoid the catastrophic failures and increase the life of components of machinery. In this paper, a novel methodology was proposed to identify the damage location on the beam-like structure like cantilever (fixed-free) beam. In this proposed technique, two approaches have been followed to estimate the damage location on the beam-like structures. First approach is used to identify the damage location in terms of small zones with the help of normalized frequency information. Second approach is used to identify the exact damage location of the beam with help of vibration nodes. The performance of this proposed method has been verified for the finite element modal analysis (FEMA) results and experimental results.***

Index Terms: ***Damage detection, Effect of damage, Labview, Natural frequency, Modal analysis***

I. INTRODUCTION

Beams are the very important parts of engines, machines in mechanical structures and structural elements in civil engineering to transfer the dynamic and static loads. The beam like structures leads to a reduction in the stiffness, there-by change in the dynamic behavior due to damage occurrence. And also the damages may cause the change in damping ratio, mode shape and the mass distribution.

The dynamics of cantilever beams have drawn much attention because such beams are widely used in engineering applications such as flexible manipulators, thin and long wind turbine blades, high-speed rotating helicopter rotor blades, and turbine engine blades. Natural frequency is the intrinsic parameter for all structures to analyze the dynamic behavior. Regular condition based monitoring and control of engineering structures is compulsory to detect damages in real time to avoid the sudden failures, provide the comfort, reduce the noise levels and estimate the reliability of the structure. Proper programmed maintenance helps to detect early damage identification and allows to minimize the maintenance cost of machinery and to avoid accidents. During the last two decades, damage identification in structures has become more important to evaluate the variation in structural behavior.

Main focus of researchers in vibration field is damage identification of aero, mechanical and civil structures. Srinivas Rao, P. et al [1] extracted damage sensitive features using Auto regressive modal analysis on mechanical structures and also calculated residual errors**.** They identified the early health condition of welds with the help of piezo electric senors. Babu.P. R, et al. [2] applied the curvature mode shapes differences to observe the crack depth and location. They carefully examined all the modes to identify number of damages, with the help of bending strain and curvature. In a while Gillich et.al [3-4] expressed the mathematical relation between the normalized frequency shift and normalized square mode shape curvature of the structure and considered both are equal in damage identification process and they are depends on damage severity. Sarrafi, Aral, Mao Zhu [5] extracted resonant frequencies and (ODS) operational deflection shapes are used to detect the occurrence of damage. They demonstrated the feasibility of developing non-contact video measurements to detect the damage on real structures. Recorded the subtle motions(images sequence) video, data was extracted by Phase based Motion-Estimation (PBME) and the data which was extracted is helpful to estimate damage localization on 2.3m long blade of wind turbine. The structural motion observed on WTB using PME magnification approach.

Pandey. A, M. Biswas. [6] Proposed the novel method initially to detect and identify the damage in beams using the mode shape curvature changes. They plotted the mode shapes of the undamaged & damaged structures for first four mode shapes, and also with the help of sharp peak, damage area is observed in beam. Chen, Da-Ming, Xu, Y.[7] proposed a reliable method to identify the damage in plate-like structures using laser Doppler vibrometer. An aluminum plate with damage is taken to identify the cracks on the surface with an auxiliary curvature damage index (CDI), which was obtained by average CDIs at different excitation frequencies. An experiment was conducted for aluminum plate with 10.5% reduction in thickness and damaged area is 0.86% of the whole scan area. The damage is successfully estimated with high values of CDIs on the surface of plate and excited by various frequencies. Shi, Binkai et.al [8] demonstrated analytically and experimentally, evaluation process for damage identification using new surface fractal dimension technique effectively in plate-type structures.

Manuscript published on 30 March 2019.
***Correspondence Author(s)**
Siva Sankara Babu Chinka, Department of Mechanical Engineering, Lakireddy Balireddy college of Engineering, Mylavaram, India.
Balakrishna Adavi, Department of Mechanical Engineering, SRKR college of Engineering, Bhimavaram, India
, **Srinivasa Rao Putti**, Department of Mechanical Engineering, Andhra University College of Engineering(A), Visakhapatnam, India

Siva Sankar Chinka, BalaKrishna. A, Rao. P. S [9] observed the effect of damage on natural frequencies of cantilever beam using Finite element modal analysis (FEMA) and experimental modal analysis in NI Lab View environment. Developed the Labview program to get frequency response functions and phase angle of real structures to observe the effect of crack on modal parameters mode shapes and resonant frequencies. M. I. Fris well [10] pooled the genetic algorithm & eigen-sensitivity algorithm in order to estimate the damage localization in structural members. Damage location and the eigen-sensitivity is optimized using genetic algorithm for various damage depths. Sinha. J. K, Friswell M.I [11] proposed a method to evaluate the crack parameters in beams using E.Bernoulli beam like elements. This modeling approach is working due to changes in the local flexibility.

