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Active Vibration Control of Smart Alluminium Beam

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ABSTRACT

This work focuses on the frequency determination of a cracked Aluminum Beam at various locations .The influence of the crack location on natural frequency is studied and an analytical approach is proposed for the modeling of a cracked Al Beam with varying crack size. Laser cutting is used for making crack on the Aluminum Beam. An experimental validation is carried out on FFT Analyzer and Spectra plus Software. This natural frequency is determined by using Euler Beam theory. When cracks are present in structure, natural frequencies are deviates from original frequency and result are validated by using FEA like ANSYS. The control on damage of natural frequency is done by applying Piezoelectric Patch on the beam at various locations.

Keywords: Natural Frequency, Piezoelectric Patch, FFT Analyzer.

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I. INTRODUCTION

Damage is one of the important aspects in structural analysis because of safety reason as well as economic growth of the industries. Generally damage in a structural element may occur due to normal operations, accidents, deterioration or severe natural events such as earth quake or storms. To achieve their industrial goal, now a days the plants as well as industries are running round the clock fully. 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. Thus, the importance of inspection in the quality assurance of manufactured products is well understood. To avoid the unexpected or sudden failure earlier crack detection is essential. This is basically appears in the vibrating structures while undergoes operations. The most common structural defect is the existence of a crack in machine member. The presence of a crack could not only cause a local variation in the stiffness but it could affect the mechanical behavior of the entire structure to a considerable extent. The presence of crack induces local flexibility, which affects the dynamic behavior of the whole structure as a result the reduction occurs in natural frequency and mode shape. By considering the changes in those parameters crack can be identified in terms of crack depth and crack location. Beams are one of the most commonly used structural elements in several engineering applications and experience a wide variety of static and dynamic loads. Cracks may develop in beam-like structures due to such loads. Considering the crack as a significant form of such damage, its modeling is an important step in studying the behavior of damaged structures. Knowing the effect of crack on stiffness, the beam or shaft can be modeled using either Euler-Bernoulli or Timoshenko beam theories. The beam boundary conditions are used along with the crack compatibility relations to derive the characteristic equation relating the natural frequency, the crack depth and location with the other beam properties.

Many different methods have been developed in the area of crack identification and repair. Generally these methods can be categorized into frequency domain and time domain methods. These groups may be subdivided into different areas depending on the parameters used or method performed in the damage detection process.

II. LITERTURE SURVEY

D. Srinivasarao et.al. [2010], presented a method for crack identification in beam structures by analyzing the fundamental mode of cracked cantilever beam using continuous wavelet transform. The crack in the beam is modeled as combination of spiral and linear springs and the coupling of bending and longitudinal vibration of cracked cantilever beam is considered. The viability of the method is investigated both analytically and experimentally in case of a cantilever beam containing a transverse surface crack .In the light of results obtained, the advantages and limitations of the work are presented and discussed. The applicability of this method for fault diagnosis is discussed.

Dayal R. Parhi and Sasanka Choudhury, [2011] explained the damage detection methods have been considerably increased over the past few decades. A crack in a structural member introduces local flexibility that would affect vibration response of the structure. This property may be used to detect existence of a crack together with its location and depth in the structural member. The presence of damage leads to changes in some of the lower natural frequencies and mode shapes.

K. B. Waghulde and Dr. Bimlesh Kumar, [2011] have studied the smart structures and smart materials. These materials have been an emerging area of research for last few decades. A smart structure would be able to sense the vibration and generate a controlled actuation to it, so the vibration can be minimized. For this purpose, smart materials are used as actuators and sensors. In this paper, some literature review is given about smart structure and smart material. Piezoelectric material is used as smart material and cantilever beam is considered as a smart structure. Different positions are considered for the model analysis. In this case, the modal analysis is found out by using ANSYS and MATLAB.

K. B. Waghulde and Dr. Bimlesh Kumar, [2012] have studied, the locations of actuators and sensors over a structure determine the effectiveness of the controller in controlling vibrations. If we need to control a particular vibration mode, we have to place actuators and sensors in locations with high control. In many cases of vibration control, low frequency modes are considered to be important. Hence, we only need to consider a certain number of modes in the placement of actuators and sensors. We extended the methodology for finding optimal placement of general actuators and sensors over a flexible structure. For vibration analysis ANSYS software is used.

Malay Quila, et. al., [2014], studied that the presence of cracks causes changes in the physical properties of a structure which introduces flexibility, and thus reducing the stiffness of the structure with an inherent reduction in modal natural frequencies. Consequently it leads to the change in the dynamic response of the beam. This paper focuses on the theoretical analysis of transverse vibration of a fixed beam and investigates the mode shape frequency. All the theoretical values are analyzed with the numerical method by using ANSYS software and co relate the theoretical values with the numerical values to find out percentage error between them.

