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ANALYSIS OF DESTRUCTION OBSERVATION FOR CIRCULAR CONSTRUCTIONAL MACHINE COMPONENT

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Abstract— The presence of structural discontinuity in the structural member has the potential to threaten the component's ability to function safely. Components may also breakdown while in use, which could be dangerous. Monitoring the component is preferred in order to identify any damage or discontinuities as soon as possible. Many non-destructive testing (NDT) methods are used to examine a system's, component's, or material's qualities without causing harm in order to find these discontinuities. For long components like pipes, railways, and thin beams, common NDTs are expensive, time-consuming, and labor-intensive.

The primary goal of the thesis is to create a technique for detecting the size and location of cracks in slender structural elements using variations in transverse vibration's natural frequency. The cracks taken into consideration are straight-fronted, external cracks that are normal to the axis. Experimental and computational methods are used to investigate the efficacy of this approach. To illustrate the usefulness of the procedure, findings involving up to two cracks are shown after an analysis of the approach for the detection of multiple cracks.

A method for determining the size and position of a crack in a multi-span beam has been developed. The crack location's efficacy is verified using the same methodology.

Keywords: Cracks, Detection of cracks, Natural frequency, Effect on natural frequency due to crack location and size.

1. INTRODUCTION

Resonant conditions during machine operation become more common as a result of these trends, lowering the system's reliability. Structures must be able to function safely throughout their lifespan. However, damage initiates a period of structural breakdown. However, damage initiates a period of structural breakdown. In the steel construction and machinery industries, beam-type structures are frequently utilized. Because of this, the practical significance of the beam makes structural safety very important. Crack detection is crucial for structural health monitoring applications because cracks in beam-type structures can be dangerous from static or dynamic loadings [1].

Overstress or material fatigue can cause structural discontinuities (cracks or voids) to form in the manufacturing process or in use, causing damage to structural components. Their safe performance may be at risk from structural discontinuity, and components may also fail during service, putting lives at risk.

Without taking the structure apart, this phenomenon can be used to find any discontinuities, such as cracks or voids. Vibration-based inspection (VBI) uses the local or global impacts that the crack produces. The basis of the global effect is the fluctuations in natural frequency. This is beneficial for the component with partial or complete access. Pipes in nuclear power plants or undersea pipelines that are in dangerous areas typically have limited access. The local approaches, which are solely applicable to full access applications, are based on changes in displacements, mode shapes, strains, or curvature. Due to the ease with which the frequency may be measured from any place on the component, the method based on natural frequency is more suitable [2-3].

2. LITERATURE REVIEW

First, a review of the literature on free transverse vibration of beams is conducted. Then, various crack modeling methodologies are looked at. Then, many methods for beam crack detection have been presented. The information on the identification of numerous cracks has also been evaluated.

2.2.1 Free Vibration of Beams

The approximate analytical method, Rayleigh's energy method (Meirovitch [4]), Rayleigh-Ritz method (Nallim and Grossi [5]), Galerkin's technique (Meirovitch [4]), numerical methods, and the finite element method [Thomas and Abbas [6]; Yokoyama [7]] and finite difference procedures (Rao [8])) are among the solutions that have been proposed. Dimarogonas [9], Salawu [10] presented detailed review on vibration of beam with crack and that with multiple cracks by Sekhar [11].

2.2.2 Crack Modeling

Crack modeling is essential because of

- A physical breakage at the crack's site,
- High stress concentration caused by square-foot singularity at fracture tip;
- A crack causes considerable localization of the deformation, which might affect the damping or increase flexibility or decrease stiffness.

2.2.3 Open Crack Model

The local effect caused by the crack's presence can be taken into account in a variety of open crack modeling approaches. These are:

- Modeling by Flexibility Matrix

- Rotational Spring Approach
- One Dimensional Modeling
- Finite Element Modeling

2.3.1.1 Modeling by Flexibility Matrix

Local flexibility is introduced by cracks in a component and depends on the geometry and mode of loading. The displacement is connected to the relevant forces by the flexibility matrix. The maximum size of the flexibility matrix, which is 6x6, depends on the level of freedom taken into account. Irwin [12] has shown a correlation between local flexibility (compliance) and the stress intensity factor.

