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CRACK DETECTION IN STRUCTURES USING VIBRATION MODAL PARAMETERS AND TIME DOMAIN RESPONSE

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Abstract: Detection of cracks in engineering materials, structures and machines at the early stage is an important issue of concern in the field of engineering. Cracks often occur first on the surface of concrete structures under load and provide an indication for further degradation. Fatigue can have significant influence on crack. It is therefore imperative to detect crack at the early stage to avoid catastrophic effects. For this reason, a number of methods have been developed by researchers to meet this objective. In this paper, a simple cantilever beam was considered to detect the presence of crack from measured vibration data. A beam with crack at different locations and another beam without crack were considered for the experiments. At different crack locations, natural frequencies, mode shapes and acceleration responses were determined. It was found that natural frequencies and mode shapes gave no significant presence of crack but time domain acceleration response method was able to detect the presence of crack.

Keywords: Modal parameters; natural frequencies; mode space; time domain; acceleration response; crack detection

INTRODUCTION

The ability to monitor the health of structures and detect damages at the earliest stage is of great importance to industries for variety of reasons. For this reason, various crack detection techniques have been proposed by researchers [1,2]. Research is also ongoing in the area of damage detection. Significant efforts have been made by scientists and researchers in the last few years to develop non-destructive techniques (NDT) that can reliably detect faults, diagnose the type of faults, localize the fault, determine its severity and predict the remaining life of structures. Literatures show that vibration based technique is one of the methods that is widely used for damage recognition in a beam like dynamic structure.

In order to detect a crack, the whole component requires scanning which becomes uneconomical for long beams and pipelines which are widely used in bridges, power plants, railway etc. This makes the process tedious, time consuming and costly [3]. Traditional localized NDT methods for crack detection in machine and structural components pose some drawbacks. It is paramount that the location of the damage is identified and the exact area of the structural component being scrutinized is easily accessible [4]. However, global vibration based damage detection methods provide an accurate, timely, non-destructive and inexpensive means of locating or detecting cracks [5,6]. According to [7], about 80% of failures of rotating machinery lead to significant changes in vibration. By examining these changes, fault detection can be determined from the vibration data [8]. The change in vibration parameters e.g. reduction in the natural frequency, mode shapes, stiffness and increase in damping therefore becomes a major source of information available from the machinery for fault detection and diagnosis [2,3]. [8] posited that crack or damages in structures especially overloaded zones is potential due to operation of members of engineering structures under loading conditions. Therefore, for assessment of structural integrity, performance and safety, it is suitable to monitor changes in response parameters of structures.

Cracks regarded as physical discontinuity in the geometry of structures changes the dynamic behavior of a component [6,9]. They may be as a result of fatigue, mechanical defects, environmental effects or faults from manufacturing process; cracks however could be on the surface or inside the material [10,11]. The presence of cracks and its location can be characterized by change in its vibration parameters. It is therefore the purpose of this paper to present a parametric study aimed at investigating the suggested methods for crack detection.

CRACK DETECTION METHODS

As reviewed from literature, the presence of crack changes the vibration parameters of dynamic systems. [6] classified them as modal and structural parameters. According to them, the modal parameters include: mode shapes, modal frequencies and modal damping values. On the other hand, the structural parameters include: mass and damping matrices, stiffness or flexibility. According to [12], structural parameters pose some limitations, which include low sensitivity to initial tiny damage in structure, measurement of parameters are expensive and time consuming. While the modal parameters is based on online measurement, detection of small damages may be possible, measures vibration response at few locations in the structure, done without affecting production in industrial settings and interference from other structures are minimal. Using vibration response to determine damages in structures proofs to be efficient as seen from the extensive review by [13], where time-domain approach was used.

In this work, the crack modelling suggested by [14] have been used. The model is the Euler-Bernoulli beam element for the Finite Element (FE) modelling with some modification in local flexibility within the cracked region. This method is simpler and deals with the crack location and depth directly. FE model of a cantilever beam was carried out and the natural frequencies and mode shapes were calculated for both healthy and faulty states of the beam. The changes in modal parameter were analysed and used for the estimation of the presence and location of crack; to show the applicability and efficiency of the vibration modal parameters for crack detection. All simulations were done using MATLAB.