III.FINITE ELEMENT ANALYSIS OF CANTILEVER SMART BEAM

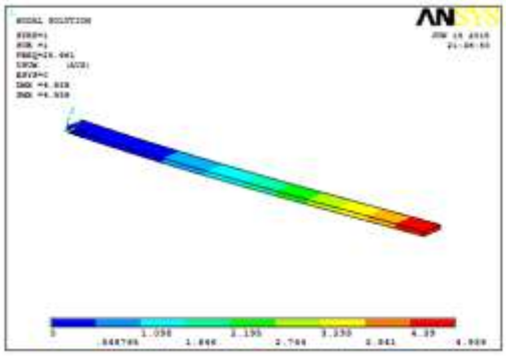
Finite Element Analysis is a mathematical representation of a physical system comprising a part/assembly (model), material properties, and applicable boundary conditions {collectively preferred to as pre-processing}, the solution of that mathematical representation {solving}, and the study of results of that solution {post-processing}.

The designing software used here is CATIA. The model of the beam having crack is generated in CAD software i.e. CATIA with different crack location and crack depth. The figures given below are the example of how models are generated in CATIA.

The model is prepared by using commercial FE software ANSYS. In ANSYS, the beam is modelled with a 2-D elastic beam element (BEAM3). Material properties are taken from the Table 1.

Dimensions/ Properties	AL	Piezoelectric actuator
Length	0.4 m	0.0762 m
Width	0.03 m	0.0254 m
Thickness	0.005 m	0.5×10^{-3} m
Density	2700 kg/m^3	7600 kg/m^3
Young modulus	70 Gpa	76 GPa
Poisson's ratio	0.3	---------
Piezoelectric Stain Constant	---------	-247×10^{-12} m/V

A unit step force is applied in the positive vertical direction at the tip of the beam. The Beam is considered to have three DOF, two translational and one rotational. Figure 1 shows mode shapes for the healthy model for beam.



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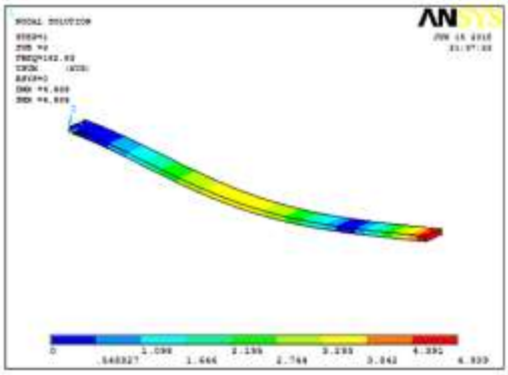

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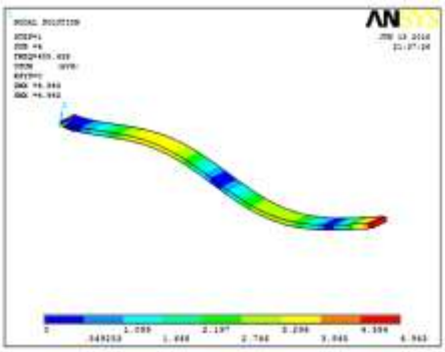


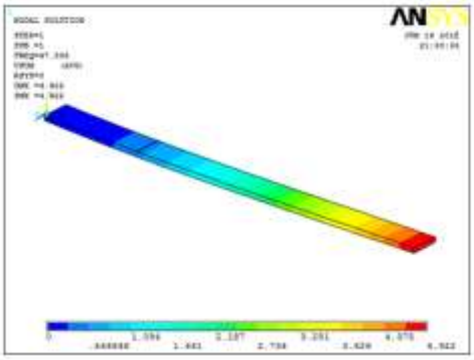
IIIrd Mode

Fig.1 Mode Shapes for Healthy Cantilever Beam Model

Table: 2 show the natural frequencies for healthy beam.

CRACK POSITION	DEPTH	NATURAL FREQUENCY				
		1st mode	2nd mode	3rd mode	4th mode	5th mode
		Ansys	Ansys	Ansys	Ansys	Ansys
UN-CRACKED	0mm	25.961	154.697	162.63	455.439	633.355

Figure 2, 3, & 4 shows mode shapes for the location at L1=0.1m, L2=0.2m, L1=0.1m and L2=0.2m (Combine) cracked model of 0.5mm depth for beam from cantilevered edge. Similar results and observations are found out for the cracks having depth 1.5, 2.5 and 3.5 mm. The results for all cases are compared in Table 3, 4 and 5.



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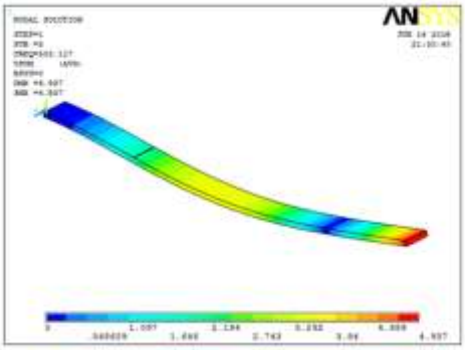