2.3.1.2 Rotational Spring Approach

A single element, namely the local bending compliance, is involved in coupling for a beam that is only susceptible to transverse vibration. As seen in Figure 1, a rotational spring can be used to illustrate this. The use of rotational springs in modal systems has been described by Rizos et al. [17].

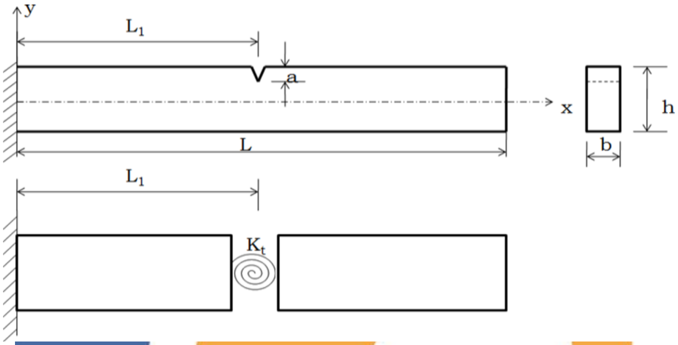


Figure 1: Cantilever beam with crack represented by rotational spring

Ostachowicz and Krawczuk [18] have provided an analytical technique. They came to the conclusion that, for cracks of the same depth and location, double-sided cracks have less of an impact than single-sided cracks.

2.3.1.3 One Dimensional Modelling

The singularity has been attempted to be incorporated into the beam equation itself.

Christides and Barr [19] used a unique function to describe the fracture for the local stress field and used the Rayleigh-Ritz approach to solve the governing equations. According to Shen and Pierre [20], the Galerkin's approach fails to satisfy the continuity criterion while the Christides and Barr's [19] solution only slowly converges. To meet the requirements for continuity, they introduced the Fourier series expansion for stresses and additional function. Shen and Pierre [21] investigated a single-crack Euler-Bernoulli beam using the generalized vibrational principle as the basis for the analysis. The theoretical natural frequency and the mode shapes produced by this method agreed well with the findings of the experiments. Chondros and Dimarogonas [22, 23] used a vibrational approach to derive crack functions from energy consideration and LEFM principles.

2.3.1.4 Finite Element Modelling

An additional matrix denotes a rate of energy release and further structural deformation. One such matrix is presented by Papadopoulos and Dimarogonas [15, 16] and was created using LEFM's basic concepts. Point finite elements joined two crack faces to depict an open and closed (breathing) crack by Ostachowicz and Krawczuk [24].

2.4 Frequency Based Damage Detection (FBDD)

This method bases crack detection on a change in frequency brought on by the crack's presence. According to Adams et al. [27], structural damage like a crack decreases stiffness while increasing damping. Natural frequencies alter as a result of changes in stiffness. increases damping. The Change in stiffness leads to change in natural frequencies.

Cawley and Adams [29, 30] have examined two dimensional domains and predicted a damage location through FEM along with sensitivity analysis considering damage over full finite element. This method was extended by Friswell et al. [31] by introducing statistical method for crack identification based on least square theory.

For segmented beams with various combinations of taper and uniform segments as well as taper beams with linearly variable depth, Chaudhari and Maiti [36, 37, 38] employed the rotational spring approach. The method's efficacy for beams with rectangular, I-section, and circular hollow sections was demonstrated by Chaudhari [39]. The rotational spring stiffness for solid rectangular or circular beams with through-the-thickness cracks can be estimated using the pre-existing relationship between stress intensity factor (SIF) and crack size (Tada et al. [40]). The effectiveness of this technique was further proved by Patil and Maiti [41, 42] for three- or four-segment beams and beams with elastic foundations. Their strategy makes use of the Transfer Matrix Method's benefit (Bapat and Bapat [43]; Singh et al. [44]; Tsi and Wang [45]; Subrahmanyam and Garg [46]). Using the transfer matrix method allowed for a significant reduction in the size of the characteristic determinant, which made it easier to analyse beams with or without cracks that included several geometric segments, intermediate supports, etc.