— Changes in Natural Frequencies

[2] conducted a deep search considering multiple crack discovery method in moving parts of structures and beams. This was achieved by constant monitoring of natural frequency to predict the depth and crack location of the existing structure. According to [9], the natural frequency of a system changes noticeably due to the presence of crack, and these significant changes is subject to the location and size of cracks. They further scrutinized that when crack locations are constant i.e. at specific crack location, the natural frequencies of a cracked or fractured beam are inversely proportional to the depth of the crack. It was further observed that the variation in frequencies is not only a function of crack depth, and crack location, but also a change in the mode number. Similar results were also reported by [15].

[8] reported that during crack location in systems and structures, natural frequencies are comparatively easier and far more accurate to measure than other modal parameters. It is reported in literature that most researchers used this method since the reduction in natural frequencies can be detected easily [16]. Hence, this method will be used to validate the applicability and effectiveness of crack detection.

— Changes in Mode Shapes

[8] demonstrated the use of mode shape to identify damages in structure. They reported that the mode shape of a structure is a function of the physical properties of that structure in a given system. Also, the variations in the physical properties of a structure as a result of fault will affect or cause a drastic change in the mode shape of that structure. [17], used the variations in alternation of mode shape as an investigative constraint to identify the presence of damage in a structure (using a steel plate model). Though the mode shapes of a structure are sensitive to small damages than the natural frequencies; one notable drawback in adopting the mode shape based method is that accuracy in measurement is critically subject to the distribution and volume of available sensors [3]. Hence, a comparison between the mode shapes of healthy and faulty state of the structure is examined to validate the use of this technique for crack detection.

— Time Domain Responses

[13] established and formulated a time domain function for effective prediction of cracks and damages in structures and beams using compiled dataset from the linear beam-oscillator dynamic interaction. The proficiencies of this established invention was extended to include the likelihood of the cracked and damaged beam structure undergoing nonlinear vibration. Hence, the time domain acceleration responses would be used to estimate the presence of crack for the healthy and cracked beam.

RESULTS AND DISCUSSION

Euler Bernoulli Beam element is used for constructing the finite element model of the cantilever beam. The beam was divided into 12 elements and each element has two degree of freedom, one rotational and one translation. Hence, the total degree of freedom (DOF) is 26. Figure 1 shows the cantilever and Table 1 gives its properties. The details of the finite element (FE) modeling, response computation and crack breathing simulation can be found in [1].

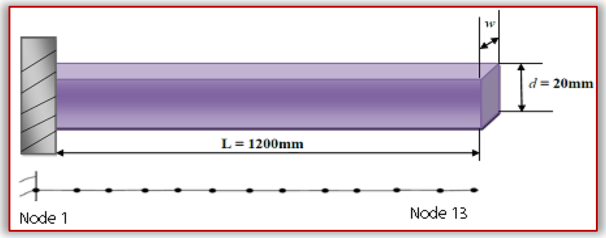


Figure 1. FE Modelling and dynamic behaviour of cantilever beam

Table 1: Properties of the cantilever beam

Boundary condition	Cantilever
Young Modules, E	210e09 N/m^2
Mass Density	7800 kg/m^3
Beam length, L	1200 mm
Beam width, *w*	20 mm
Beam depth, *d*	20 mm

The different crack location x_c where measurements were taken varied from 0.05 to 0.65mm in steps of 0.20mm with the crack ratio, ($C_r = d_c / d$), which varies from 0 to 0.25 in steps of 0.5.

— Natural Frequency

The natural frequencies for the different crack locations and sizes calculated are presented in Table 2 and represented graphically in Figures 2.

From Table 2 and Figure 2, it was observed that the changes in natural frequencies from the healthy state of the beam to the damaged state at the different crack location is very small and do not provide enough information to aid crack detection. They do not indicate the change in the natural frequencies clearly, hence for clear observation, these natural frequencies were re-arranged as given in Tables 3-6 for all cases for Mode 1 to Mode 4 respectively and also represented in the 3D plot as shown in Figures 3-6. In the 3D plot, x-axis, y-axis and z-axis represents the crack location, crack ratio and modes respectively.