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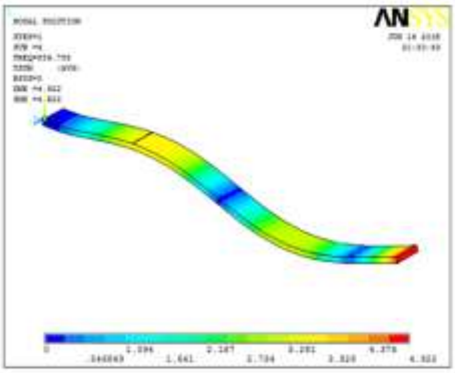
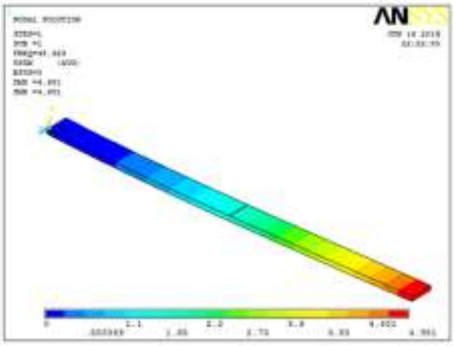


III rd Mode

Fig.2 Mode Shapes for 0.5mm crack for Cantilever Beam (L_1=0.1m)



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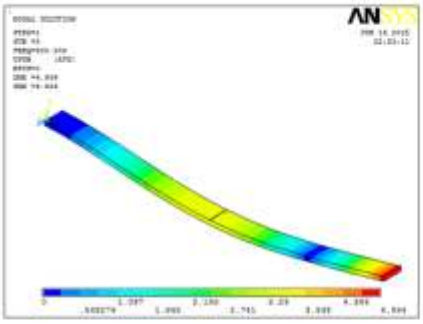
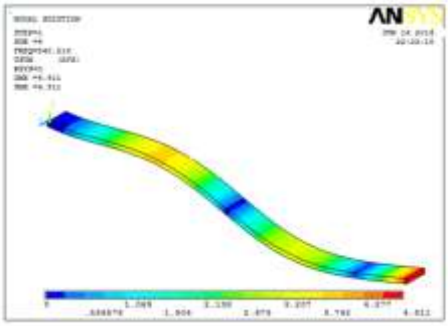
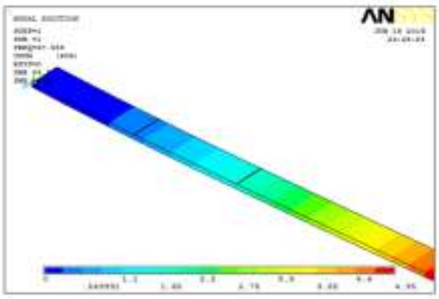


II nd Mode

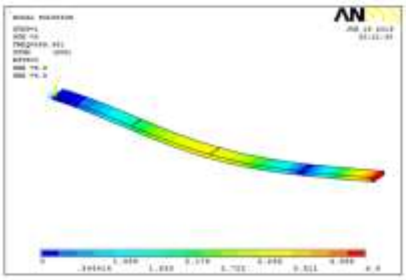


III rd Mode

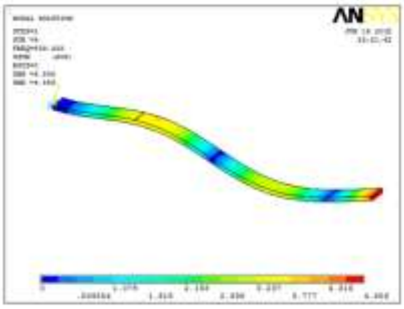
Fig.3 Mode Shapes for 0.5mm crack for Cantilever Beam (L_2=0.2m)



I st Mode



II nd Mode



III[rd] Mode

Fig.4 Mode Shapes for 0.5mm crack for Cantilever Beam (L_1=0.1m and L_2=0.2m)

Table-3 Natural Frequencies for Healthy Beam by FEM

CRACK POSITION	DEPTH	NATURAL FREQUENCY				
		1st mode	2nd mode	3rd mode	4th mode	5th mode
		Ansys	Ansys	Ansys	Ansys	Ansys
UN-CRACKED	0mm	25.961	154.697	162.63	455.439	633.355

Table-4 Natural Frequencies for different Crack Depth at L_1=0.1m by FEM

CRACK POSITION	DEPTH	NATURAL FREQUENCY				
		1st mode	2nd mode	3rd mode	4th mode	5th mode
		Ansys	Ansys	Ansys	Ansys	Ansys
200mm	0.5mm	48.423	157.86	300.302	840.216	963.867
	1.5mm	48.261	157.815	297.775	842.455	962.863
	2.5mm	47.929	157.67	289.661	842.165	959.155
	3.5mm	47.559	157.401	281.476	842.399	952.424

Table-5 Natural Frequencies for different Crack Depth at L_2=0.2m by FEM

CRACK POSITION	DEPTH	NATURAL FREQUENCY				
		1st mode	2nd mode	3rd mode	4th mode	5th mode
		Ansys	Ansys	Ansys	Ansys	Ansys
100mm	0.5mm	47.535	157.779	303.117	859.755	963.612
	1.5mm	47.35	157.746	301.355	845.284	963.848
	2.5mm	46.563	157.185	304.032	837.179	963.747
	3.5mm	45.102	156.207	303.655	819.38	963.421

Table-6 Natural Frequencies for different Crack Depth at L_1=0.1m and L_2=0.2m by FEM