2.5 Wavelet Based Damage Detection (WBDD)

Recently, wavelet analysis has become a potential method for damage identification and structural health monitoring. An extension of the conventional Fourier transform with adjustable window location and size is wavelet analysis. Wavelet analysis's benefits come from its capacity to analyse local data using a "zoom lens with an adjustable focus" to produce various levels of good details and close approximations of the original signal. As a result, the data's transient behaviour can be preserved. Chui [51], Sone and Yamamoto [52], and Benedetto and Frazier [53] are recent publications that discuss the mathematical theory of wavelets and some of their applications. Cumulative damage of a building with bilinear restoring force subjected to a real earthquake ground motion was estimated in terms of the accumulated ductility ratio, which is related to the number of spikes in the wavelet results (Masuda et al.[54]; Sone et al. [55]). The wavelet approach for on-line detection of an abrupt stiffness loss was studied and the results were compared with other approaches such as a neural net-work based on-line approximation technique and the empirical mode decomposition method (Demetriou and Hou [56]; Hou and

Noori [57]; Vincent et al. [58]). Faults in gear systems were detected using wavelet approaches and some results were verified by an inspection (Wang and McFadden [59]; Staszewski and Tomlinson [60]; Ferlez and Lang [61]; Samuel et al. [62]). The operating condition for a silicon-wafer slicer cutting process was monitored and a maintenance decision of whether to sharpen the cutting blade could be made based on the wavelet analysis (Jiang et al. [63]).

2.5 Approaches for Multiple Cracks

Complexity increases when there are more cracks present than in a single crack situation. Several cracks in a component can be evaluated using two different methods:

- Forward Approach

This method makes an attempt to determine modal parameters while taking into account the size and position of the crack.

- Inverse Approach

This method makes an effort to determine crack size and location using modal characteristics.

Several experts have conducted extensive research on the free vibration of beams with varying cross sections. There are many other crack modelling techniques, but crack modelling employing rotational springs appears to be more accurate, quick, and computationally economical. Frequency Based Damage Detection (FBDD) is more practical among the crack detection methods because it is simpler to obtain the component's frequency.

Both the forward and the inverse techniques are well developed for the multiple crack situation. Both approaches the forward approach, which uses knowledge of the crack conditions to establish the natural frequencies of the free vibration, and the inverse approach, which uses knowledge of the crack conditions to estimate the crack parameters will be thoroughly examined. After considerable research, a more practical and cost-effective method of detecting cracks or damage using this methodology still needs to be developed. Research on using this method to find many cracks is still ongoing.

3. DETECTION OF SINGLE CRACK IN STRUCTURAL MEMBERS

The method has been used to find cracks in straight pipes, and validation of the method has been completed with successful crack detection. The structural beam's double-sided open crack is found using the same method, and the method has been validated.

Ostachowicz and Krawczuk [18] proposed the torsional spring stiffness as,

$$K_t = \frac{E\ b\ h^2}{72\ \pi\ a^2\ \frac{a}{h}}$$

Where,

$f(a/h) = 0.6384 - 1.035(a/h) + 3.7201(a/h)^2 - 5.1773(a/h)^3 + 7.553(a/h)^4 - 7.332(a/h)^5 + 2.4909(a/h)^6$

This is employed by Nandwana and Maiti [35], Chaudhari and Maiti [37, 38] and Lele and Maiti [75] and Patil and Maiti [72]. Mohammad H. Dado et al. [76] suggested the stiffness of the rotational spring as,

$$K_t = \frac{E\ I}{287.73\ h}\left(\frac{1-\left(\frac{a}{h}\right)}{\frac{a}{h^2}}\right)$$

3.1 Detection of crack location and the crack size

The mathematical framework described here can be used to anticipate the location and magnitude of cracks by using the experimental natural frequencies of various cantilever beams. As illustrated in Figure 2, the changes of normalized crack depth (a/h) with normalized crack location (x/L) is produced and corresponds to the first three natural frequencies. The location and magnitude of the crack will be precisely predicted by the junction of these three graphs.