P. Srinivasa Rao, et al [12] applied statistical process control in terms of acceleration time and response data to estimate the early damage detection on welded structures. With the help of auto-regression model, the residual errors are extracted from the measured acceleration-time response data. Since the natural frequency has a relation with the crack depth and location for damaged structure, frequency contours methods are used by many researchers to effective damage identification. Nahvi & Jabbari [13] plotted the graphs for the beams between normalized frequencies, crack depth and location using the FEM. They assumed the structure into small parts and the crack is supposed to be on surface of beam. The crack location and depth were identified from contours.

Mustapha Dahak, Noureddine Touat and Noureddine Benseddiq [14] developed a reliable method for cantilever beams, to estimate the damage location approximately by descritize the beam into zones by studying the normalized frequencies. That method is based on the vibration nodes, frequency will not change at nodes even damage exists on the structure. Ahmet can altunõsüõk [15] estimated change in dynamic behavior of the steel beams subjected to multi damages. Operational modal analysis has been applied to damaged and undamaged beams. Siva Sankara babu Chinka, et al [16] developed a novel method to identify the damage for fixed-fixed beam with the help of normalized frequencies.

The proposed method has been applied to the cantilever beam to detect the damage. Location of damage estimated by using normalized frequencies and their sequence as a primary source. Vibration nodes are considered as secondary source for exact damage location identification. This data is used for damage identification for cantilever beams irrespective of geometric parameters, material properties and damage severity.

II. NUMERICAL ANALYSIS

The finite element modal analysis (FEMA) applied to the beam like structure using ANSYS workbench software. The intact cantilever aluminum beam with the length (L)=800mm, the width (B)=25mm and the height (H)=10mm has been tested. The material density (ρ)=2700kg/m^3 and young's modulus(E) = 6.89 x 10^{10} N/m^2. First six natural frequencies of intact and damaged cantilever beam with various crack depths (α)=2mm, 4mm and 6mm for every 50 mm crack location from fixed end to free end support has been measured and represented in the table I and II. Natural frequency decreases at some crack locations, increases for some other crack locations and maintained no change at certain locations for various crack depths. Fig. 1 represents finite element model for damaged beam has crack location 100mm from fixed end with crack depth 2mm. The frequency changes as the crack depth and crack location are changes. The frequency shifts of the cantilever beam are represented in table I and II. But at nodal points there is no change in frequency as the crack depth changes. The frequency will not change at one nodal point for second mode and at two nodal points for third mode as shown in fig. 3.

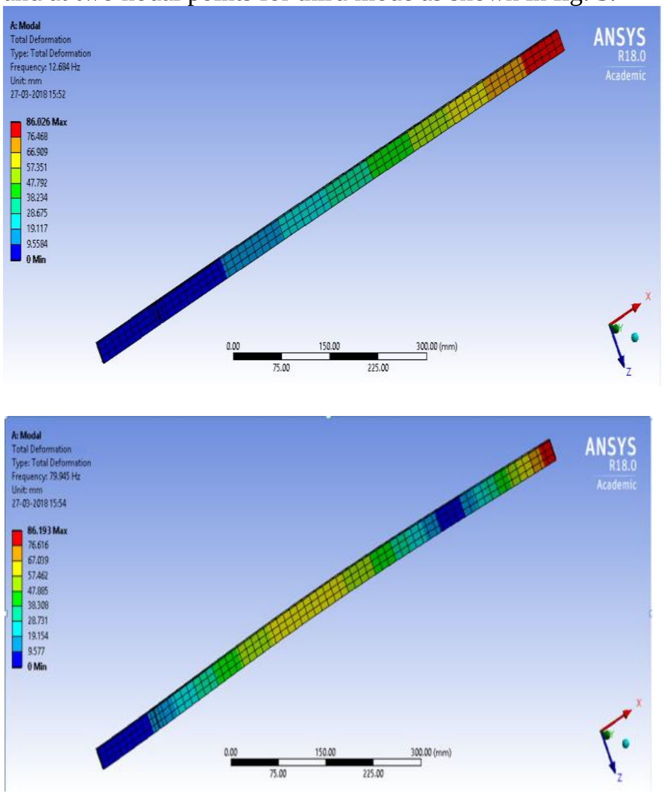

Fig. 1 Finite element model of cracked beam has crack location 100mm and crack depth 2mm with frequencies 12.684Hz and 79.945Hz.

III. PROPOSED METHODOLOGY

A. *Cantilever beam discretization into zones*

Normalized frequencies have been calculated using the equation (1) for all six modes of beam. Normalized frequency is the ratio of natural frequency of damaged beam ($f_i^{damaged}$) to the natural frequency of undamaged beam ($f_i^{undamaged}$). Considered ∇F_{ij} is the ratio of the normalized frequencies of the mode i (df_i) and mode j (df_j), (i,j=1to 4) using equations (1) , (2) and (3).

$$df_i = \frac{f_i^{damaged}}{f_i^{undamaged}} \quad \text{---(1)}$$

$$df_j = \frac{f_j^{damaged}}{f_j^{undamaged}} \quad \text{---(2)}$$

$$\nabla F_{ij} = \frac{df_i}{df_j} \quad \text{---(3)}$$

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

OPEN ACCESS
International Journal of Innovative Technology and Exploring Engineering (IJITEE)
ISSN: 2278-3075 (Online), Volume-8 Issue-5, March 2019

