KAUNAS UNIVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING AND DESIGN

Robert Vilayil Mathew

CRACK DETECTION IN CANTILEVER TYPE TOOLS

Final project for Master degree

Supervisor
Assoc. Prof. Dr. Inga Skiedraite

KAUNAS, 2015

KAUNO TECHNOLOGIJOS UNIVERSITETAS
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Robert Vilayil Mathew

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Magistro baigiamasis darbas

Vadovas
Doc. dr. Inga Skiedraite

KAUNAS, 2015

KAUNAS UNIVERSITY OF TECHNOLOGY
FACULTY OF MECHANICAL ENGINEERING AND DESIGN
DEPARTMENT OF MECHANICAL ENGINEERING

CRACK DETECTION IN CANTILEVER TYPE TOOLS

Final project for Master degree
Mechanical Engineering (code 621H30001)

Supervisor
Assoc. Prof. Dr. Inga Skiedraite

Reviewer
Lect. Dr. Darius Mažeika

Project made by
Robert Vilayil Mathew

KAUNAS, 2015

KAUNAS UNIVERSITY OF TECHNOLOGY
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(Student's name, surname)
Mechanical Engineering code 621H30001
(Title and code of study programme)

DECLARATION OF ACADEMIC HONESTY

2015 JUNE ____
Kaunas

I confirm that a final project by me, **Robert Vilayil Mathew**, on the subject "Crack detection in cantilever type tools" is written completely by myself; all provided data and research results are correct and obtained honestly. None of the parts of this thesis have been plagiarized from any printed or Internet sources, all direct and indirect quotations from other resources are indicated in literature references. No monetary amounts not provided for by law have been paid to anyone for this thesis.

I understand that in case of a resurfaced fact of dishonesty penalties will be applied to me according to the procedure effective at Kaunas University of Technology.

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KAUNAS UN IVERSITY OF TECHNOLOGY
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Approved:

Head of Mechanical Engineering Department

____
(Signature, date)

Vytautas Grigas
(Name, Surname)

BACHELOR STUDIES FINAL PROJECT TASK ASSIGNMENT
Study programme MECHANICAL ENGINERING

The final project of Bachelor studies to gain the bachelor qualification degree, is research or applied type project, for completion and defence of which 18 credits are assigned. The final project of the student must demonstrate the acquired knowledge and gained skills to formulate and solve an actual problem having limited and (or) contradictory information, independently conduct scientific or applied analysis and properly interpret data. By completing and defending the final project Bachelor studies student must demonstrate the creativity, ability to apply fundamental knowledge, understanding of social and commercial environment, Legal Acts and financial possibilities, show the information search skills, ability to carry out the qualified analysis, use numerical methods, applied software, common information technologies and correct language, ability to formulate proper conclusions.

1. Title of the Project

Crack Detection in Cantilever Type Tools

Approved by the Dean 2015 May 11d. Order No. **Nr. ST17-F-11-2**

2. Aim of the project

The aim of this project is to propose a method that can be used to detect the crack in machine tool by analysing its natural frequency

3. Structure of the project

Introduction, Aim, Objectives, Literature Review and Theoretical study on crack analysis, Experimental method and analysis, Numerical analysis of three dimensional beam employed with piezoelectric, Comparison of experimental and numerical results and result analysis, Conclusion, References, Appendix

4. Requirements and conditions

Requirements of project are piezo film sensors, data aquisition card and labVIEW software.

5. This task assignment is an integral part of the final project

6. Project submission deadline: 2015 June 1st.

Given to the student ___Robert Vilayil Mathew_________________________

Task Assignment received ____Robert Vilayil Mathew___ __________________
(*Name, Surname of the Student*) (*Signature, date*)

Supervisor ___Dr. Inga Skiedraite___ ___________________
(*Position, Name, Surname*) (*Signature, date*)

Vilayil Mathew Robert, “Crack detection in cantilever type machine tool”. Final master’s degree project / supervisor Assoc. Prof. Dr. Inga Skiedraite; Kaunas University of Technology, Faculty of Mechanical Engineering and Design, Department of Mechanical Engineering.

Kaunas, 2015. 45 p.

SUMMARY

The thesis objective is to investigate and propose a method that can be used to detect the crack in machine tool by analysing its natural frequency. Firstly the literature review of existing methods were done. Based on the existing methods, a new method was proposed and investigated, to detect the crack in machine tool, by conducting an experiment to analyse the difference in natural frequency on a cracked cantilever, with the help of piezo film sensor and data acquisition card. The data obtained from data acquisition card can be used for plotting natural frequency graphs in cantilever, with the help of LabVIEW software. By using ANSYS the same experiment is modelled. Finally the result obtained in experiment and modelling is compared.

Vilayil Mathew Robert. **Įtrūkio aptikimas gembinio tipo įrankiuose**. Magistro baigiamasis projektas / vadovas doc. dr. Inga Skiedraitė; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas, Mechanikos inžinerijos katedra.

Kaunas, 2015. 45 psl.

SANTRAUKA

Darbo tikslas yra ištirti ir pasiūlyti metodą, kuris nustatytų įrankių įtrūkimus, analizuojant jų savąjį dažnį. Pirmiausia atlikta literatūros apžvalga apie jau egzistuojančius metodus. Remiantis jais, buvo pasiūlytas naujas metodas ir ištirti įrankių įtrūkimai, analizuojant eksperimentiškai savitų dažnių skirtumus gembinio tipo įrankiuose su įtrūkiais, naudojantis pjezo jutikliu ir duomenų kaupimo kortelės pagalba. Gauti duomenys iš duomenų kaupimo kortelės gali būti naudojami braižant savito dažnio grafikus įtrukusioje gembėje LabVIEW programinės įrangos pagalba. Tas pats eksperimentas buvo sumodeliuotas, naudojant ANSYS programą. Gauti eksperimentų ir modeliavimo rezultatai palyginti.

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Introduction

Machine tool damage is one of the important problems during machining, tools may get broken due to fatigue. Cracks are among the most encountered damage types in the machine tools, tools are weakened by cracks. When the crack size increases in the course of time, the tool becomes weaker than its previous condition. Finally, the tool may break down due to a minute crack. Therefore, crack detection plays an important role in machine tool applications. Cracks are present in structures due to various reasons. Cracks may be caused by fatigue under service conditions as a result of the limited fatigue strength. The cracks may occur due to mechanical defects. Another group of cracks is initiated during the manufacturing processes. Generally they are small in sizes. Such small cracks are known to propagate due to fluctuating stress conditions. If these propagating cracks remain undetected and reach their critical size, then a sudden structural failure may occur. Hence it is possible to use natural frequency measurements todetect cracks [1].

Machine tools are generally cantilevered type because they are fixed at one end and force is applied at the other end. Metal cutting broadly constitutes turning, boring, drilling, facing, forming and parting-off, milling and shaping/planning. Cutting tools generally can be classed into two categories: single point tools (turning, shaping, and planning) which have one cutting part and a shank, while multiple tool points (drilling, milling, broaching) have more than one cutting parts. The execution of a machine instrument is inevitably surveyed by its capacity to create a segment of the obliged geometry in least time and at a little working expense. It is standard to base the basic configuration of any machine device essentially upon the prerequisites of static inflexibility and least regular recurrence of vibration [2]. This study mainly focuses on process like turning, shaping planning etc. which could be defined as a machining process for generating external surfaces by the action of a cutting tool on a rotating or reciprocating work piece, usually carried out on a lathe.

Crack in vibrating components causes a change in physical properties of a structure which in turn affects dynamic response characteristics. Therefore the analysis of the dynamic response characteristics helps to avoid any catastrophic failures and to follow structural integrity and performance. Crack damage is the one of the main reasons for the machine tool structure damage. The study on monitoring and identifying method of structure crack damage has caused wide attention. Ultrasonic, eddy current, magnetic powder and infrared detection method have made certain achievement on crack detection, but these methods are only applicable to static object detection [3]. The effects of cracks on structures and its property changes are discussed in several papers [4-6]. Machine tool damage analysis is to make sure that there is no damage in the tool during machining and to predict the breakage of the tool by identifying the appearance of small cracks in the tool during machining. Cracks in vibrating components can initiate catastrophic failures. Therefore, there is a need to understand the dynamics of cracked structures. When a structure suffers from damage, its dynamic properties can change [7]. Specifically, crack damage can cause a stiffness reduction, with an inherent reduction in natural frequencies, an increase in modal damping, and a change in the mode shapes. This inherent reduction in natural frequencies can be identified and presence of a crack formation can be detected. It is also possible that from these changes the crack position and magnitude can be identified. Since the reduction in natural frequencies can be easily observed, most researchers use this feature.