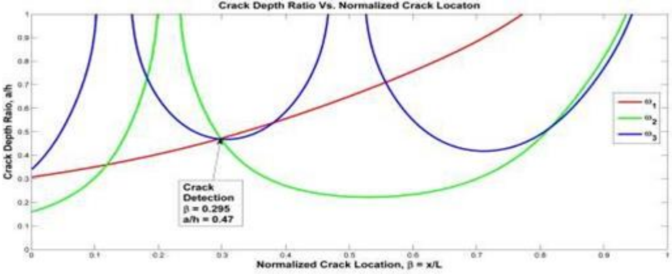


Figure 2: Detection of the Crack in Cantilever Beam having a Single Crack

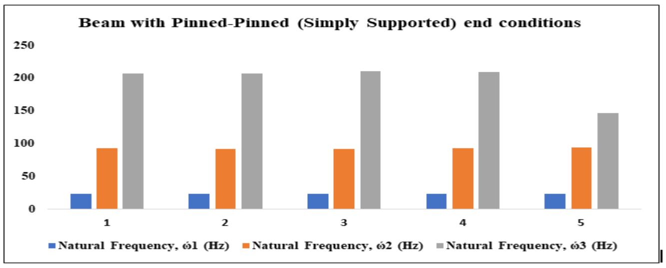


Figure 3: Comparison of Natural frequency at various crack locations

3.2 Effect of Normalized crack location and crack depth ratio on natural frequency

The depth and location of the crack have a significant impact on the natural frequency. The condition |A| = 0 is added for various crack depth ratios, crack locations, and crack frequencies to illustrate this.

Figure 3 depicts how the location of the crack affects the first natural frequency for different crack depth ratios, while Figure 4 depicts how the crack depth ratio affects the first natural frequency for different crack locations in the case of a beam with fixed-free (cantilever) end conditions.

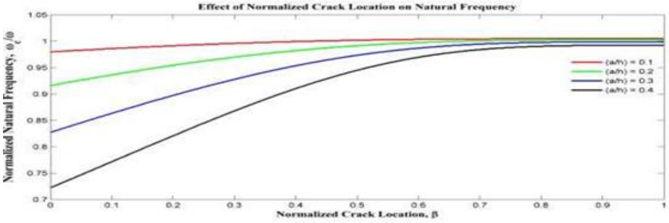


Figure 4: Effect of Normalized Crack Location on the Normalized Natural Frequency for Fixed-Free (Cantilever) end conditions

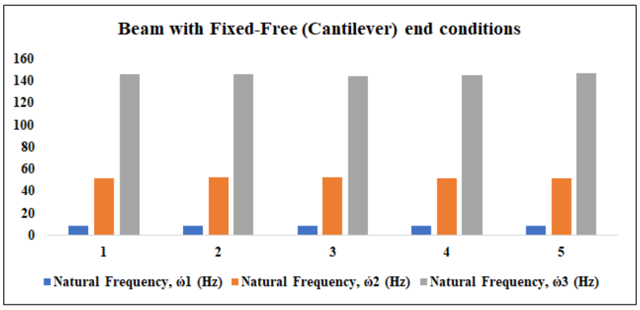


Figure 5: Comparison of Natural frequency at various crack locations

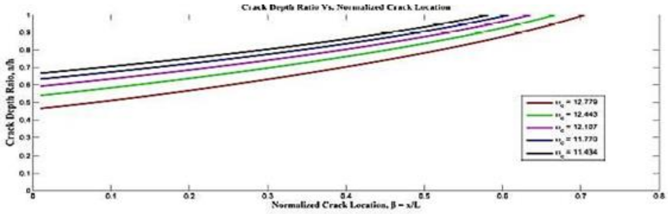


Figure 6: Contours of Crack Depth Ratio to Normalized Crack Locations for Various Normalized Natural Frequency of Cantilever Beam with a Single Crack

For the beam with fixed-free end circumstances, Figure 3.4 shows a contour diagram of various natural frequencies for each crack location and the crack depth ratios. If the location of the fracture is identified through Mode Shape Damage Detection (MBBD), the crack depth can be determined from its cracked natural frequency from this diagram.