Table I. First three natural frequencies of cantilever beam with various crack locations and crack depths (α)

Crack Location from fixed end (mm)	First mode			Second mode			Third mode		
	Crack Depth (mm)								
	α=2	α=4	α=6	α=2	α=4	α=6	α=2	α=4	α=6
0	12.681	12.29	11.354	79.423	77.821	73.751	222.16	217.97	208.45
100	12.684	12.377	11.566	79.945	79.488	78.393	224.1	224.03	223.97
200	12.721	12.517	11.929	80.09	80.057	79.956	223.2	220.63	213.52
300	12.753	12.639	12.236	79.855	79.07	77.00	223.28	220.99	215.44
400	12.773	12.72	12.58	79.631	78.23	73.918	224.06	224.03	224.13
500	12.787	12.768	12.704	79.698	78.35	74.334	223.03	219.88	211.57
600	12.794	12.795	12.786	79.945	79.386	77.033	222.65	218.38	213.8
700	12.799	12.808	12.822	80.086	80.051	79.904	223.7	222.88	219.74
free end	12.82	12.82	12.82	80.104	80.104	80.104	224.07	224.07	224.07

Table II. Cantilever beam's fourth, fifth and sixth natural frequencies with various crack locations and crack depths (α)

Crack Location from fixed end (mm)	Fourth mode			Fifth mode			Sixth mode		
	Crack Depth (mm)								
	α=2	α=4	α=6	α=2	α=4	α=6	α=2	α=4	α=6
0	434.68	427.02	411.33	717.13	705.3	683.04	1068.7	1052	1022.4
100	438.03	436.94	434.46	721.08	715.14	699.37	1072.5	1058.5	1024.1
200	436.45	430.97	417.79	722.46	720.91	718.21	1071.3	1066.6	1066.3
300	438.23	437.8	437.34	718.96	707.8	681.42	1072.5	1070.3	1069.6
400	435.79	428.68	409.08	722.88	722.86	722.92	1070.7	1054.5	1004
500	438.26	437.96	437.54	719.14	707.12	676.66	1072.5	1069.7	1068.8
600	633.7	429	408.29	722.2	720.21	719.02	1070.7	1064.3	1050.9
700	436.9	432.51	417.18	718.89	707.84	671.16	1069.8	1050.6	1000.3
free end	438.46	438.46	438.46	723.47	723.47	723.47	1072.6	1072.6	1072.6

The graphs were drawn between ∇F_{ij} values and crack locations with various crack depths. After assembling all the graphs in an order with all combination of i and j (i, j <= 4), vertical lines has been drawn for every unchanged frequency of individual. The length between two successive vertical lines is taken as one zone. Similarly convert the total structure length into damaged zones represented in fig. 2

Fig. 2 indicates the relation between ∇F_{ij} values and crack locations with various crack depth ratios (α). For example in first zone [0-100]; $\nabla F_{34}<1$ indicates df3 must be less than df4, for second zone [100-112]; $\nabla F_{34}>1$ indicates df_3 must be greater than df_4.

After defining the zones, the normalized frequencies has been mentioned in ascending order and represented in III. To identify the damaged zone in a beam, the classification of normalized frequencies arrangement is useful. Here every zone is inferior /superior to unity of each ∇F_{ij} (i=1 to 4, j =1 to 4 and $i \neq j$) is represented in table III. This zones arrangement informs a normalized frequencies (df_i) classification for all modes. For example, if the normalized frequency classification arrangement is ($df_1<df_3<df_4<df_2$), then the crack is in the fifth zone with crack location in the range of [200-223].

B. *Identification of Vibration nodes*

The frequency remains unchanged at certain crack location. In this section, this information useful to identified the precise damage location. The damage location is symmetric to one of the mode shape nodes, gives the exact location of the damage on the beam. Fig. 3 shows the first six normalized natural frequencies (df_i) w.r.to the crack location for various crack depths (α). Exact damage location estimation is depends on the number of node points for all modes.

For second mode, beam has one vibration node; for third mode, beam has two vibration node points, similarly for fourth mode, beam has three node points and in case of fifth mode, beam has four node points. All nodes are represented by arrows in fig. 3, shows that there is no change in natural frequencies at certain nodes. More number of mode shapes will have more number of node points, these node points are useful to identify exact damage location.

Therefore, when there is no change in frequency, the particular normalized frequency is equal to one. This indicates that the damage is near the symmetric points to one of the corresponding mode shape nodes.

C. *Damage detection*

In this paper, a new method has been proposed to detect the damage in cantilever beam. By applying two approaches mentioned in sections III-A and III-B, the damage can be identified using an algorithm shown in flowchart 1.

The proposed method will work by the following steps.

Step 1: Determine the resonant frequencies of the damaged beam and undamaged cantilever beam.

Step 2: calculate the normalized natural frequencies (df_i).