CRACK POSITION	DEPTH	NATURAL FREQUENCY				
		1st mode	2nd mode	3rd mode	4th mode	5th mode
		Ansys	Ansys	Ansys	Ansys	Ansys
100mm & 200mm	0.5mm	47.955	157.838	299.451	839.335	963.865
	1.5mm	46.821	157.651	293.403	822.985	962.951
	2.5mm	45.621	156.954	287.825	816.566	958.931
	3.5mm	44.048	156.731	280.295	800.827	952.132

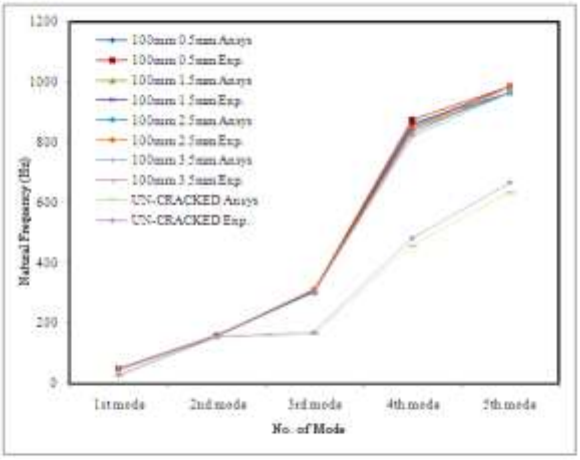


Fig.5 Comparison for Natural Frequencies for Healthy Beam with Crack Beam L1 = 100mm

The natural frequency obtained experimentally compared with FEM both the results was with close agreement. The variation between ANSYS results and Experimental results are due to different crack depth and crack distance. The fundamental mode shapes for vibration of cracked and un-cracked beams are plotted. The results obtained from the Experimental and FEA analysis are presented in graphical form. The first to fifth natural frequencies corresponding to various crack locations and depths are obtained.

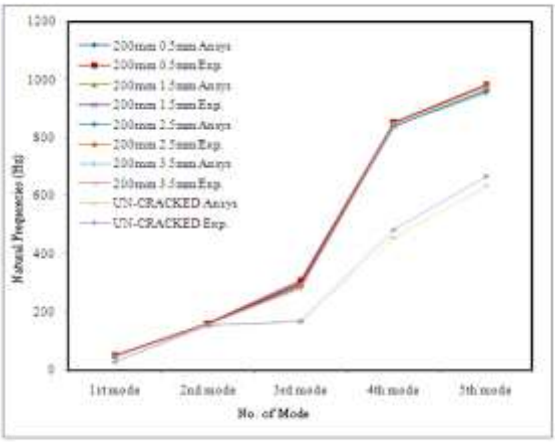


Fig.6 Comparison for Natural Frequencies for Healthy Beam with Crack Beam L2 = 200mm

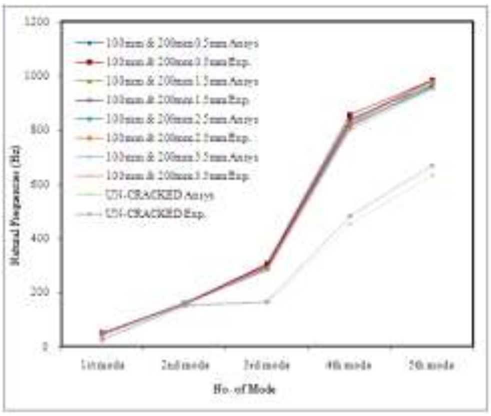


Fig.7 Comparison for Natural Frequencies for Healthy Beam with Crack Beam L_1 = 100mm and L_2 = 200mm

Experimental Analysis and Control of Cantilever Crack Beam:

In this case, a simple cantilever beam is tested for vibration analysis. The length, width and depth of the beam are taken as 0.4, 0.030 and 0.005 m, respectively. To actuate the beam, circular piezoelectric actuator is used and for sense the changes in the beam sensor is used.

The cracked and un-cracked aluminum beam is considered as a cantilever beam. The free end has been vibrated by using exciting actuator. The function of the actuator is to produce under control vibration on the beam and the nature of the vibration is depending upon the input signal form the function generator. Whatever will be the nature of the waveforms, similar kind of vibration is produced in the beam. The function generator is used to generate the desired wave form which can be either of sinusoidal, triangular or Square in nature. The frequency range can be adjusted and set anywhere between 1Hz to 1000 KHz but as the present amplifier has limitations so it can set the frequency between 1Hz to 5Khz. The frequency is high but the amplitude of the wave form is very low to produce any notable vibration in the beam. Therefore an amplifier is used to amplify the signal. The range of amplification can be varied using the knob provider at the amplifier but should not amplify more than the safe limit of the actuator. The procedure has been repeated for all other conditions for cracked and un-cracked beam to find out their natural frequencies. Figure 8 shows the frequency response curve for healthy cantilever beam. For cracked beam having 0.5mm depth at L1=0.1m, L2=0.2m, L1=0.1m and L2=0.2m, the frequency response curves are shown in following figures 9, 10 and 11. For cracked beam having different depth (0.5mm, 1.5mm, 2.5mm and 3.5mm) at L1=0.1m, L2=0.2m, L1=0.1m and L2=0.2m, the combine frequency response curves are shown in following figures 12, 13, and 14.