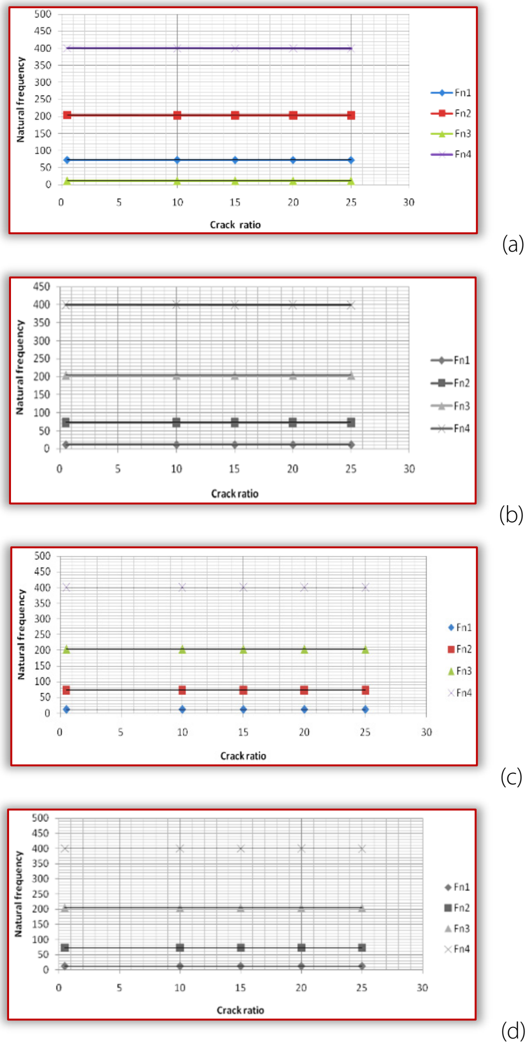


Figure 2. Natural frequencies vs crack ratio for the 4 different crack locations: a)x_c =50mm; b)x_c =250mm; c)x_c =450mm; d)x_c =650mm

Table 2: Changes in Natural Frequency at Different Crack Locations

Cases	Crack Location	Crack ratio (Cr)%	Natural frequency fn1 (Hz)	Natural frequency fn2 (Hz)	Natural frequency fn3 (Hz)	Natural frequency fn4 (Hz)
1	50	0	11.637	72.925	204.21	400.28
2	50	5	11.633	72.908	204.17	400.24
3	50	10	11.623	72.862	204.08	400.12
4	50	15	11.606	72.789	203.94	399.93
5	50	20	11.585	72.694	203.75	399.96
6	50	25	11.559	72.579	203.53	399.41
7	250	0	11.637	72.925	204.21	400.28
8	250	5	11.634	72.908	204.19	400.23
9	250	10	11.629	72.862	204.16	400.08
10	250	15	11.619	72.789	204.10	399.84
11	250	20	11.607	72.694	204.02	399.54
12	250	25	11.592	72.579	204.02	399.17
13	450	0	11.637	72.925	204.21	400.28
14	450	5	11.636	72.918	204.19	400.28
15	450	10	11.633	72.897	204.12	400.27
16	450	15	11.628	72.865	203.03	400.25
17	450	20	11.622	72.822	203.90	400.24
18	450	25	11.615	72.771	203.75	400.22
19	650	0	11.637	72.925	204.21	400.28
20	650	5	11.636	72.912	204.20	400.23
21	650	10	11.635	72.874	204.19	400.08
22	650	15	11.634	72.816	204.17	399.84
23	650	20	11.632	72.739	204.15	399.54
24	650	25	11.629	72.646	204.11	399.17

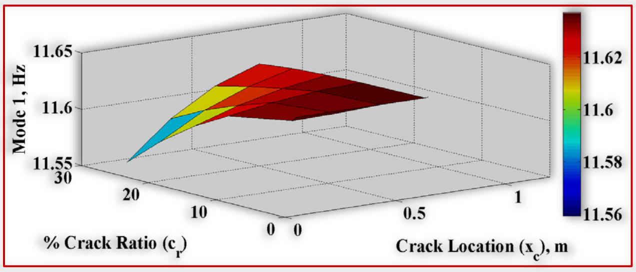


Figure 3. Variation of the first natural frequency with crack location and size

From Figure 3, it was observed that the highest frequency is the frequency of the beam at the healthy state whereas the lowest natural frequency occurs at the point when the crack is located at 50mm of the beam length with a crack ratio of 20%. The difference between the two natural frequencies is: 11.635 – 11.606 = 0.031 Hz.