Aim

To propose a method that can be used to detect the crack in machine tool by analysing its natural frequency.

Objectives

1) To obtain a set of model analysis data of cracked structures such as beams with different crack location and different crack depth.

2) To model a cantilever beam employed with a piezoelectric sensor to find the natural frequency.

3) Conducting the experimental analysis of the above and then comparing the FEA result with the experimental result.

4) To propose a model or methodology for online machine tool damage prediction system.

1. Literature Review and Theoretical study on crack analysis

In the work Effect of crack on modal parameters of a cantilever beam subjected to vibration [8] by D.K. Agarwalla et. al, they have shown that Mode shapes and natural frequencies of the vibrating structures are susceptible to change under the influence of crack depth & crack location. Mode shapes in magnifying views allow the researchers to get an idea of the significant changes at the crack location. They had verified experimental results with the results obtained from cracked beam numerically.

Kaushar H. Barad et. al, in their work Crack detection in cantilever beam by frequency based method [9] they proved that damage detection can be done using natural frequency. Also from their work it is clear that crack with larger crack depth ratio (a/h) imparts greater reductions in natural frequency than that of the smaller crack depth ratio. Hence, the accuracy of results improves as crack depth increases. Crack present near to fixed end imparts greater reductions in natural frequency than that to present at away from the fixed end.

In 2005 a study by Bo-Wun Huang on The crack effect on instability in a machine tool spindle with gas bearings [10] they found that with gas bearings, the natural frequencies of a spindle system will decrease as the crack depth increases, especially for higher mode frequencies. The unstable zones of a spindle with gas bearings may broaden, as a crack exists in the spindle system. The effects of the provided air pressure and the crack location significantly change the dynamic instability of a spindle with gas bearings and the rotational speed will dramatically affect the dynamic instability of a spindle with gas bearings.

E. Douka et. al, in their work A method for determining the location and depth of cracks in double-cracked beams [11] they investigated the effect of two transverse open cracks on the mechanical impedance of a double-cracked cantilever beam both analytically and experimentally. They have proved that far from the expected changes in natural frequencies, the antiresonance frequencies change substantially. The changes follow definite trends depending upon the location and size of the cracks. Thus, antiresonance changes can be used as an additional information carrier for crack appearance which, complementary with natural frequency changes, can be used for crack identification.

D.E. Dimla Sr. et. al, in their work On-line metal cutting tool condition monitoring: force and vibration analyses [12] they have made an experimental tool wear monitoring method based on multivariate analysis of data acquired on-line from a turning process using two differently coated indexable inserts has been investigated and results are obtained, the result trend seem to suggest that the vertical components (*z*-direction) of both cutting forces and the vibration signatures were the most sensitive to tool wear, with nose wear being the most useful indicator of eminent tool failure.

In the article “Identification of crack location and magnitude in a cantilever beam from the vibration modes” by A D Dimarogonas [13] state that the position of crack can identify by vibration modes.

1.1 Classification of cracks

The dynamic response of a structure is normally determined by the physical properties, boundary conditions and the material properties. The depth, location, orientation and the number of crack influence the dynamic response of the structure. On the basis of geometry, cracks can be broadly classified into:

Transverse cracks - These cracks are perpendicular to the beam axis. Due to transverse cracks the cross-section of the structure got reduced and thus weakens the beam. Due to the reduction in the cross-section it introduces a local flexibility in the stiffness of the beam due to strain energy concentration in the vicinity of the crack tip [14].

Longitudinal cracks - The cracks are parallel to the beam axis. It is dangerous when tensile load is applied at right angles to the crack direction ie. perpendicular to beam axis or perpendicular to crack [14].

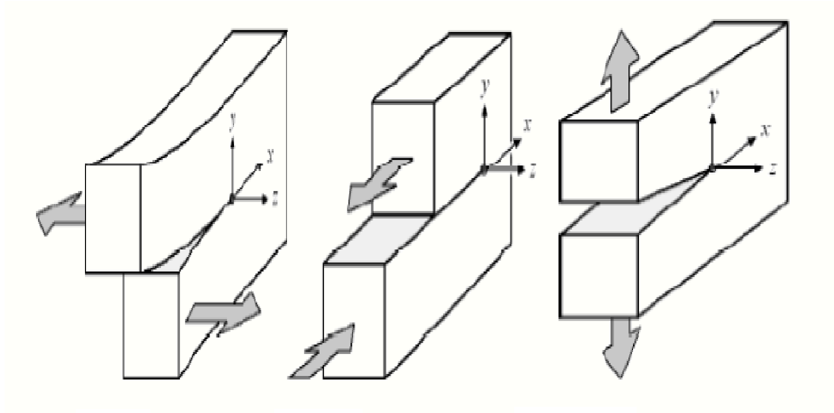
Slant cracks - These cracks are at an angle to the beam axis. It influences the torsional behavior of the beam. Their effect on lateral vibrations is less than that of transverse cracks of comparable severity [15].

Breathing cracks - These are the cracks that open when the affected part of the material is subjected to tensile stresses and close when the stress is reversed. When under tension the stiffness of the component is most influenced. A crack breathes when crack sizes are small, running speeds are low and radial forces are large [15].

Surface cracks - These are the cracks that open on the surface. These can be easily detected by dye-penetrations or visual inspection. Surface cracks have a greater effect than subsurface cracks on the vibration behavior of shafts [15].

1.2 Modes of fracture

The modes of cracks are shown in Fig. 1. The crack experiences three specific types of loading which are-



a b c

Figure 1 Three modes of cracks [16]

Mode 1: Fig. 1(a) represents the opening mode. In this opening mode the crack faces separates in a direction perpendicular to the plane of the crack and the respective displacements of crack walls are symmetric with respect to the crack front. Loading is perpendicular to the crack plane, and it has the tendency to open the crack. Generally Mode I is considered the most dangerous loading condition [16].

Mode 2: Fig. 1(b) represents the in-plane shear loading. In this one crack face tends to slide with respect to another (shearing mode). Here the stress is parallel to the crack growth direction [16].

Mode 3: Fig.1(c) represents the out-of-plane shear loading. Here the crack faces are sheared parallel to the crack front [16].

2. Experimental method and analysis

The natural frequency of beam varies when a crack formed in that. So the experiment is based on the frequency analyzing in cracked and non-cracked machine tool. The cracks or fractures in the machine tool changes the frequencies, amplitude of free vibration and dynamic stability areas to an inevitable extent [17]. In this experiment the effect of an open crack on the modal parameters of the cantilever beam subjected to free vibration is analyses by the help of piezoelectric sensors and the respectively connected data acquisition card. The labview software was used to produce the result in graphical form. The experiment was done at Musaliar College of Engineering and Technology, Pathanamthitta. The schematic diagram of the experiment is shown in Fig. 2.