Step 3: If all of (df_i) are equal to one, then the beam in undamaged.

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

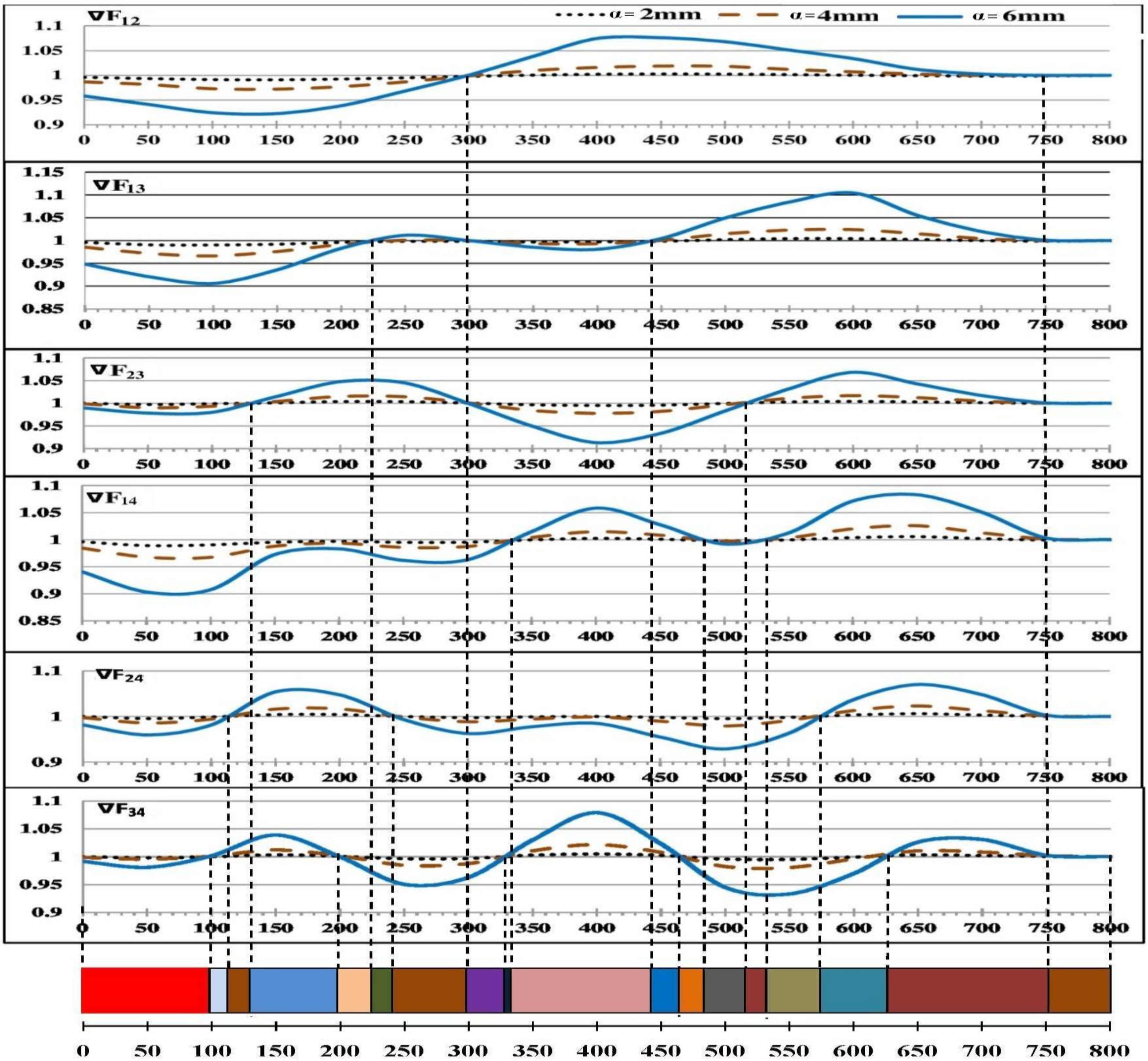

Fig.2. Cantilever beam divided into zones based on ratio of normalized natural frequencies.