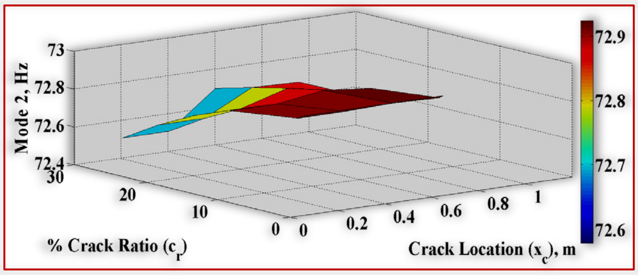


Figure 4. Variation of the second natural frequency with crack location and size

From Figure 4, it is observed that the highest frequency is the frequency of the beam at healthy state, whereas, the lowest natural frequency occurs at the point when the crack is located at 50mm of the beam length with a crack ratio is 25%. The difference between the two natural frequencies is: 72.925 – 72.579 = 0.346 Hz.

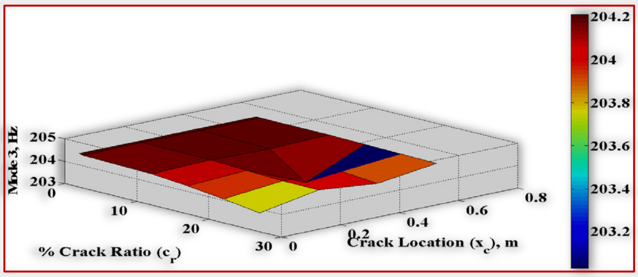


Figure 5. Variation of the third natural frequency with crack location and size

The highest frequency is the frequency of the beam at healthy state, whereas, the lowest natural frequency occurs at the point when the crack located at 450 mm of the beam length with a crack ratio is 15%. The difference between the two natural frequencies is: 204.21 – 203.03 = 1.18 Hz.

From Figure 6, it is observed that the highest frequency is the frequency of the beam at healthy state, whereas, the lowest natural frequency occurs at the point when the crack location is x_c = 250 mm and 650 mm and crack ratio is 25%. The difference between the two natural frequencies is: 73.00 – 71.89 = 1.11 Hz.

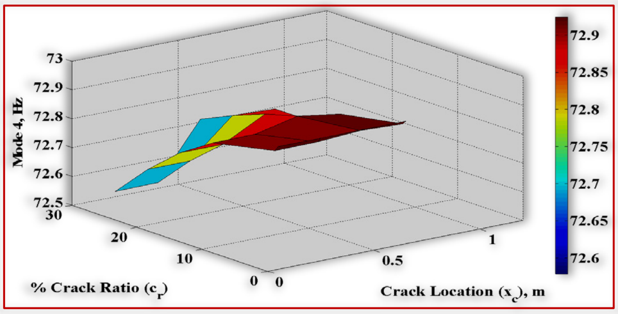


Figure 6. Variation of the fourth natural frequency with crack location and size

From the analysis of the natural frequencies, it was gathered that the changes in natural frequencies is very small (< 2Hz) and it is only noticeable at the fixed end of the beam. Hence, crack detection by changes in natural frequencies is not possible due to the insignificant changes in natural frequencies.

Table 3: The First Natural Frequency

Crack location, x_c Natural Freq. Hz Crack ratio	50mm fn_1	250mm fn_1	450mm fn_1	650mm fn_1
0	11.637	11.637	11.637	11.637
0.5	11.633	11.634	11.636	11.636
10	11.623	11.629	11.633	11.635
15	11.606	11.619	11.628	11.634
20	11.585	11.607	11.622	11.632
25	11.559	11.592	11.615	11.629

Table 4: Second Natural Frequency

Crack location, x_c Natural Freq Hz Crack ratio	50mm fn_2	250mm fn_2	450mm fn_2	650mm fn_2
0	72.925	72.925	72.925	72.925
0.5	72.908	72.908	72.918	72.912
10	72.862	72.862	72.897	72.874
15	72.789	72.789	72.865	72.816
20	72.694	72.694	72.822	72.739
25	72.579	72.579	72.771	72.646