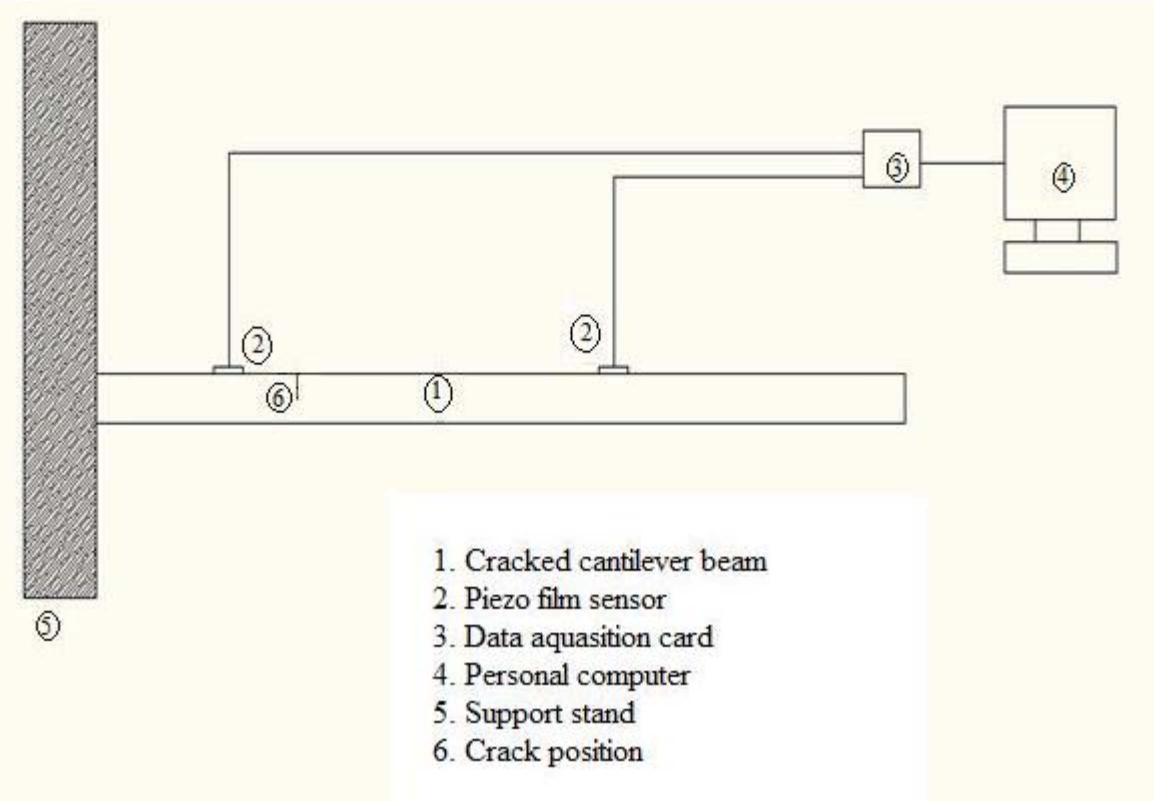


Figure 2 Schematic Diagram of Experimental Set Up

In this experiment, the machine tool which is going to test fixed on the support stand. One or two piezoelectric film sensors are overlapped on the machine tool. The number of sensors are depends upon the accuracy of the work. If two sensors are sing in the experiment which give more accurate result. But here in this experiment only one sensor is used for finding the natural frequency, it is because the experiment need to prove by numerical method. The sensor is connected one data acquisition card. The data acquisition card is used for converting the signals which receive from the sensors to the personal computer which is connected to the card. With the support of labview software the signals are analyses and produce the result. The experiment was done at Musaliar College of Engineering and Technology, Pathanamthitta. The experiment set up is shown in Fig.3.

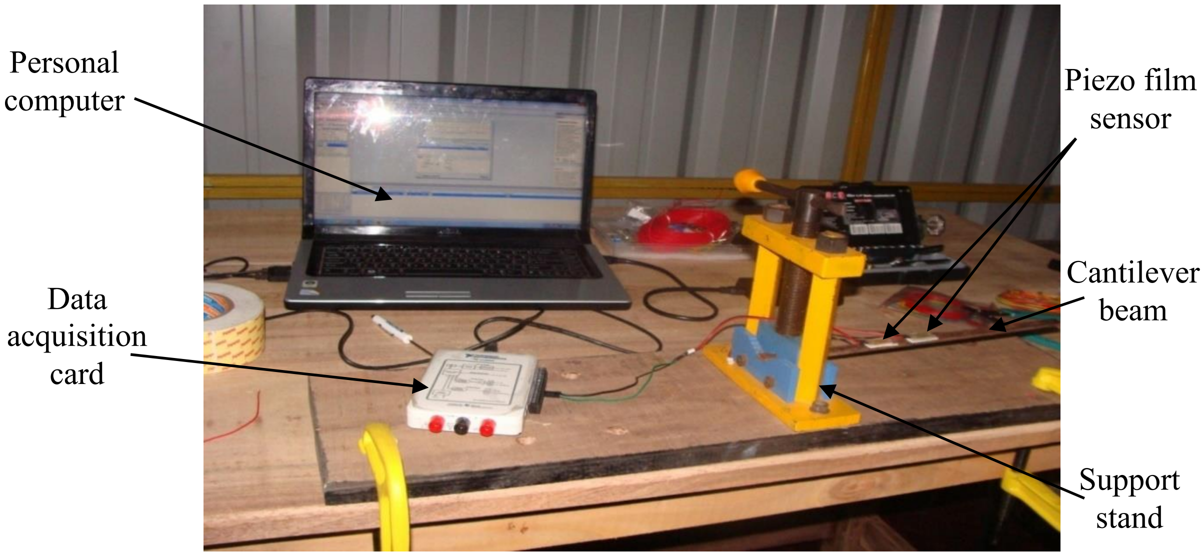


Figure 3 Experimental setup

The experiment conducted on Steel specimen (290mmx12mmx4mm) with transverse cracks for determining the natural frequencies and mode shapes for different crack depths. The material of the specimen was stainless steel with density of (7700 kg/m3), Young modulus (210 GPa) and Poisson's Ratio (0.3) [18]. Non-cracked beam is simply supported is shown in Fig.4.

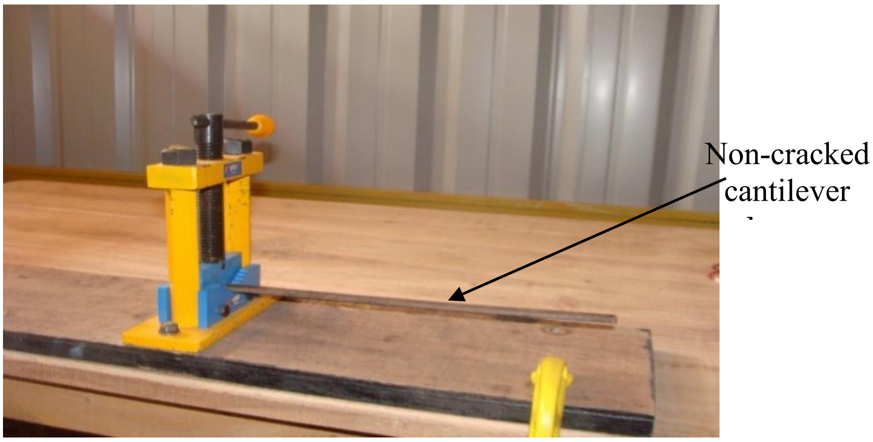


Figure 4 Non-cracked cantilever beam

As indicated earlier, for the experiment the speciment used is steel specimen with length 290 mm, Width 12 mm and having a height of 4 mm. The material, stainless steel having a density of 7700 kg/m3, Young modulus - 210 GPa and Poisson's Ratio - 0.3 [19]. The cracks to the made in the experiment are created by using a hacksaw blade. The support stand for the experiment is provided by using a pipe vice. G clamps are used in the experiment to firmly support the whole set up rigidly on the table. The piezo film sensors are attached to the beam by using double sided tape. The necessary excitation is supplied to the beam by using an impact hammer.

2.1 Piezo film sensor

Piezoelectric materials are ceramics or polymers which can produce a linear change of shape in response to an applied electric field. The direct piezoelectric effect consists of the ability of certain crystalline materials (i.e. ceramics) to generate an electrical charge in proportion of an externally applied force. The direct piezoelectric effect has been widely used in transducers design (accelerometers, force and pressure transducers etc.). Piezoelectric materials are extensively used in Shape control, Nano positioning, Noise and Vibration Suppression Systems, Lasers and optics, Ultrasonic Motors, Positioning Devices, Relays etc. The engineering advantages of piezoelectric materials include compact and lightweight, rapid response, low power consumption etc. [20]. The best known piezoceramic is the Lead Zirconate Titanate (PZT); it is widely used as actuator and sensor for a wide range of frequencies including ultrasonic applications; it is well suited for high precision as well. Piezopolymers are mainly used as sensors; the best known is the Polyvinylidene Fluoride (PVDF). When a poled piezoelectric ceramic is mechanically strained, it becomes electrically polarized, producing an electric charge on the surface of the material. This property is referred to as the "direct piezoelectric effect" and is the basis upon which the piezoelectric materials are used as sensors.