Table III. The zones classification with dfi values in ascending order

Zones	Damage Zone (mm)	∇F_{12}	∇F_{13}	∇F_{23}	∇F_{14}	∇F_{24}	∇F_{34}	Normalized frequencies classification of df_i
1	[0-100]	<1	<1	<1	<1	<1	<1	$df_1<df_2<df_3<df_4$
2	[100-112]	<1	<1	<1	<1	<1	>1	$df_1<df_2<df_4<df_3$
3	[110-130]	<1	<1	<1	<1	>1	>1	$df_1<df_2<df_3<df_4$
4	[130-200]	<1	<1	>1	<1	>1	>1	$df_1<df_4<df_3<df_2$
5	[200-223]	<1	<1	>1	<1	>1	<1	$df_1<df_3<df_4<df_2$
6	[223-240]	<1	>1	>1	<1	>1	<1	$df_3<df_1<df_4<df_2$
7	[240-300]	<1	>1	>1	<1	<1	<1	$df_3<df_1<df_2<df_4$
8	[300-328]	>1	<1	<1	<1	<1	<1	$df_2<df_1<df_3<df_4$
9	[328-334]	>1	<1	<1	<1	<1	>1	$df_2<df_1<df_4<df_3$
10	[334-442]	>1	<1	<1	>1	<1	>1	$df_2<df_4<df_1<df_3$
11	[442-464]	>1	>1	<1	>1	<1	>1	$df_2<df_4<df_3<df_1$
12	[464-483]	>1	>1	<1	>1	<1	<1	$df_2<df_3<df_4<df_1$
13	[483-517]	>1	>1	<1	<1	<1	<1	$df_2<df_3<df_1<df_4$
14	[517-533]	>1	>1	>1	<1	<1	<1	$df_3<df_2<df_1<df_4$
15	[533-574]	>1	>1	>1	>1	<1	<1	$df_3<df_2<df_4<df_1$
16	[574-627]	>1	>1	>1	>1	>1	<1	$df_3<df_4<df_2<df_1$
17	[627-750]	>1	>1	>1	>1	>1	>1	$df_4<df_3<df_2<df_1$
18	[750-800]	≈1	≈1	≈1	≈1	≈1	≈1	$df_1≈df_2≈df_3≈df_4$

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

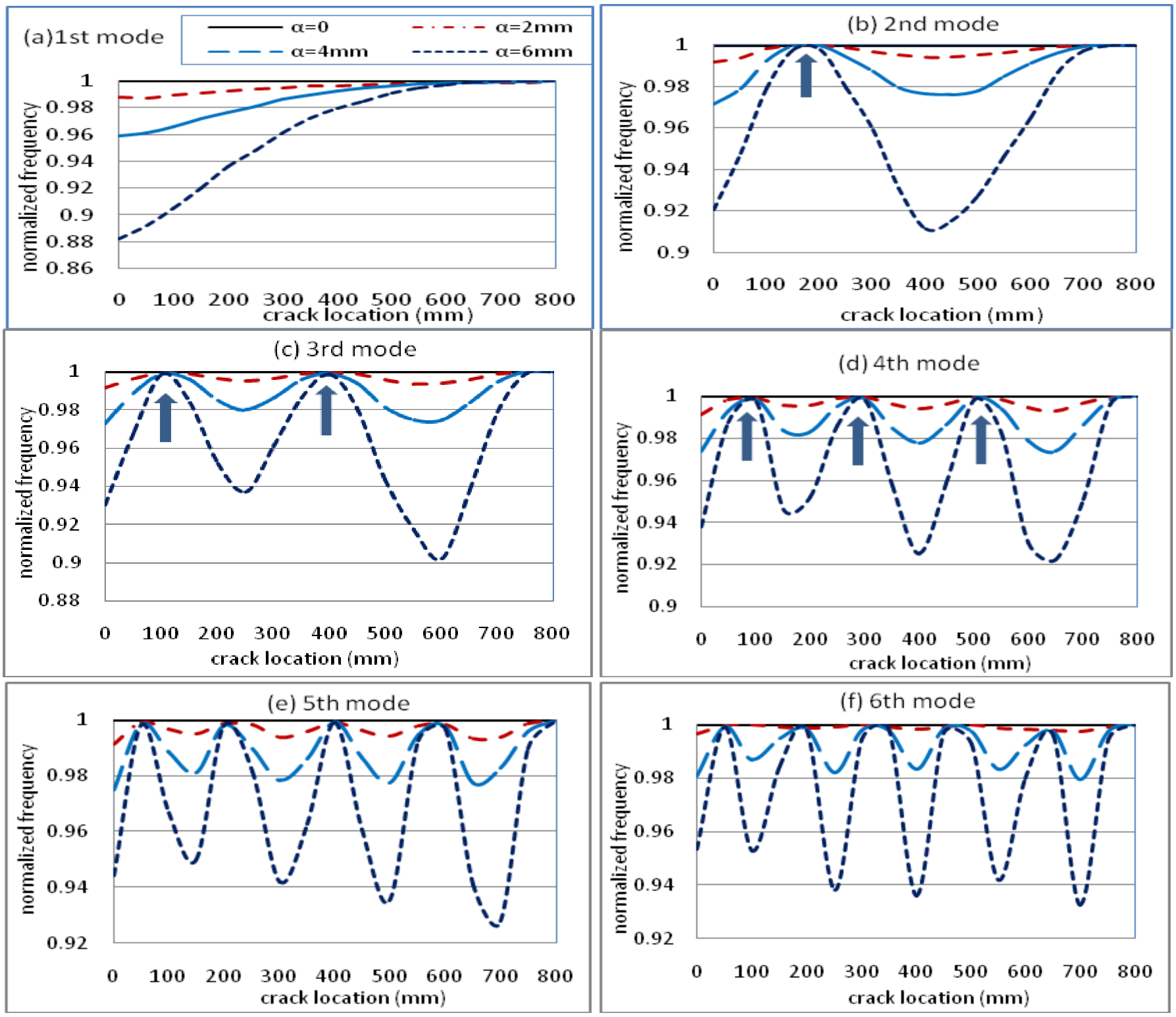

Fig.3. First six normalized natural frequencies (df_i) verses the crack location, for various crack depths.