Table 5: Third Natural Frequency

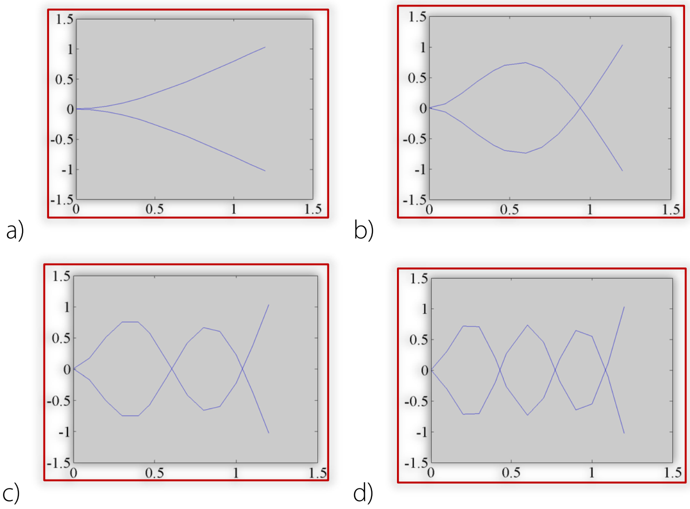
Crack location, x_c Natural Freq Hz Crack ratio	50mm fn_3	250mm fn_3	450mm fn_3	650mm fn_3
0	204.21	204.21	204.21	204.21
0.5	204.17	204.19	204.19	204.20
10	204.08	204.16	204.12	204.19
15	203.94	204.10	203.03	204.17
20	203.75	204.02	203.90	204.15
25	203.53	204.02	203.75	204.11

Table 6: Fourth Natural Frequency

Crack location, x_c Natural Freq Hz Crack ratio	50mm fn_4	250mm fn_4	450mm fn_4	650mm fn_4
0	400.28	400.28	400.28	400.28
0.5	400.24	400.23	400.28	400.23
10	400.12	400.08	400.27	400.08
15	399.93	399.84	400.25	399.84
20	399.96	399.54	400.24	399.54
25	399.41	399.17	400.22	399.17

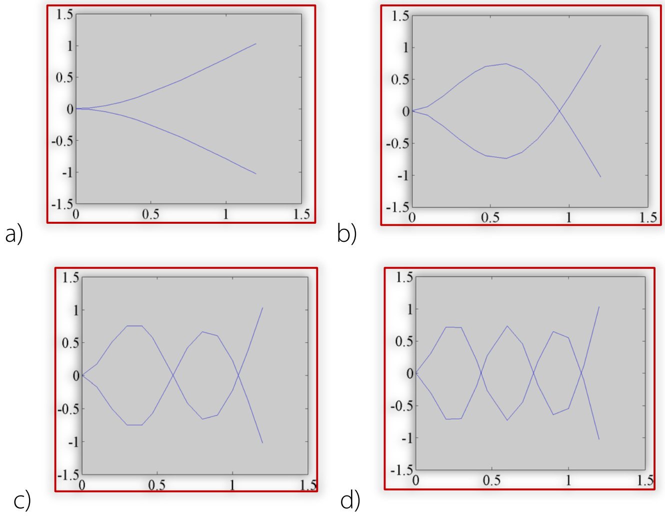
MODE SHAPES

Few typical mode shapes are shown in Figures 7-9 for 3 different cases: Case 1, 8, and 15.



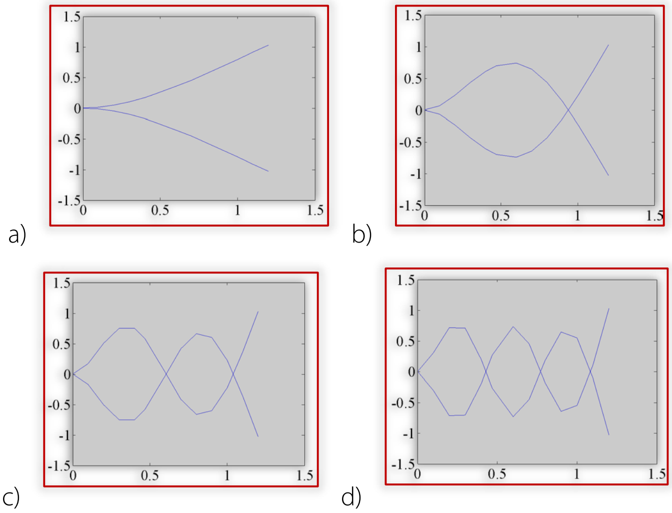
a) b) c) d)

Figure 7. Mode shape for Case 1 (Healthy): (a) Mode shape 1; (b) Mode shape 2; (c) Mode shape 3; (d) Mode Shape 4



a) b) c) d)

Figure 8. Mode shape for Case 8 ($x_c = 250$mm, $c_r = 5\%$): (a) Mode shape 1; (b) Mode shape 2; (c) Mode shape 3; (d) Mode Shape 4



a) b) c) d)

Figure 9. Mode shape for crack case 15 ($x_c = 450$mm, $c_r = 10\%$): (a) Mode shape 1; (b) Mode shape 2; (c) Mode shape 3; (d) Mode Shape 4

ACCELERATION RESPONSE

The changes in the natural frequencies and mode shapes were insignificant which makes detection of crack location and size difficult using this method. Hence, there was need to explore other methods of crack detection. The simulation is carried out for both the healthy state (Case 1) and for crack in different locations (Case 8, 15 and 22) as presented in Table 7, for which comparisons between the healthy and faulty states were made from Figures 10-13.