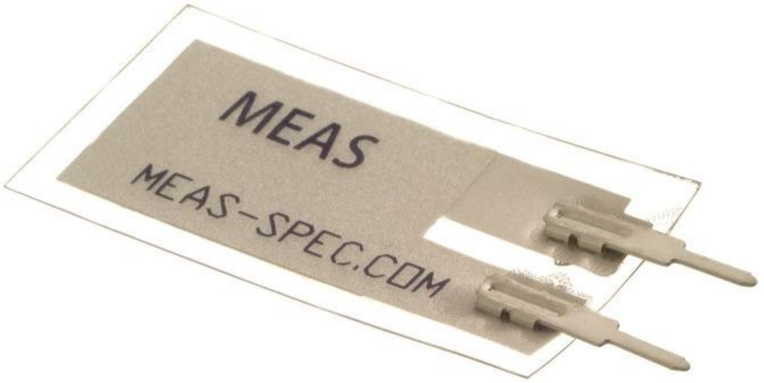


Figure 5 Piezo film sensor [21]

The LDT0-028K is a flexible component comprising a 28 μm thick piezoelectric PVDF polymer film with screen-printed Ag-ink electrodes, laminated to a 0.125 mm polyester substrate, and fitted with two crimped contacts [22]. As the piezo film is displaced from the mechanical neutral axis, bending creates very high strain within the piezo polymer and therefore high voltages are generated. When the assembly is deflected by direct contact, the device acts as a flexible "switch", and the generated output is sufficient to trigger MOSFET or CMOS stages directly. If the assembly is supported by its contacts and left to vibrate "in free space", the device will behave as an accelerometer or vibration sensor [22]. The LDTO-028 K piezo film sensor used in the experiment is shown in the Fig. 5.

LDT0 can be used as Vibration Sensor. With the crimped contacts pushed through a printed-circuit board, the LDT0 was soldered carefully in place to anchor the sensor. The photograph of the sensor used in the experiment is shown in Figure 6. Two piezo films sensors can be used in the experiments to get the most accurate results by taking the mean value of the indicated result.

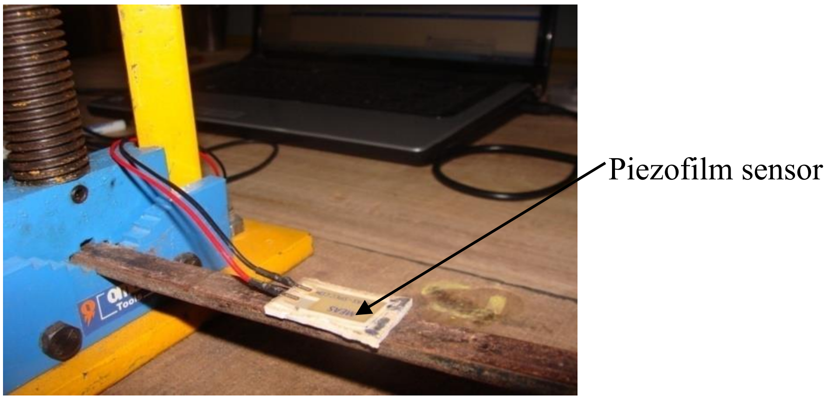


Figure 6 Piezo film sensor used in experiment

2.2 Data Acquisition Card

The data acquisition card used in the experiment is NI myDAQ [23], the photograph of which is displayed in Fig. 7. The output from the piezo film sensors passes through a data acquisition system, which processes the transducer signals and outputs the frequency response function between the input and the output. The data acquisition system includes a data acquisition box (DAQ) and a host computer which displays the data in real-time and provides a graphical-user interface (Labview software) [24]. NI myDAQ is a low-cost portable data acquisition (DAQ) device that uses NI LabVIEW-based software instruments allow to measure and analyze real-world signals. NI myDAQ is ideal for exploring electronics and taking sensor measurements. Combined with NI LabVIEW on the PC analyze and process acquired signals and control simple processes anytime, anywhere. NI myDAQ provides analog input (AI), analog output (AO), digital input and output (DIO), audio, power supplies, and digital multimeter (DMM) functions in a compact USB device [24].

Analog Input**:** There are two analog input channels on NI MyDAQ. These channels can be configured either as general-purpose high-impedance differential voltage input or audio input. The analog inputs are multiplexed; meaning a single analog-to-digital converter (ADC) is used to sample both channels. In general-purpose mode, you can measure up to ±10 V signals. In audio mode, the two channels represent left and right stereo line level inputs. Analog inputs can be measured at up to 200 kS/s per channel, so they are useful for waveform acquisition. Analog inputs are used in the NI ELVISmx Oscilloscope, Dynamic Signal Analyzer, and Bode Analyzer instruments [25].

Analog Output**:** There are two analog output channels on NI myDAQ. These channels can be configured as either general-purpose voltage output or audio output. Both channels have a dedicated digital-to-analog converter (DAC), so they can update simultaneously. In general-purpose mode, you can generate up to ±10 V signals. In audio mode, the two channels represent left and right stereo outputs [25].

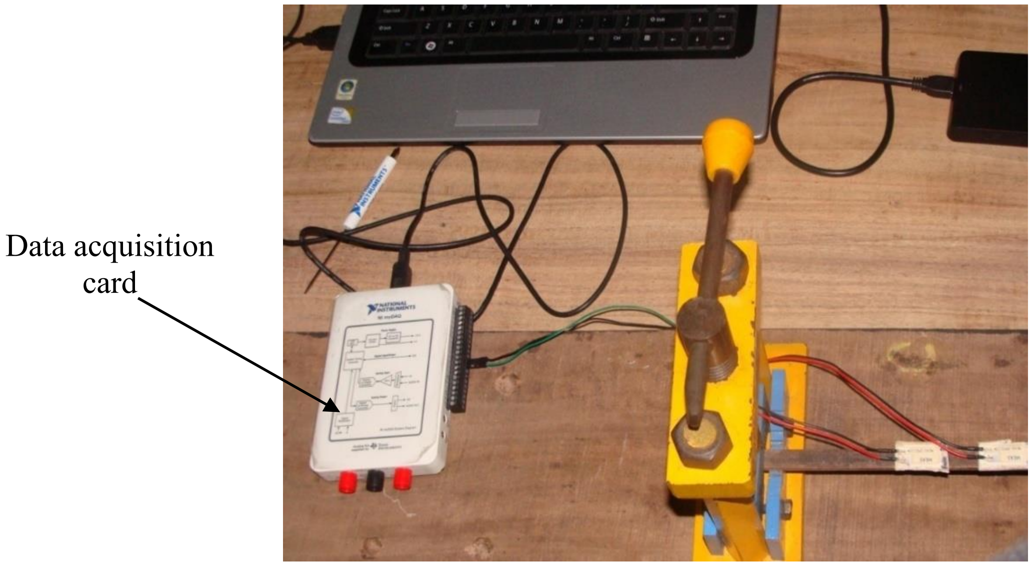


Figure 7 NI MyDAQ Used In the Experiment

Digital Input/Output (DIO)**:** There are eight DIO lines on NI myDAQ. Each line is a Programmable Function Interface (PFI), meaning that it can be configured as a general-purpose software-timed digit.al input or output, or it can act as a special function input or output for a digital counter [25]. Fig. 8-9 displays the various crack configurations that have been used in the experiment.