Table 1 Comparison of Actual and Predicted Crack Location and Crack Size by Natural Frequency for a Beam with Fixed-Free (Cantilever) end conditions

Normalized Crack Lo- cation, (β= x/L)	Crack Depth Ratio ,(a/h)	Natural Fre-quency ,$\dot{\omega}_1$ (Hz)	Natural Fre-quency ,$\dot{\omega}_2$ (Hz)	Natural Fre-quency ,$\dot{\omega}_3$ (Hz)	Predicted Crack Location , (β_P) (Pre-sented Method)	Error in Pre-dicted Crack Location ,(%)	Predicted Crack Depth, $(a/h)_P$ (PresentedMethod)	Error in Pre-dicted Crack Depth , (%)
Uncracked		8.3493	52.308	146.39	-	-	-	-
0.1	0.5	8.0681	51.682	146.06	0.099	1	0.486	2.8
0.2	0.5	8.16	52.303	145.46	0.206	3	0.4785	4.3
0.3	0.5	8.22	52.091	143.79	0.295	1.67	0.47	6
0.4	0.5	8.2721	51.548	145.03	0.402	-0.5	0.4736	5.28
0.5	0.5	8.3088	51.224	146.41	0.504	-0.8	0.45	10

4. DETECTION OF MULTIPLE CRACKS IN STRUCTURAL MEMBERS

The detection of multiple cracks in the slender structural members is considered. Presence of the crack in the structural member reduces the strain energy of the component as the member deforms easily as compared to the member without the presence of crack. Released strain energy is stored as the strain energy of equivalent rotational spring. Strain energy stored in the beam having crack is given by,

$$U_c=U_{nc}-(M^2/2k)$$

Where, `Uc' and `Unc' are strain energy stored in the beam with and without crack respectively, `M' is the bending moment of the pipe with no crack at the crack location and `k' is the spring stiffness equivalent to present crack.

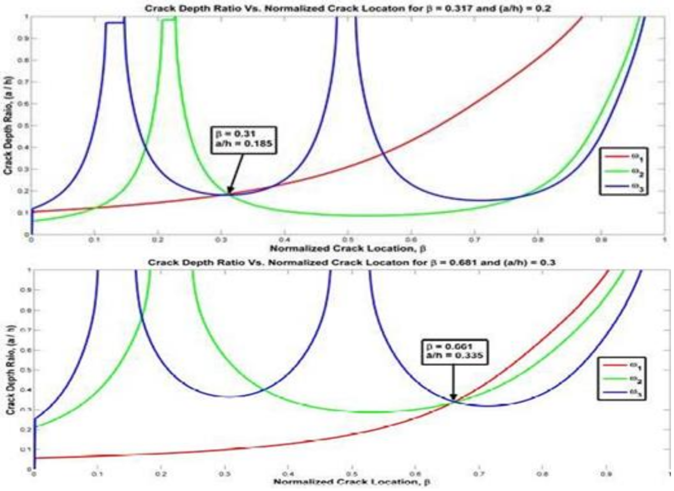


Figure 7: Multiple Crack Detection in the Cantilever Beam

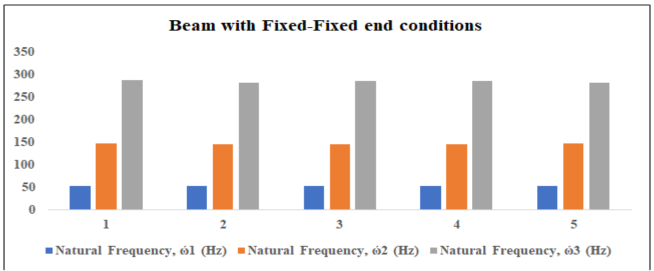


Figure 8: Comparison of Natural frequency at various crack locations

The intersection of these three curves will precisely predict the crack location and the crack size. The Figure 5 is prepared for the natural frequencies of the beam corresponding to β1 = 0.317; (a/h)1 =0.2 andβ2 = 0.681; (a/h)2 = 0.3. The predicted location and the crack size are β1 = 0.31; (a/h)1= 0.185 and β2 = 0.661; (a/h)2 = 0.335, respectively. Comparison of the actual and the predicted crack locations and the sizes along with natural frequencies of the beam are presented in the Table 2.