Table 7: The four cases used for further analysis

Case	Crack location (x_c)mm	Crack ratio (C_r) %
1	50	0
8	250	5
15	450	10
22	650	15

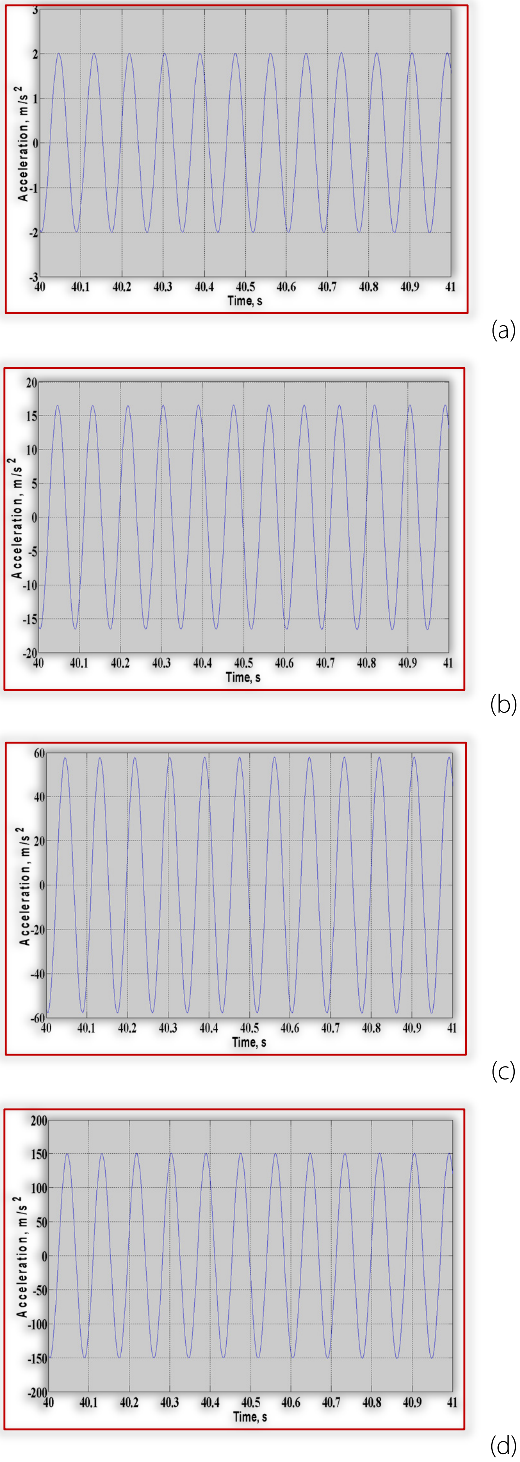


Figure 10. Acceleration Responses at different node for Case 1 (Healthy case): (a) Node 2; (b) Node 4; (c) Node 7; (d) Node 12

Since excitation is at first natural frequency, the time domain response shows an increase in acceleration across the beam towards its free end and there is no distortion in the wave form.