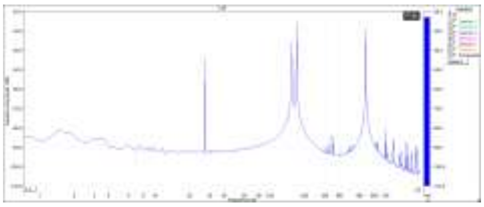


Fig. 8 Frequency Response Curve for Healthy Cantilever Beam

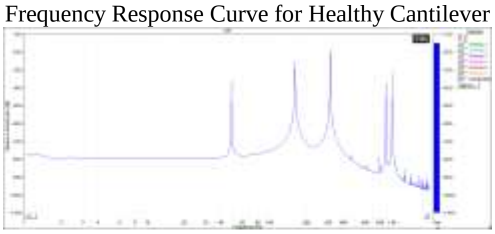


Fig. 9 Frequency Response Curve for L_1=0.1m having 0.5mm Depth

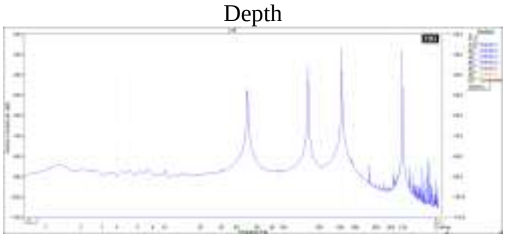


Fig. 10 Frequency Response Curve for L_2=0.2m having 0.5mm Depth

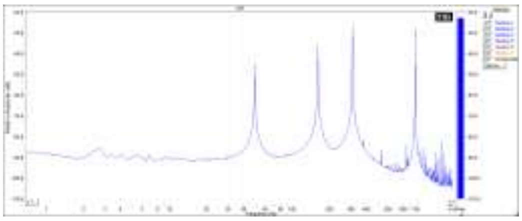


Fig. 11 Frequency Response Curve for L_1=0.1m and L_2=0.2m having 0.5mm Depth

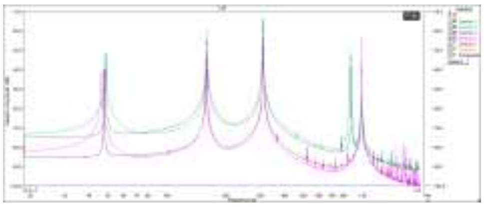


Fig. 12 Frequency Response Curve for L_1=0.1m having all Depth (0.5mm, 1.5mm, 2.5mm and 3.5mm)

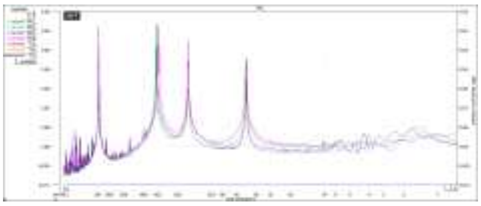


Fig. 13 Frequency Response Curve for L_2=0.2m having all Depth (0.5mm, 1.5mm, 2.5mm and 3.5mm)

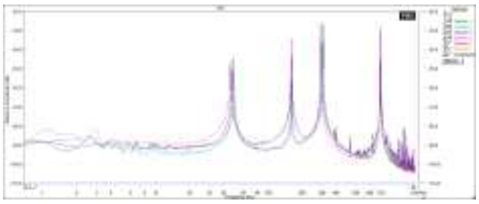


Fig. 14 Frequency Response Curve for L_1=0.1m and L_2=0.2m having all Depth (0.5mm, 1.5mm, 2.5mm and 3.5mm)

Table 7 shows the natural frequencies for healthy beam by experimental method. The results for all cases are compared in Table 8, 9, and 10.

Table 7 Natural Frequencies for Healthy Beam by Experimental

CRACK POSITION	DEPTH	NATURAL FREQUENCY				
		1st mode	2nd mode	3rd mode	4th mode	5th mode
		Exp.	Exp.	Exp.	Exp.	Exp.
UN-CRACKED	0mm	27.10	152.83	168.42	481.93	667.36

Table-8 Natural Frequencies for Different Crack Depth at L_1=0.1m by Experimental

CRACK POSITION	DEPTH	NATURAL FREQUENCY				
		1st mode	2nd mode	3rd mode	4th mode	5th mode
		Exp.	Exp.	Exp.	Exp.	Exp.
100mm	0.5mm	48.43	158.97	308.42	875.24	983.59
	1.5mm	48.24	158.94	306.66	852.76	983.83
	2.5mm	47.45	158.38	309.33	844.66	983.73
	3.5mm	45.99	157.40	308.96	826.86	983.40

Table-9 Natural Frequencies for Different Crack Depth at L_2=0.2m by Experimental