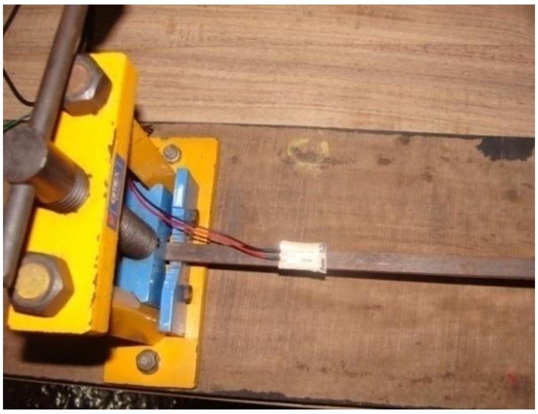


Figure 8 Non-cracked Beam

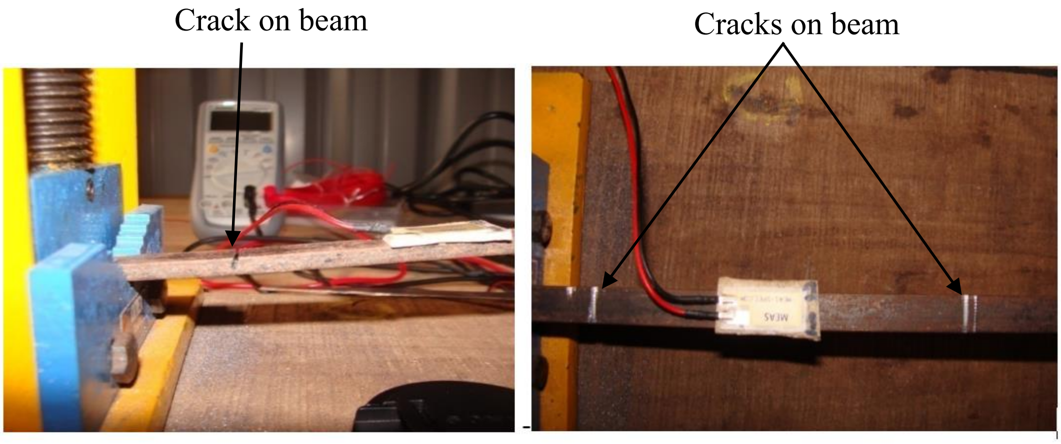
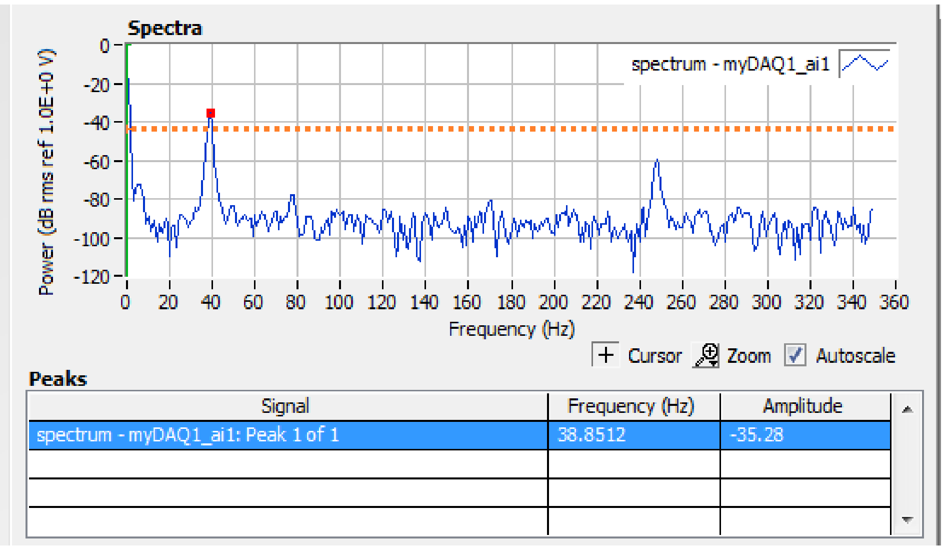


Figure 9 Single and Double cracked beams

The non-cracked and cracked beams both single and double cracked beams are arranged as shown in the Fig 8-9.

2.3 Experiment Results

These results correspond to different crack configuration used in the experiments shown in Fig. 10-15. Several sets of readings were taken for one particular cracked or non-cracked configuration and the average or more prominent results are taken. Frequency values are obtained from the piezo film sensors while giving an excitation to the beam with an impact hammer.



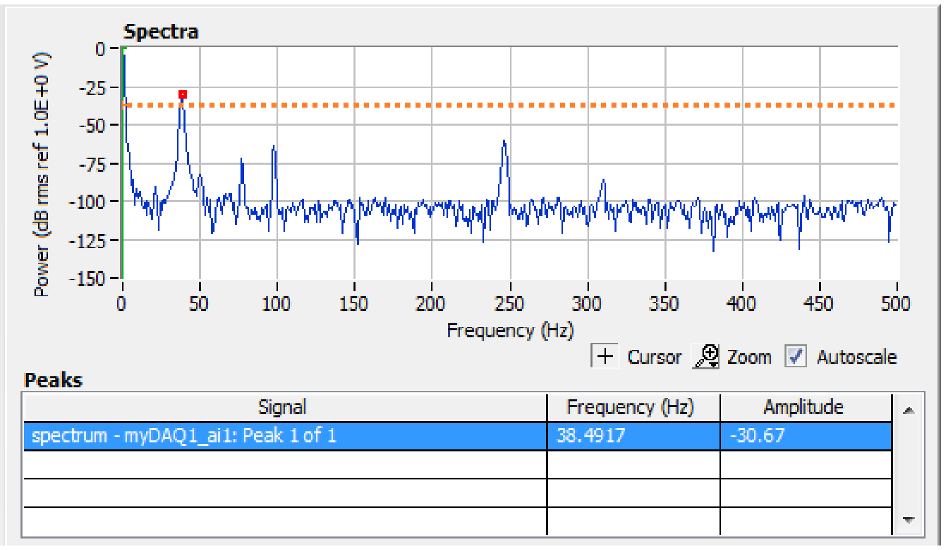
☑ Autoscale

Peaks

Signal	Frequency (Hz)	Amplitude
spectrum - myDAQ1_ai1: Peak 1 of 1	38.8512	-35.28

Figure 10 Experimental Result of non-cracked Beam

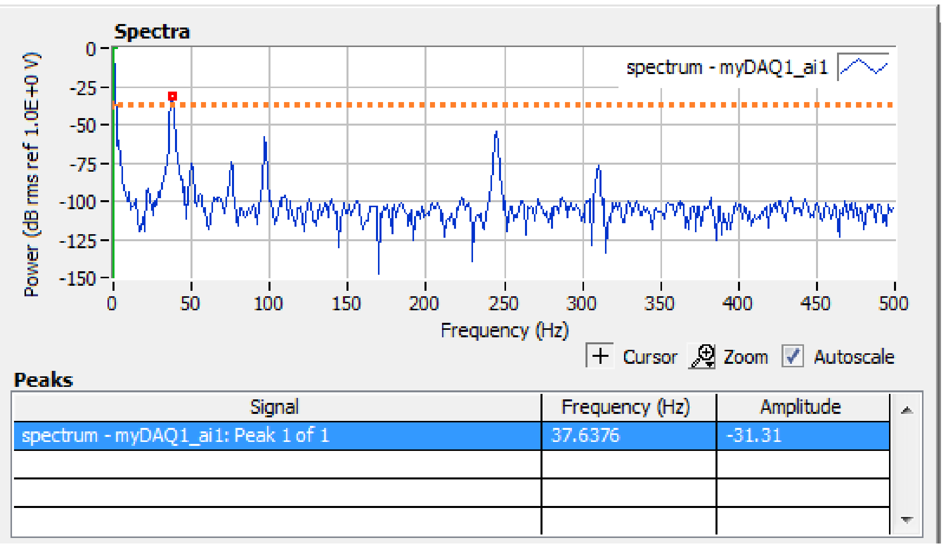
The graph shown in Fig.10 represent result of the experiment on a non-cracked beam to find natural frequency using piezo film sensors. It is to noted that the natural frequency of the non-cracked will be somewhere around 38.8512 Hz and it represented using red dot in the graph. The natural frequency is considered as the maximum frequency which received by the graph.



Signal	Frequency (Hz)	Amplitude
spectrum - myDAQ1_ai1: Peak 1 of 1	38.4917	-30.67

Figure 11 Experimental Result of cracked Beam (Depth 1 mm)

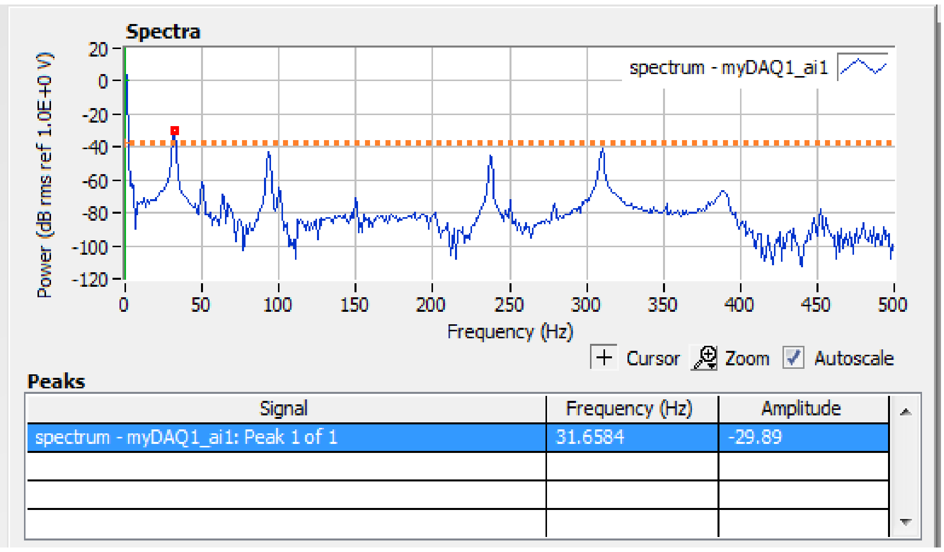
The graph shown in Fig. 11 providing the experiment result of a cracked beam with a depth of 1 mm and the position is 27 mm from the fixed end, to find natural frequency using the piezo film sensors. It is to be noted that the natural frequency of the cracked beam is around 38.4917 Hz and is represented using a red dot in the graph.