Table 2 Comparison of Actual and Predicted Crack Location and the Crack Size by Natural Frequencies

Normalized Crack Lo- cation, (β = x/L)	Crack Depth Ratio ,(a/h)	Natural Fre-quency ,$\dot{\omega}_1$ (Hz)	Natural Fre-quency ,$\dot{\omega}_2$ (Hz)	Natural Fre-quency ,$\dot{\omega}_3$ (Hz)	Predicted Crack Loca-tion, (β_P)(present method)	Error in Pre-dicted Crack Location ,(%)	Predicted Crack Depth Ra-tio, $(a/h)_P$ (Present Method)	Error in Pre-Dicted Crack Depth Ratio, (%)
Uncracked		24.248	152.026	424.457	-	-	-	-
0.317 0.681	0.2 0.2	24.066	150.612	416.579	0.31 0.66	2.2 3.08	0.223 0.2217	-11.5 -10.85
0.317 0.681	0.2 0.3	24.044	149.268	409.287	0.31 0.661	2.2 2.93	0.185 0.335	7.5 -11.67
0.317 0.681	0.3 0.2	23.892	150.26	411.265	0.31 0.658	2.2 3.37	0.29 0.26	-3.45 -30

5. CRACK DETECTION IN MULTI-SPAN BEAM

The rotational spring approach has been applied to detect the crack present in the multi-span beam. Free transverse vibration of the multi-span beam like fixed-fixed beam with hinged support at center and the pinned-pinned support with hinged support at the center has been analyzed. Further, the crack detection approach is applied to the beam with the above-mentioned end conditions and the effect of the crack location and the crack depth on the natural frequency has been studied. Using this approach, the crack on the multi-span beam with above mentioned an end condition has been predicted and results are found to be in good agreement with the actual crack conditions.

Boundary conditions for the fixed-fixed beam having hinged support at center are as follows: For Fixed end at support 1,

Displacement, W1 (0) = 0
Slope, W1'(0) = 0
For Fixed end at support 3,
Displacement, W2 (l) = 0
Slope, W2' (l) = 0
For Hinged Support at Support 2,
Displacement, W1 (l) = 0
Displacement, W2 (0) = 0
Slope, W1' (l) = W2' (0)
Moment, W1" (l) = W2" (0)

We can get different mode shapes of the free transverse vibration of the fixed-fixed beam with hinged support at center. Two different types of mode shapes of the free transverse vibration of the fixed-fixed beam with hinged support at center are shown in Figure 6 and Figure 7.