CRACK POSITION	DEPTH	NATURAL FREQUENCY				
		1st mode	2nd mode	3rd mode	4th mode	5th mode
		Exp.	Exp.	Exp.	Exp.	Exp.
200mm	0.5mm	49.31	159.05	305.60	855.70	983.85
	1.5mm	49.15	159.01	303.08	849.94	982.84
	2.5mm	48.82	158.86	294.96	849.65	979.14
	3.5mm	48.45	158.59	286.78	849.88	972.40

Table-10 Natural Frequencies for different Crack Depth at L_1=0.1m and L_2=0.2m by Experimental

CRACK POSITION	DEPTH	NATURAL FREQUENCY				
		1st mode	2nd mode	3rd mode	4th mode	5th mode
		Exp.	Exp.	Exp.	Exp.	Exp.
100mm & 200mm	0.5mm	48.85	159.03	304.75	854.82	983.85
	1.5mm	47.71	158.84	298.70	830.47	982.93
	2.5mm	46.51	158.14	293.13	824.05	978.91
	3.5mm	44.94	157.92	285.60	808.31	972.11

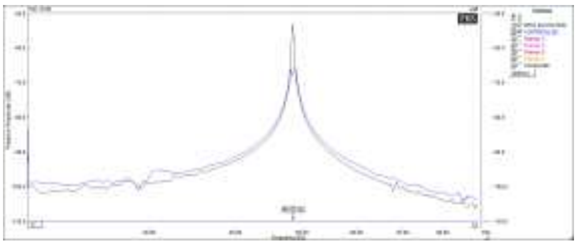
Repair of Cracked Beam using Piezoelectric Patch:

An elasticity-based approach for modeling the strain transfer from the piezo-actuator to the substrate beam through an adhesive layer. They assumed a uniform strain within the actuator and a pure one-dimensional shear strain state within the adhesive layer.

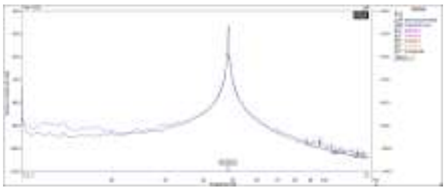
Vibration Control of Cracked beam by using PZT Actuator and LQG Controller:

The effect of position of actuator at different locations for controlling the amplitude of vibration of the cracked beam is tested using simulations (FEM) and experimental methods. The location of the sensor has been fixed throughout the simulation, where the actuators are placed at different locations.

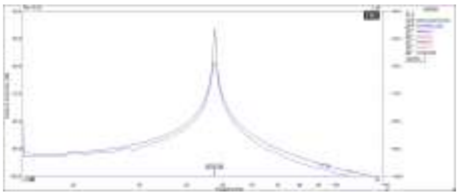
Figures 15, shows the frequency response curves for open loop and closed loop system. It is clearly seen that for closed loop system the resonance of modes are reduced as compared to open loop system.