Signal	Frequency (Hz)	Amplitude
spectrum - myDAQ1_ai1: Peak 1 of 1	37.6376	-31.31

Figure 12 Experimental Result of single cracked Beam (Depth 2mm)

The graph shown in Fig. 12 providing the experiment results of a cracked beam with a depth of 2 mm at the position of 27 mm from the fixed end, to find natural frequency using the piezo film sensors. It is to be noted that the natural frequency of the cracked beam is around 37.638 Hz. The natural frequency is considered as maximum frequency which received in graph. The natural frequency is represented using a red dot in the graph.

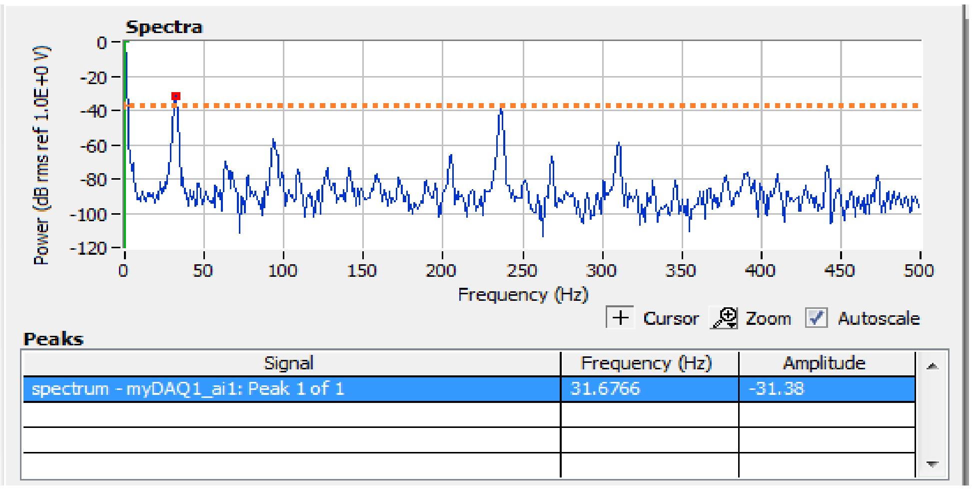


Peaks

Signal	Frequency (Hz)	Amplitude
spectrum - myDAQ1_ai1: Peak 1 of 1	31.6584	-29.89

Figure 13 Experimental Result of single cracked Beam (Depth 3mm)

The graph shown in Fig. 13 providing the experiment results of a cracked beam with a depth of 3 mm at the position of 27 mm from the fixed end, to find natural frequency using the piezo film sensors. It is to be noted that the natural frequency of the cracked beam is around 32.941 Hz. The natural frequency is considered as maximum frequency which received in graph. The natural frequency is represented using a red dot in the graph.

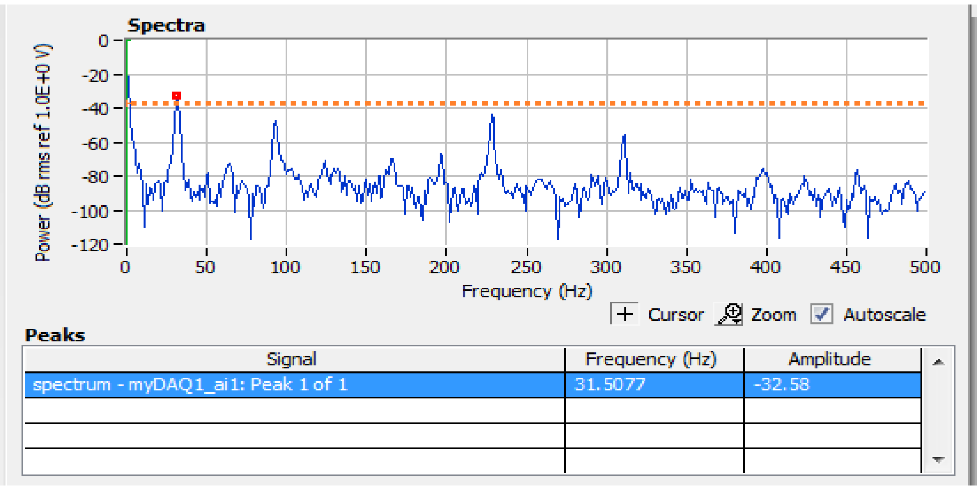


Peaks

Signal	Frequency (Hz)	Amplitude
spectrum - myDAQ1_ai1: Peak 1 of 1	31.6766	-31.38

Figure 14 Experimental Result of double cracked Beam (Depth 3mm, 1mm)

The graph shown in Fig. 14 providing the experiment results of a cracked beam with a depth of 3 mm and 1 mm at the position of 27 mm and 137 respectively from the fixed end, to find natural frequency using the piezo film sensors. It is to be noted that the natural frequency of the double cracked beam is around31.658Hz. The natural frequency is considered as maximum frequency which received in graph. The natural frequency is represented using a red dot in the graph.



Peaks

Signal	Frequency (Hz)	Amplitude
spectrum - myDAQ1_ai1: Peak 1 of 1	31.5077	-32.58

Figure 15 Experimental Result of double cracked Beam (Depth 3mm, 2mm)

The graph shown in Fig. 15 providing the experiment results of a cracked beam with a depth of 3 mm and 2 mm at the position of 27 mm and 137 respectively from the fixed end, to find natural frequency using the piezo film sensors. It is to be noted that the natural frequency of the double cracked beam is around31.677 Hz. The natural frequency is considered as maximumfrequency which received in graph. The natural frequency is represented using a red dot in the graph.

The beam with and without cracks are tested and the result are produced by the LabVIEW software. The Fig. 10-15 shows the natural frequency of the beam by the experimental method and the result in Table 1.

Table 1 Results of experiment on cracked and non-cracked beam

Crack Configuration	Crack depth (mm)	First mode frequencies (Hz)
Non-cracked	-	38.851
Single Crack	1	38.492
	2	37.638
	3	31.658
Double Crack	3	31.677
	1	
	3	31.508
	2	

The LabVIEW software uses an optimized tool kit that is the external disturbance and other factors are automatically controlled. There is no need of designing circuit. Disturbance from the external power supplies are keenly observed and avoided before taking the readings. Noise disturbances are not considered seriously since it will not affect the natural frequency values. Readings are taken with piezo film sensors at different positions, it is found that it shows more prominent results at some positions. The piezo film sensor sensed the frequency which occurred in the beam and the data acquisition card covert the signal to the software for producing the result. The piezo film sensor attached to the beam near the constrained end gives the more prominent result and can be identified by the blue line in the power spectra. LabVIEW software was used to produce the result in graphical form. According to the proposed experiment the natural frequency of the non-cracked and cracked beam found and the result in Table 1. From the result, the natural frequency of the beam changes with respect to the position and depth of the crack. The natural frequency of the beam is maximum when there is no crack on it. The natural frequency of the beam is low when the crack is far from the fixed end when the depth of the crack is maximum. Here it is going to validate the experiment result by numerical method. The methodology implied here is to find out the cracks by analyze the variations in the frequency. For getting more accurate frequencies more than one film sensors can be used. The above mention the experiment the frequency of the cracks have been estimated six times in order to understand and evaluate the intensity of changes in machine tool.

3. Numerical analysis of three dimensional beam employed with piezoelectric

The numerical analysis of three dimensional beam employed with piezoelectric is the method to prove the experiment result. The experiment results are verifying by the numerical result which is developed by the ANSYS software. In the same time it is trying to prove that the presence of the piezo film sensor doesn't affect the natural frequency of the beam. It is to prove that the presence of the piezo film sensor doesn't affect the natural frequency of the beam. The presence of the of piezo film sensors which is very minute factor when compare to the beam. It is to prove with two numerical results of the beam with and without piezo film sensors.

The finite elements method is applied by using the ANSYS program (ver.13). The three dimensional model were built and the element Solid Tet 10 node 186 were used. The numerical analysis is carried out for the non-cracked and cracked cantilever beam to find the natural frequencies of transverse vibration at different crack location and crack depth. Different crack depth of 1mm, 2mm and 3mm at different locations of the beam is made modeling of crack is explained in the following sections. Material properties and parameters are as shown in the Table 2. The numerical analysis of three dimensional beam employed with piezoelectric is the method to prove the experiment result. In this section the experiment results are verifying by the numerical result

Table 2 Parameters for cantilever beam

Parameter	Values
Beam Length (L)	L=290 mm
Beam Width (W)	W=12 mm
Beam Height (H)	H=4mm
Modulus of Elasticity (E)	E=210 GPa
Density of Beam Material	7700 kg/m3),
Poisson's Ratio	0.3

The natural frequency element has twenty nodes with up to five degrees of freedom per node. Structural capabilities include elasticity, plasticity, viscoelasticity, viscoplasticity, creep, large strain, large deflection, stress stiffening effects, and prestress effects. Thermoelectric capabilities include See beck, Peltier, and Thomson effects, as well as Joule heating. In addition to thermal expansion, structural-thermal capabilities include the piezocaloric effect in dynamic analyses. The Coriolis Effect is available for analyses with structural degrees of freedom. Since our work needs both the structural variables and electrical variables like voltage coupled field analysis is necessary.