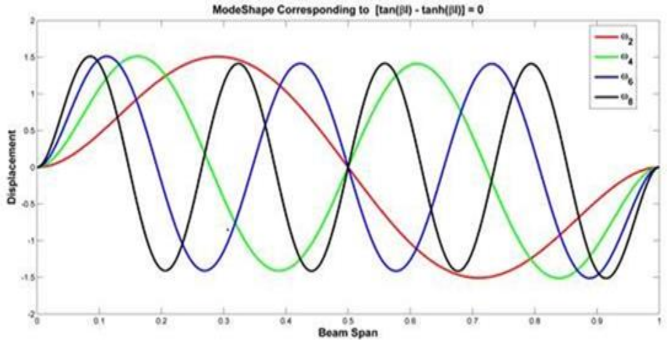


Figure 9: Mode Shape Type-1 of the Fixed-Pinned-Fixed Beam

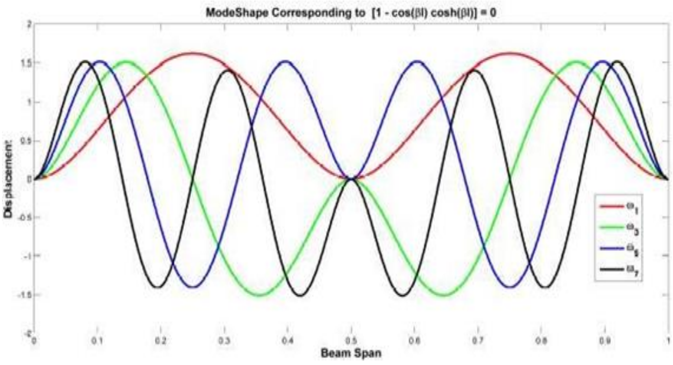


Figure 10: Mode Shape Type-2 of the Fixed-Pinned-Fixed Beam

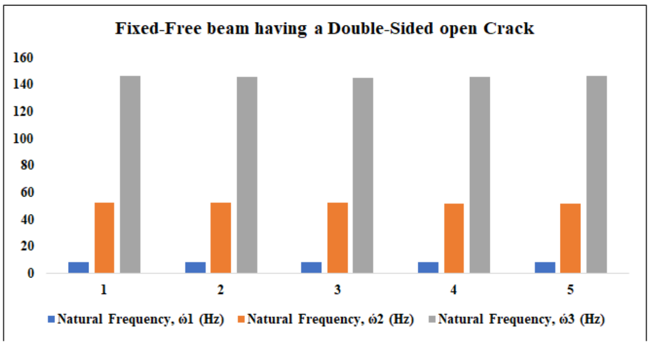


Figure 11: Comparison of Natural frequency at various crack locations

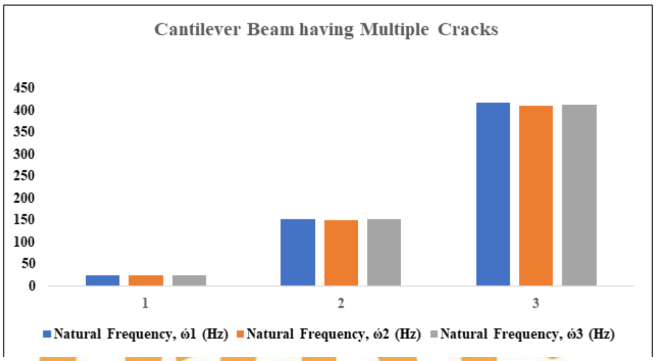
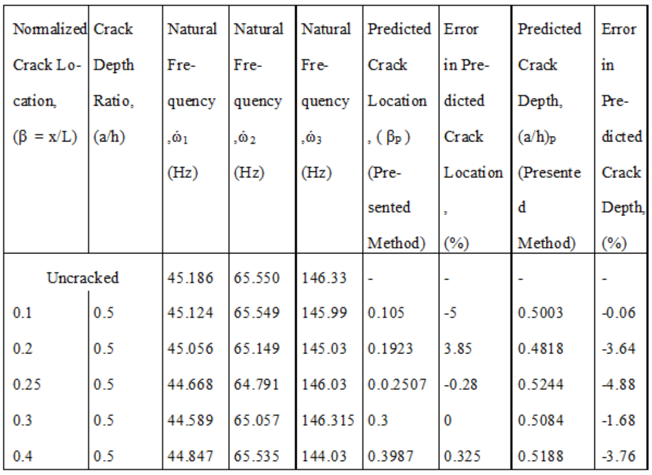


Figure 12: Comparison of Natural frequency at various crack locations

Table 3 Represents the error between the actual and the predicted crack locations and the crack sizes from the presented study



Normalized Crack Location, (β = x/L)	Crack Depth Ratio, (a/h)	Natural Frequency ,$\acute{\omega}_1$ (Hz)	Natural Frequency ,$\acute{\omega}_2$ (Hz)	Natural Frequency ,$\acute{\omega}_3$ (Hz)	Predicted Crack Location , (β_P) (Presented Method)	Error in Predicted Crack Location , (%)	Predicted Crack Depth, $(a/h)_P$ (Presented Method)	Error in Predicted Crack Depth, (%)
Uncracked		45.186	65.550	146.33	-	-	-	-
0.1	0.5	45.124	65.549	145.99	0.105	-5	0.5003	-0.06
0.2	0.5	45.056	65.149	145.03	0.1923	3.85	0.4818	-3.64
0.25	0.5	44.668	64.791	146.03	0.0.2507	-0.28	0.5244	-4.88
0.3	0.5	44.589	65.057	146.315	0.3	0	0.5084	-1.68
0.4	0.5	44.847	65.535	144.03	0.3987	0.325	0.5188	-3.76

6. CONCLUSION

Damage detection is possible using natural frequency with this method. The conclusions drawn from the current investigation are as follows:

- As compared to cracks with lesser crack depth ratio(a/h), larger cracks transmit significant reductions in natural frequency. As a result, results become more accurate as rack depth increases.
- A crack that is present close to the fixed end reduces the natural frequency more than one that is present farther away from the fixed end.

- The method that is being shown can also be used to find multiple cracks in structural members.
- The method that is being used produces successful results for locating cracks in multi-span beams.
- This technique can also be used to find cracks in in the pipes filled with and without containing pressurized fluid.
- The multi-span beam can have several cracks, therefore this method can be expanded to find them. The method can be expanded even further to include the detection of cracks in constructions of the frame type.
- In pressurized pipelines, cracks may be found, some of which have several supports. The detection of a crack in a fluid-carrying pipe can be done using the same method.

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