Table IV Vibration node locations

Normalized frequencies(df_i)	Unchanged frequency nodes from fixed end	Frequencies of other nodes	Damage zones
$df_2 \approx 1$	170	$df_1<df_4<df_3$	Zone 4
$df_3 \approx 1$	105	$df_1<df_2<df+$	Zone 2
	400	$df_2<df_4<df_1$	Zone 10
$df_4 \approx 1$	90	$df_1<df_2<df_3$	Zone 1
	290	$df_3<df_1<df_2$	Zone 7
	505	$df_2<df_3<df_1$	Zone 13
$df_5 \approx 1$	55	$df_1<df_2<df_3<df_4$	Zone 1
	210	$df_1<df_3<df_4<df_2$	Zone 5
	400	$df_2<df_4<df_1<df_3$	Zone 10
	580	$df_3<df_4<df_2<df_1$	Zone 16
$df_6 \approx 1$	50	$df_1<df_2<df_3<df_4$	Zone 1
	190	$df_1<df_4<df_3<df_2$	Zone 4
	330	$df_2<df_1<df_4<df_3$	Zone 9
	475	$df_2<df_3<df_4<df_1$	Zone 12
	640	$df_4<df_3<df_2<df_1$	Zone 17

Step 4: If df_i not equal to one, there is an occurrence of damage in beam. Categorize the first four normalized frequencies in ascending order.

Step 5: Identify the damage zone from adequate classification in table III. Check whether any one of the (df_i) is matches to unity or not, if yes, the crack is symmetric to the node represented in the zone using table IV. If no, continue step 6.

Step 6: Verify whether two normalized frequencies are equal or not. If equal, the crack is in the change point between the successive zones. If no, the damage is not near the nodes and far away from the node point, damaged zone may be reduced. The method is presented as flowchart shown in fig. 4.

Published By:
Blue Eyes Intelligence Engineering
and Sciences Publication (BEIESP)

Table V Normalized natural frequencies of the cantilever beam and numerical result study

Case	Actual Crack location (mm)	Normalized Frequencies						Zones	Condition	Measured location (mm)
		df_1	df_2	df_3	df_4	df_5	df_6			
N-1	50	0.892	0.948	0.969	0.988	0.998	0.999	1	$df_6 \approx 1$	crack is at node 50mm
N-2	250	0.948	0.979	0.937	0.986	0.981	0.938	7	df4≠1,	crack is far away from 290; so damage in [240-290]
N-3	350	0.972	0.936	0.986	0.958	0.963	0.998	10	df3 ≠1 and df5 ≠1	crack is far away from 442, so damage zone is reduced to [334-400] crack is far away from 400
N-4	500	0.990	0.927	0.943	0.998	0.935	0.996	13	df4 ≠ 1	crack is far away from 517, so damage zone is reduced to [483-505]

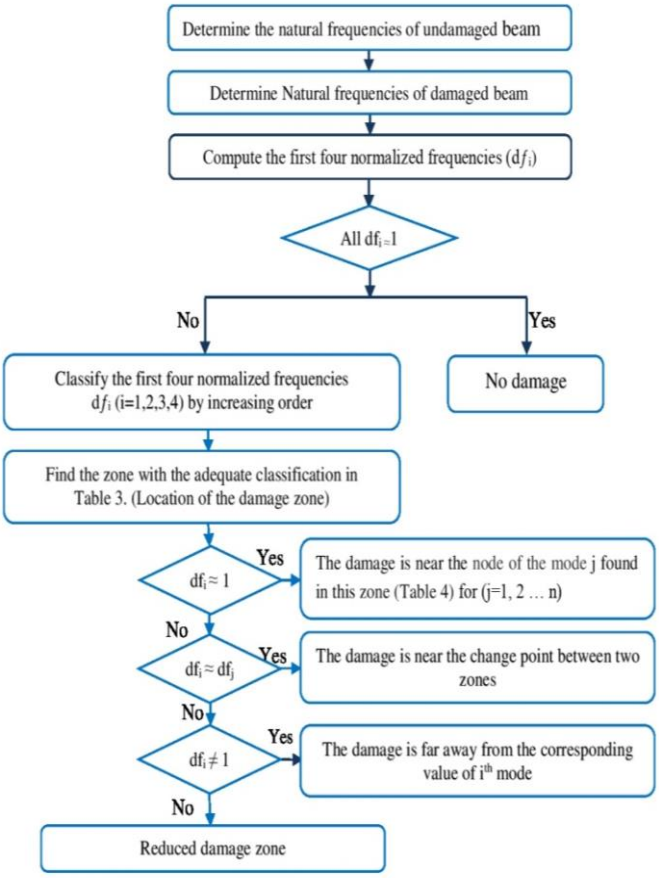

Fig. 4 Proposed method flow chart

IV. EXPERIMENTAL MODAL ANALYSIS

In the previous section, the crack identification by proposed method has been done in numerical analysis for fixed-free beams. In this section, to observe the applicability of the above proposed method in real mechanical structures, an experimental frame work has been designed and developed. An experimental modal analysis used to extract the modal parameters for the damaged and undamaged beams.