Element type is solid 186 which is a higher order 3-D 20-node solid element that exhibits quadratic displacement behavior. Modal analysis is done on the beam to obtain the natural frequencies. Various modes of vibrations can be achieved since almost all natural vibrations are of first mode we are mainly focusing on first mode only. Higher modes cannot be excited during the experimental validation process.

3.1 Modelling of cantilever beam with piezoelectric

Firstly the beam is modeled without crack. The Non-cracked and cracked cantilever beam modal analysis was done with element type as solid 186. A finite-element mesh of 12800 eight-node 3D brick element was used. Firstly, the beam is modeled with dimensions mentioned in the Table 2. After giving the material properties of structural steel, next is to make the 3D model with the above mentioned dimensions. The given dimensions are entered and the three dimensional beam is generated. Meshing should be done to make the infinite number of particles to finite numbers. The beam is meshed with proper aspect ratio, each side is divided and a quadrilateral mesh is made. Each brick element is in quadrilateral form. In this section, the modal analysis of a three dimensional beam with piezoelectric is done. For that a beam is modeled with the dimensions which shown in the Table 2. The piezoelectric sensor film dimensions are shown in Table 3.

Table 3 Parameters for piezoelectric sensors

Parameter	Values
Length	L = 20 mm
Width	W = 12 mm
Height	H = 1 mm

The method of compare the experiment result with numerical result is already done in several experiment to prove their result [8, 26-27]. If the result are approximately same then it can proved with these result. It is to prove that the presence of the piezo film sensor doesn’t affect the natural frequency of the beam. The presence of the of piezo film sensors which is very minute factor when compare to the beam. It is to prove with two numerical results of the beam with and without piezo film sensors.

After modeling of three dimensional beam the piezoelectric is modeled, for that solid 226 as the element type is used. Solid 226 is used as the element type because it is a mid-nodded element. Solid 186 a mid-nodded element type for modeling of beam this solid geometry is most suitable for piezoelectric model. During modeling shifting of the coordinate system is done and made that coordinate system the active coordinate system, piezoelectric is modeled from that co-ordinate system with the following dimensions. The natural frequency of the beam with piezoelectric sensor is going to compare with the natural frequency of the beam by numerical method and then experiment result is validate with it.

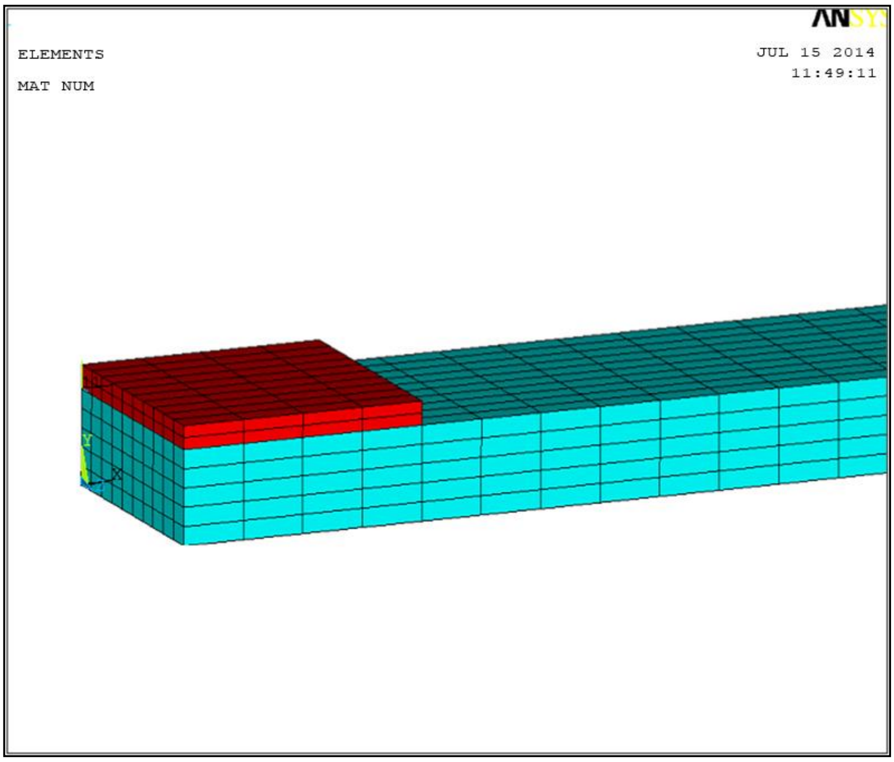


Figure 16 Meshed model of beam with piezoelectric

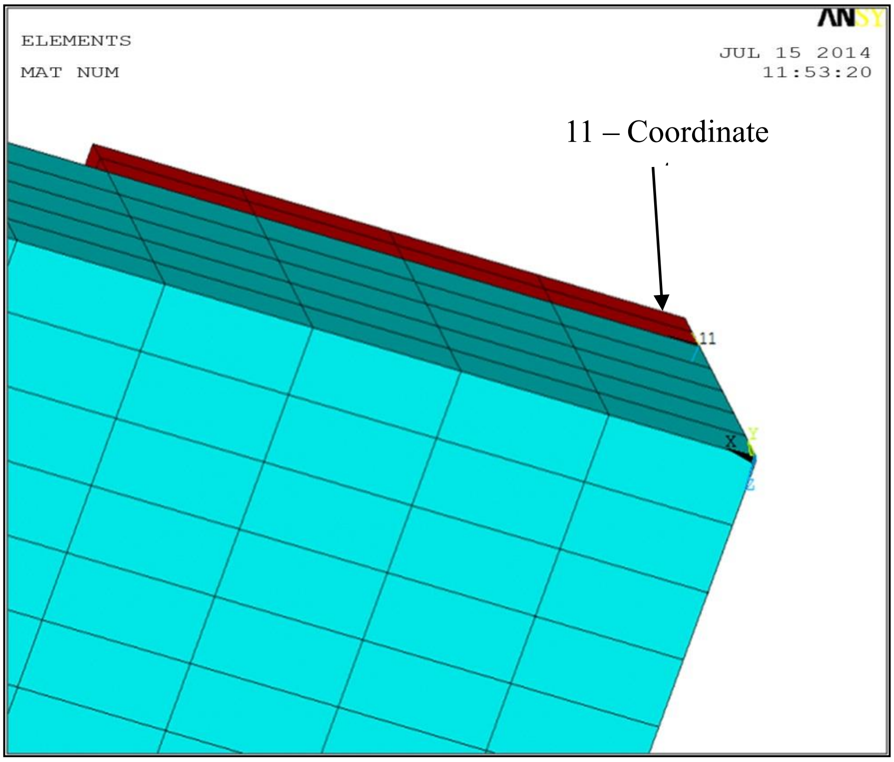


Figure 17 Piezoelectric coordinate system

After modeling of three dimensional beam the piezoelectric is modeled, for that solid 226 as the element type is used. Solid 226 is used as the element type because it is a mid noded element. By using solid 186 mid noded element type for modeling of beam this solid geometry is most suitable for piezoelectric model. During modeling shifting of the coordinate system is done and made that co ordinate system the active coordinate system, piezoelectric is modeled from that co-ordinate system with the respective dimensions.After modeling meshing is done, meshed model of piezoelectric on a solid beam is shown in the Fig. 16-17. The shifted coordinate system can be seen from the Fig. 17. It is named as 11. After modelling merging of two volumes is done. Grounding of nodes is also performed to obtain the output from the piezoelectric as voltage. Harmonic analysis is done for around 50 Hz. Piezoelectric shows the peak at resonance, at the resonance the beam is under maximum stress. Piezoelectric attached to the beam will also experience that maximum stress. This stress developed produced corresponding output voltage in the piezoelectric and shows the peak value at maximum stress and that point will be the natural frequency of that beam. Results can be plotted as both voltage and displacement, graphs shown below gives the output of piezoelectric.