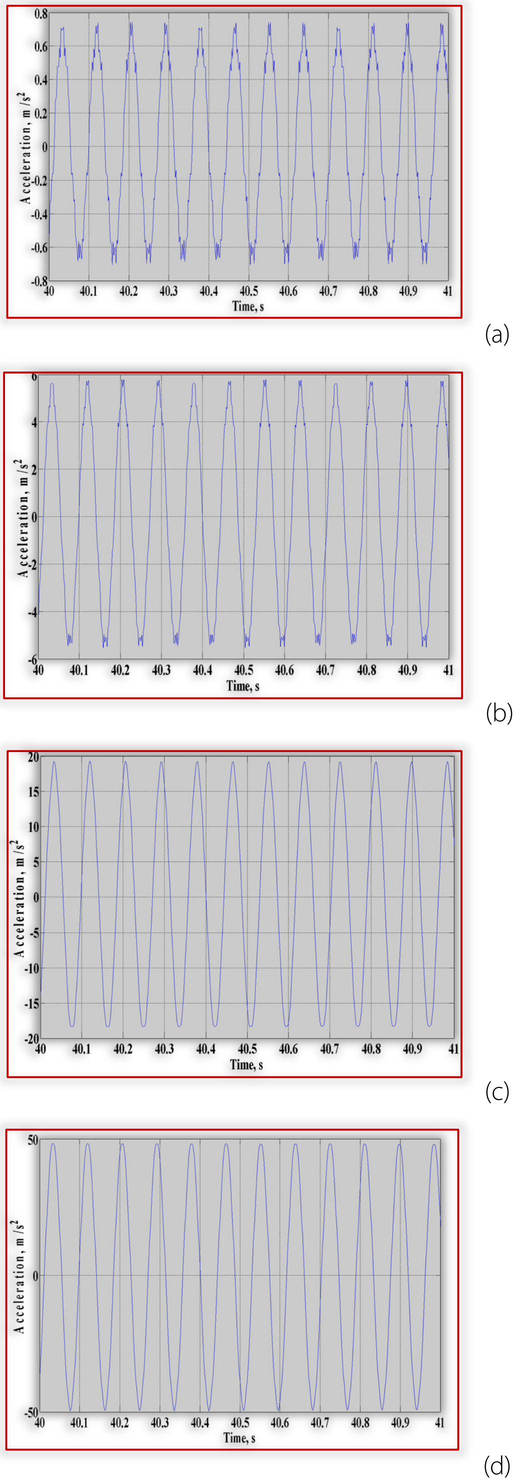


Figure 11. Acceleration Responses at different node for Case 8 (x_c = 250, c_r = 5%): (a) Node 2; (b) Node 4; (c) Node 7; (d) Node 12

A decrease in amplitude of acceleration along the beam is observed and a change in wave form for node 2 and 4 but not towards the free end (nodes 7 and 12).

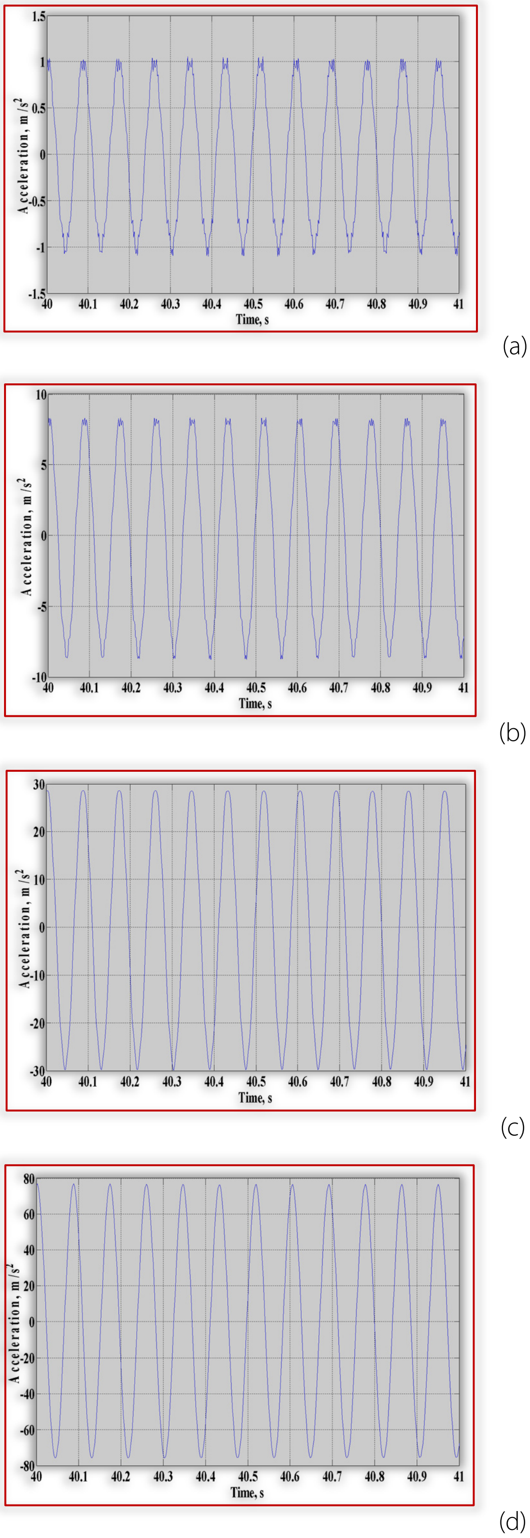


Figure 12. Acceleration Responses at different node for Case 15 (x_c = 450, c_r = 10%)): (a) Node 2; (b) Node 4; (c) Node 7; (d) Node 12

There (Figure 12) is a change in wave form for nodes 2 and 4 when compared with that of the healthy state but no visible change in wave form for nodes 7 and 12.