The experimental setup consists of impact hammer type 086C03, an accelerometer 352C03, four channels NI 9234 data acquisition system and NI Labview sound & vibration tool kit. These are useful to get frequencies of undamaged & damaged cantilever beams.

The damage has been introduced on surface of beam in the transverse axis, with Electrical-Discharge-Machining (EDM). Labview program was developed to get the time response and frequency response functions (FRFs) of the real structure. The frequencies of the undamaged and damaged beams are measured for different material type cantilever beams with various geometric dimensions from FRFs and represented in table VI. Normalized frequencies were calculated for three different types of beams and damage location has been identified using approaches mentioned in III-A & B sections mentioned in table VII.

Table VI Measured natural frequencies using experiment analysis

Case	Type of material	Young's Modulus (N/m^2)	Density P(kg/m^3)	Length L(mm)	Width B(mm)	Thickness T(mm)	Natural Frequencies(Hz)					
							F_1	F_2	F_3	F_4	F_5	F_6
E-1	Structural Steel	2.10 X 10^{11}	7860	760	150	14.5	19.57	129.5	359.2	715.56	1180.25	1750.25
E-2	Copper	1.20 X 10^{11}	8933	1000	25	15	8.2	53.25	152.54	300	498.5	749.1
E-3	Mild Steel	2 X 10^{11}	7850	1000	50	5	30.21	207.77	579.770	1140.61	1890.98	2827.75

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)

Table VII Experimental analysis results study

Case	Actual Crack location (mm)	Actual Crack depth (mm)	Normalized Frequencies						Zone	Measured Location (mm)
			df_1	df_2	df_3	df_4	df_5	df_6		
E-1	100	6	0.9701	0.9779	0.9880	0.9921	0.9852	0.9726	1	$df_3 \neq 1$; crack is far from 90 and $df_4 \neq 1$; crack is far from 105. So damage zone is [90-105]
E-2	200	10	0.9768	0.9927	0.9897	0.9897	0.9932	0.9821	4 or 5	The crack is in between both zones [130-200] and [200-233]. so crack is at 200
E-3	525	2	0.9906	0.9879	0.9766	0.9932	0.9799	0.9856	14	Damage zone is [517-533].

V. RESULTS AND DISCUSSION

Finite element model was developed for damaged and undamaged beams in ANSYS workbench to identify the transverse vibrations. Table I and II shows the first six resonant frequencies of the damaged beam having single crack with various crack depths and compute the normalized frequencies. The beam is descritized into number of zones based on the values of ∇F_{ij} and crack locations with various crack depths. The normalized natural frequencies are classified in ascending manner and represented in table III. Using these, the damage locations estimated exactly by steps followed as per flow chart. To verify the proposed method for damage identification, considered four cases with different crack locations and determined the normalized frequencies for aluminum beam represented in table V.

Case (N-1): Based on the normalized frequencies order ($df_1<df_2<df_3<df_4$), the damage is in first zone. And $df_6 \approx 1$, this indicates no change in frequency, so the crack is exactly at 50 mm from fixed end or at 750mm from free end of the beam.

Case (N-2): Based on the normalized frequencies order ($df_3<df_1<df_2<df_4$), the damage is in seventh zone [240-300]. And $df_4 \neq 1$, the crack is far away from 290 mm, so the damaged zone is reduced to [240-290].

Case (N-3): The normalized frequencies order is $df_2<df4<df_1<df_3$, the damage is in tenth zone [334-442]. In this case $df_3 \neq 1$, the crack is far away from 442, so damage zone is reduced to [334-400]

$df_5 \neq 1$, the crack is far away from 400; df_6 is approximately one (0.998), so the crack is nearer to 334 mm.

Case (N-4): The normalized frequencies order is $df_2<df_3<df_1<df_4$, the damage is in thirteenth zone [483-517]. And $df_4 \neq 1$, the crack is far away from 517mm. so the damage zone is reduced to [483-505].

Experimental modal analysis was carried out to calculate the natural frequencies and normalized frequencies for damaged and undamaged beam at different locations. Analyze the FRFs to estimate the natural frequencies of the three different cantilever beams mentioned in table VI and VII.

Case (E-1): The normalized frequencies order for structural steel beam is $df_1<df_2<df_3<df_4$, the damage is in first one [0-100]. And $df_3 \neq 1$; Damage is far from 90, and $df_4 \neq 1$; Damage is far from 105. So finally the damage zone is reduced to [90-105].