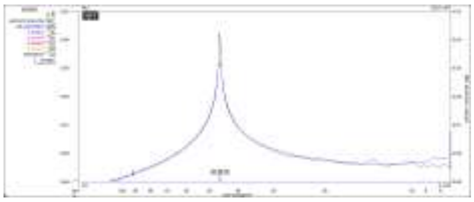
A) For crack Depth 0.5mm at L_1=0.1m



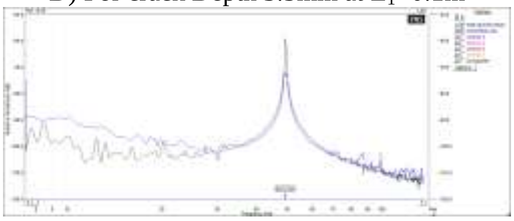
B) For crack Depth 1.5mm at L_1=0.1m



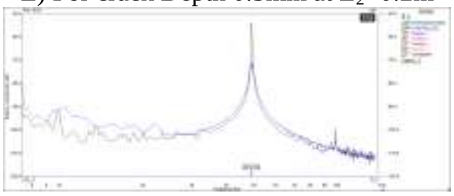
C) For crack Depth 2.5mm at L_1=0.1m



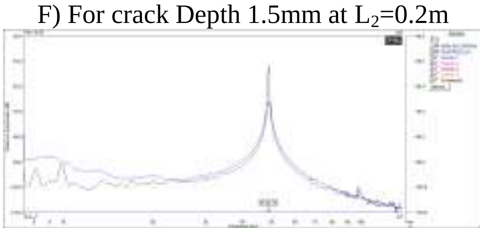
D) For crack Depth 3.5mm at L_1=0.1m



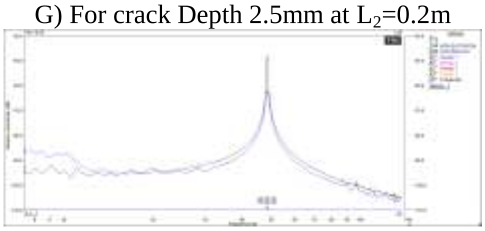
E) For crack Depth 0.5mm at L_2=0.2m



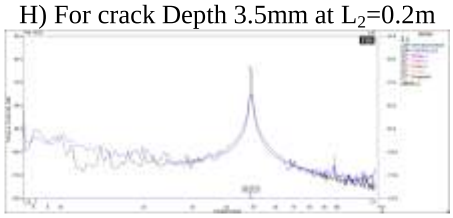
F) For crack Depth 1.5mm at L_2=0.2m



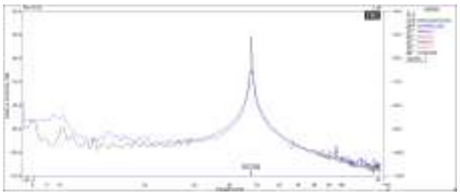
G) For crack Depth 2.5mm at L_2=0.2m



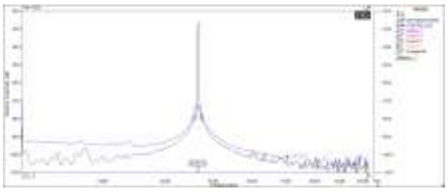
H) For crack Depth 3.5mm at L_2=0.2m



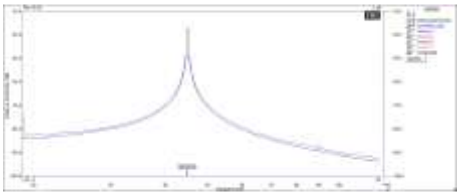
I) For crack Depth 0.5mm at L_1=0.1m and L_2=0.2m



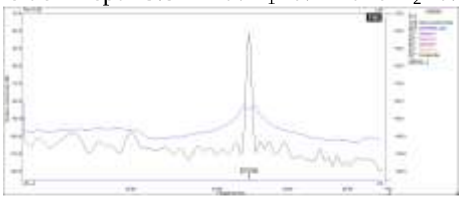
J) For crack Depth 1.5mm at L_1=0.1m and L_2=0.2m



K) For crack Depth 2.5mm at L_1=0.1m and L_2=0.2m



L) For crack Depth 3.5mm at L_1=0.1m and L_2=0.2m



M) For Healthy Beam

Fig. 15 The Frequency Response Curves for Open Loop and Closed Loop System

IV. RESULTS

I have compared the results of Finite Element Method with Experimental method for natural frequencies at first five modes. Following tables and graphs shows the variation of FEM with Experimental for all positions with all crack depth.

CRACK POSITION	DEPTH	NATURAL FREQUENCY					
			1st mode	2nd mode	3rd mode	4th mode	5th mode
100mm	0.5mm	Ansys	47.535	157.779	303.117	859.755	963.612
		Exp.	48.43	158.97	308.42	875.24	983.59
	1.5mm	Ansys	47.35	157.746	301.355	845.284	963.848
		Exp.	48.24	158.94	306.66	852.76	983.83
	2.5mm	Ansys	46.563	157.185	304.032	837.179	963.747
		Exp.	47.45	158.38	309.33	844.66	983.73
	3.5mm	Ansys	45.102	156.207	303.655	819.38	963.421
		Exp.	45.99	157.40	308.96	826.86	983.40
UN-CRACKED		Ansys	25.961	154.697	162.63	455.439	633.355

Table 11. Natural Frequencies for position of crack at L_2=0.2m

CRACK POSITION	DEPTH	NATURAL FREQUENCY					
			1st mode	2nd mode	3rd mode	4th mode	5th mode
200mm	0.5mm	Ansys	48.423	157.86	300.302	840.216	963.867
		Exp.	49.31	159.05	305.60	855.70	983.85
	1.5mm	Ansys	48.261	157.815	297.775	842.455	962.863
		Exp.	49.15	159.01	303.08	849.94	982.84
	2.5mm	Ansys	47.929	157.67	289.661	842.165	959.155
		Exp.	48.82	158.86	294.96	849.65	979.14
	3.5mm	Ansys	47.559	157.401	281.476	842.399	952.424
		Exp.	48.45	158.59	286.78	849.88	972.40
UN-CRACKED		Ansys	25.961	154.697	162.63	455.439	633.355
		Exp.	27.10	152.83	168.42	481.93	667.36

Table 12. Natural Frequencies for position of crack at L_1=0.1m and L_2=0.2m

CRACK POSITION	DEPTH	NATURAL FREQUENCY					
			1st mode	2nd mode	3rd mode	4th mode	5th mode
100mm & 200mm	0.5mm	Ansys	47.955	157.838	299.451	839.335	963.865
		Exp.	48.85	159.03	304.75	854.82	983.85
	1.5mm	Ansys	46.821	157.651	293.403	822.985	962.951
		Exp.	47.71	158.84	298.70	830.47	982.93
	2.5mm	Ansys	45.621	156.954	287.825	816.566	958.931
		Exp.	46.51	158.14	293.13	824.05	978.91
	3.5mm	Ansys	44.048	156.731	280.295	800.827	952.132
		Exp.	44.94	157.92	285.60	808.31	972.11
UN-CRACKED		Ansys	25.961	154.697	162.63	455.439	633.355
		Exp.	27.10	152.83	168.42	481.93	667.36