In the healthy state of the cantilever beam, the acceleration response was a pure sine wave as expected and since the excitation is at first natural frequency, the amplitude of the acceleration responses increasing from the fixed end to free end of the cantilever beam. Also, for the crack condition, amplitude pattern is the same; however, it seems to be less than that of the healthy state which is due to the presence of crack. The same changes were confirmed in the experiment carried out by [18]. Hence this method is capable of estimating the presence of cracks.

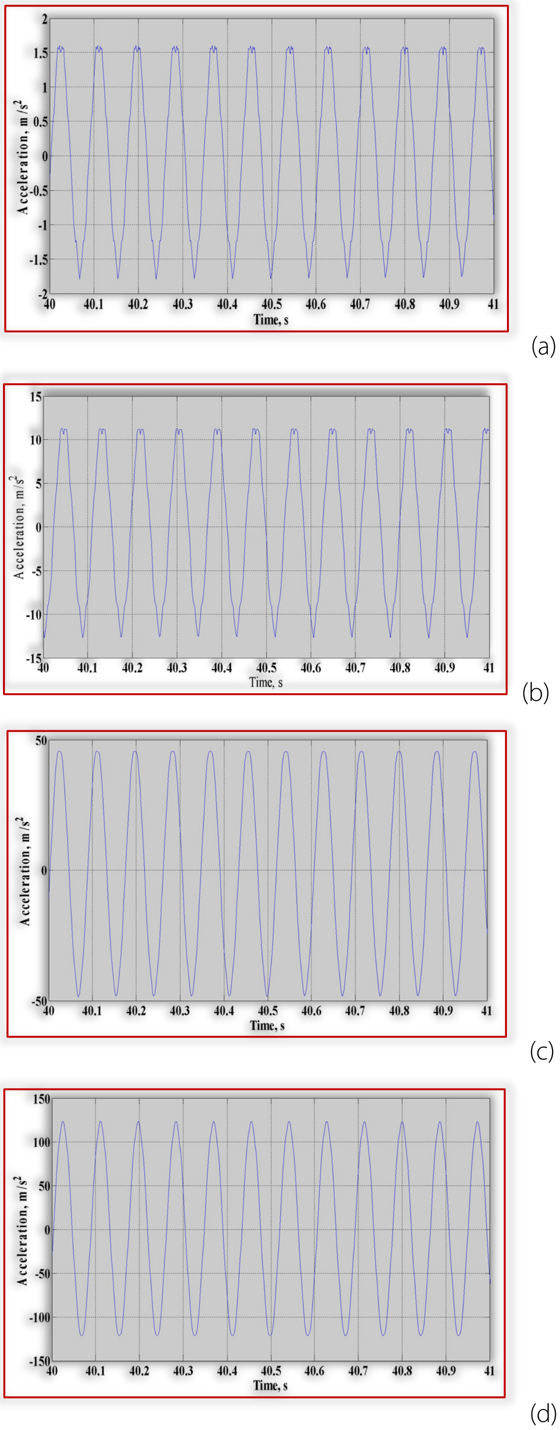


Figure 13. Acceleration Responses at different nodes for Case 22 (x_c = 650, c_r = 15%)): (a) Node 2; (b) Node 4; (c) Node 7; (d) Node 12

CONCLUSION

Using the natural frequencies, mode shapes and time domain acceleration responses, it was observed that the changes in natural frequencies from the healthy state of the beam to the damaged state at the different crack location were very small and do not provide enough information to aid crack detection. Representing the changes in 3D plot, changes in natural frequencies were very small and it was only noticeable at the fixed end of the beam. The mode shapes gave no significant change between the healthy and crack states of the beam. The presence of crack was detected without difficulty using the time domain acceleration changes as significant changes where noticed.

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