Case (E-2): The normalized frequencies order for copper beam is $df_1<df_3<df_4<df_2$ and $df_1<df_4<df_3<df_2$, that indicates the damage may be in fourth zone [130-200] or fifth [200-233]. But $df_3=df_4$, that represents the crack is near the change point of two zones. i.e. is crack is at 200mm.

Case (E-3): The normalized frequencies order for Mild steel beam is $df_3<df_2<df_1<df_4$, the damage is in fourteenth zone. The damage is in [517-533].

With the help of fig. 2, table III and IV, the damage location has been calculated by using the proposed techniques for cantilever beams which are manufactured with Aluminum, structural steel, mild steel and copper.

VI. CONCLUSION

In this study, a new method has been proposed to identify crack in the cantilever beam like structures. Beam has been discritized into number of zones based on the normalized frequencies of first six natural frequencies. Damage location was identified using classification of zones and vibration nodes successfully for aluminum cantilever beams. Experimental analysis was conducted for beams to identify the crack location using proposed method. FEMA and experimental results shows that, the precise damage locations can be estimated using unchanged frequency at node points. This technique is applied for cantilever beams which are manufactured with other materials to identify the damage location. This method is independent on severity of damage, type of material and geometrical parameters of beams. It provides simple algorithm for detection of damage on cracked cantilever beams.

REFERENCES

1. Rao, P. Srinivas. and Ratnam, Ch., Vibration Based Damage Identification Using Burg's Algorithm and Shewhart Control Charts, Journal of ASTM International, Volume. 8, No. 4, (2011) pp. 1-12
2. K. Ravi Prakash Babu, B. Raghu Kumar, K.L. Narayana, K. Mallikarjuna Rao, Multiple crack detection in beams from the differences in curvature mode shapes, J. Eng. Appl. Sci. 10 (4) (2015) 1701–1710.
3. G.R. Gillich, Z.I. Praisach, Modal identification and damage detection in beam-like structures using the power spectrum and time-frequency analysis, Signal Process. 96 (2014) 29–44.
4. G.R. Gillich, N.M.M. Maia, I.C. Mituletu, Z.I. Praisach, M. Tufoi, N. Ionica, Early structural damage assessment by using an improved frequency evaluation algorithm, Lat. Am. J. Solids Struct. 12 (12) (2015) 2311–2329.
5. Sarrafi, Aral; Mao, Zhu; Niezrecki, Christopher; Poozesh, Peyman, Vibration-based damage detection in wind turbine blades using Phase-based Motion Estimation and motion magnification, Journal of Sound and Vibration, Volume 421, p. 300-318.(05/2018)
6. A. Pandey, M. Biswas, M. Samman, Damage detection from changes in curvature mode shapes, J. Sound Vib. 145 (1991) 321–332.
7. Chen, Da-Ming; Xu, Y. F.; Zhu, W. D. Identification of damage in plates using full-field measurement with a continuously scanning laser Doppler vibrometer system, Journal of Sound and Vibration, Volume 422, p. 542-567, DOI:10.1016/j.jsv.2018.01.005

Published By:
Blue Eyes Intelligence Engineering and Sciences Publication (BEIESP)

8. Shi, Binkai; Qiao, Pizhong A new surface fractal dimension for displacement mode shape-based damage identification of plate-type structures Mechanical Systems and Signal Processing, Volume 103, p. 139-161 (2018)
9. S. Chinka, B. Adavi, and S. R. Putti, "Influence of Crack on Modal Parameters of Cantilever Beam Using Experimental Modal Analysis", J. Mod. Sim. Mater., vol. 1, no. 1, pp. 16-23, Jun. 2018. doi:10.21467/jmsm.1.1.16-23
10. M.I. Friswell, J.E.T. Penny, S.D. Garvey, A combined genetic and eigen sensitivity algorithm for the location of damage in structures, Comput. Struct. 69 (1998) 547–556.
11. J.K. Sinha, M.I. Friswell, S. Edwards, Simplified models for the location of cracks in beam structures using measured vibration data, J. Sound Vib. 251 (1) (2002) 13–38.
12. P. Srinivasa Rao, Ch. Ratnam, Health monitoring of welded structures using statistical process control, Mechanical Systems and Signal Processing, Volume 27,(2012) pg-683-695
13. H. Nahvi, M. Jabbari, Crack detection in beams using experimental modal data and finite element model, Int. J. Mech. Sci. 47 (2005) 1477–1497.
14. Mustapha Dahak a, On the classification of normalized natural frequencies for damage detectionin cantilever beam, 402(2017) 70-84, http://dx.doi.org/10.1016/j.jsv.2017.05.007 0022-460X & 2017
15. Ahmet can altunõsüõk , fatih yesevi okur , volkan kahya , structural identification of a cantilever beam with multiple cracks: modelling and validation, international journal of mechanical sciences (2017), doi: 10.1016/j.ijmecsci.2017.05.039
16. Siva Sankara Babu. Chinka, Balakrishna. A, Srinivasa Rao. P, damage idenfication of fixed- fixed beam using normalized natural frequency zones, Jour of Adv Research in Dynamical & Control Systems, Vol. 10, 10-Special Issue, 2018