Table 13 Amplitude of Tip Displacement for Open Loop and Closed Loop System

CRACK POSITION	0.5mm		1.5mm		2.5mm		3.5mm	
	excited	controlled	excited	controlled	excited	controlled	excited	controlled
0mm	-42.01	-81.65	-42.01	-81.65	-42.01	-81.65	-42.01	-81.65
100mm	-52.42	-66.28	-50.23	-63.52	-44.28	-57.70	-40.50	-52.71
200mm	-57.21	-71.23	-53.11	-70.99	-50.12	-65.35	-46.49	-61.63
100 & 200 mm	-60.43	-74.38	-54.40	-69.50	-31.18	-76.15	-40.70	-53.46

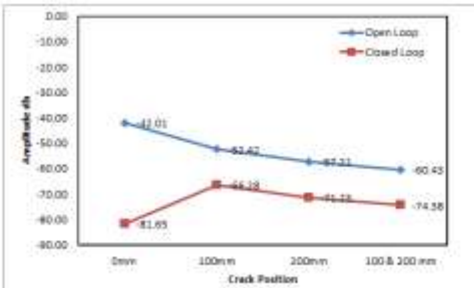


Fig. 16 Tip Displacement for Open Loop and Closed Loop System for 0.5mm Crack Depth

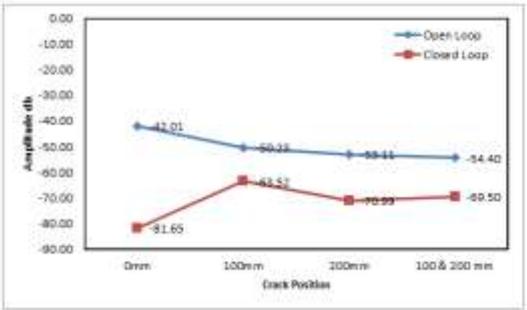


Fig. 17 Tip Displacement for Open Loop and Closed Loop System for 1.5mm Crack Depth

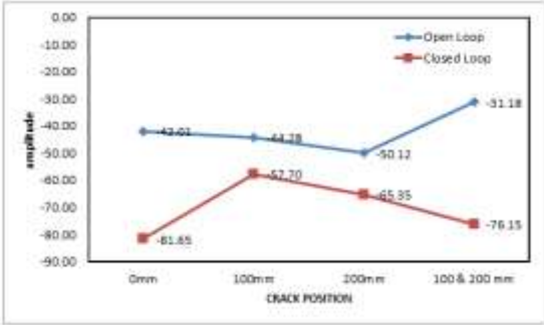


Fig. 18 Tip Displacement for Open Loop and Closed Loop System for 2.5mm Crack Depth

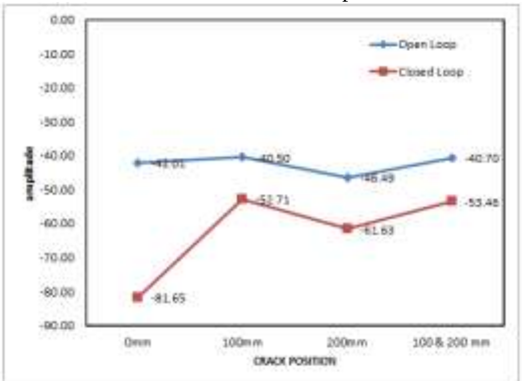


Fig. 19 Tip Displacement for Open Loop and Closed Loop System for 3.5mm Crack Depth

From figure 16 to 17, it is clear that when the system is excited by piezoelectric patch for open loop system, the amplitude of vibration observed is much more as shown in the figures. But when the same system is excited with piezoelectric patch for closed loop system with LQG controller, the amplitude of vibration decreases which shows that the smart materials with controller can be utilize for controlling the amplitude of vibration.

V. CONCLUSION

In aluminium cantilever beam with one end fixed and one end free, it was seen that the results were in good co-ordinance with FEA by ANSYS and Experimental by spectra plus software values. It is seen that the natural frequency changes substantially due to the presence of cracks. The changes depending upon the location and depth of cracks. In the FEA and Experimental setup, crack depth and crack location are taken as the input and the structural natural frequencies are taken as output. From the both methods, it is observed that the first natural frequency increases as the crack location moves from the clamped end to the free end when the crack depth is kept constant. Whereas, the second to fifth natural frequencies decreases as the crack depth increases. Also it is seen that,

1. The frequencies of vibration of cracked beams decrease with increase of crack depth for crack at any particular location due to reduction of stiffness.
2. The effect of crack is more pronounced near the fixed end than at far free end.
3. The natural frequency decreases with increase in relative crack depth.
4. The position of the cracks can be predicted from the deviation of the fundamental modes between the cracked and un-cracked beam.

The results obtained are expected to be useful to other researchers for comparison. The study in this work is also necessary for a correct and thorough understanding of the Vibration analysis techniques.

With the purpose of active vibration suppression of the smart beam, piezoelectric sensor and actuator pair are used to sense the disturbance of the smart beam and counteract to suppress the disturbance with the designed LQG controller. The results of the active vibration control experiments proved that piezoelectric sensor/actuator pair is an effective sensor and actuator configuration for active vibration control to reduce the amplitude of vibration for closed loop system.

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