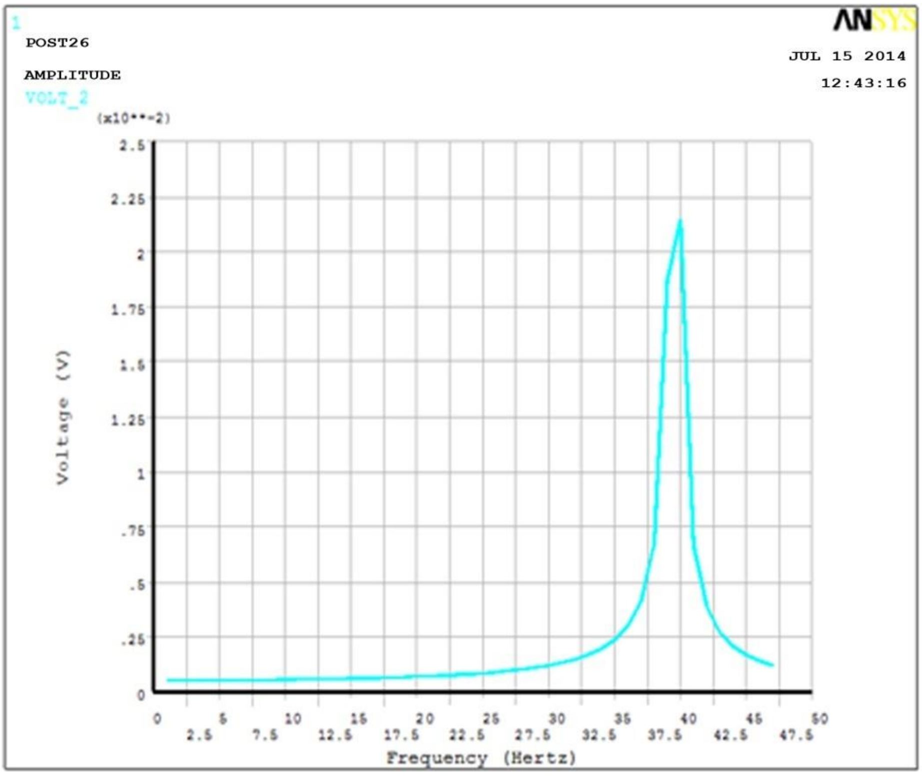


Figure 18 Natural frequency at maximum voltage

The Fig.18 shows that the natural frequency is approximately 40Hz at maximum voltage (V). The Fig. 19 shows the natural frequency is also approximately 40Hz with respect to the displacement. The experimental result can prove by the numerical result which is developed with respect to the presence of piezoelectric sensors. Now it is necessary to prove that the presence of the piezoelectric sensors doesn’t affect the natural frequency of the specimen. This can prove by modelling and find the natural frequency of the specimen without piezoelectric sensor.

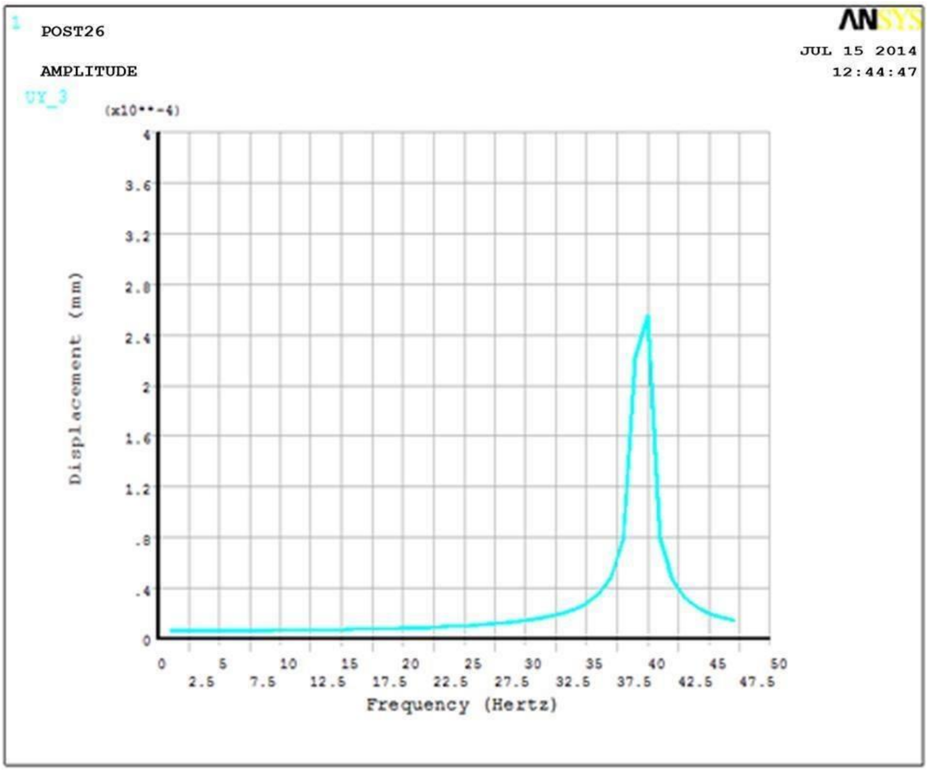


Figure 19 Natural frequency at maximum displacement

3.2 Modeling of non-cracked beam

Model the non-cracked beam with the dimension of the beam which experimented as shown in Table 2. This modeling is going to prove that the piezo film sensors doesn't affect the frequency which occurred in the beam. Then it will be compare with the experimental result for validating the experimental result. The first step of the validation is going to finish by this comparison. Firstly the beam is modeled without crack. The non-cracked and cracked cantilever beam modal analysis was done with element type as solid 186. A finite-element mesh of 12800 eight-node 3D brick element was used. Firstly, the beam is modeled with dimensions mentioned in the Table 2. After giving the material properties of structural steel, next is to make the 3D model with the above mentioned dimensions.

The given dimensions are entered and the three dimensional beam is generated. Meshing should be done to make the infinite number of particles to finite numbers. The beam is meshed with proper aspect ratio, each side is divided and a quadrilateral mesh is made. Each brick element is in quadrilateral form. The meshed model of 3D beam model is shown in Fig. 20. After meshing next part is the solution part in which analysis type and number of modes to be extracted is specified. Since the beam is a cantilever beam make one end fixed for that nodes on one side is selected and will lock all degrees of freedom. After constraining the type of analysis should be specified since it using the modal characteristics modal analysis is selected. Number of modes to be extracted should be given also the limit of natural frequencies should be given in the next step. After all the preprocessing is done the model is send for solving, the solution is done in the solution phase and plot the results of different modes and even animate the vibration of the beam.

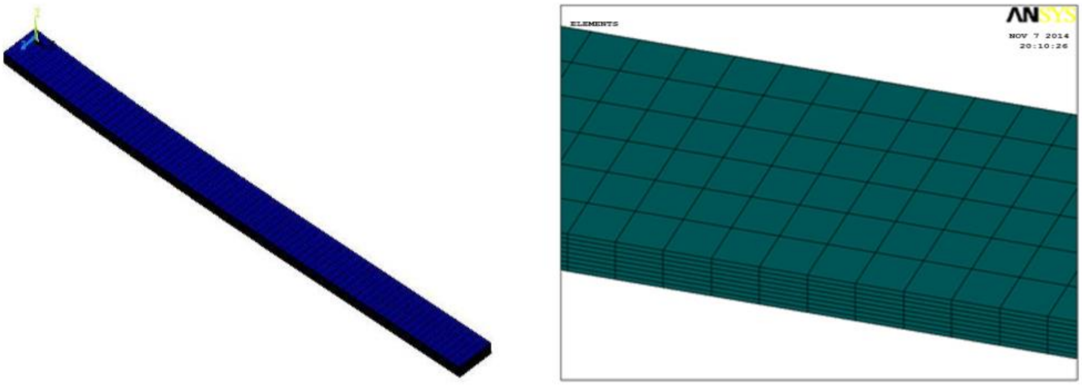


Figure 20 Meshed 3D Beam Model

The numerical result of the non-cracked beam is developed in different mode of crack. The result is going to compare and validate with the numerical result of the beam with piezoelectric beam. Fig. 21-24 shows the numerical results for the non-cracked beam used in the experiment. The natural frequency of the beam is found in its 4 different modes. The natural frequency of the non-cracked beam by experimental and the two numerical results (with piezoelectric and without piezoelectric sensors) are compared to validate the experiment result.

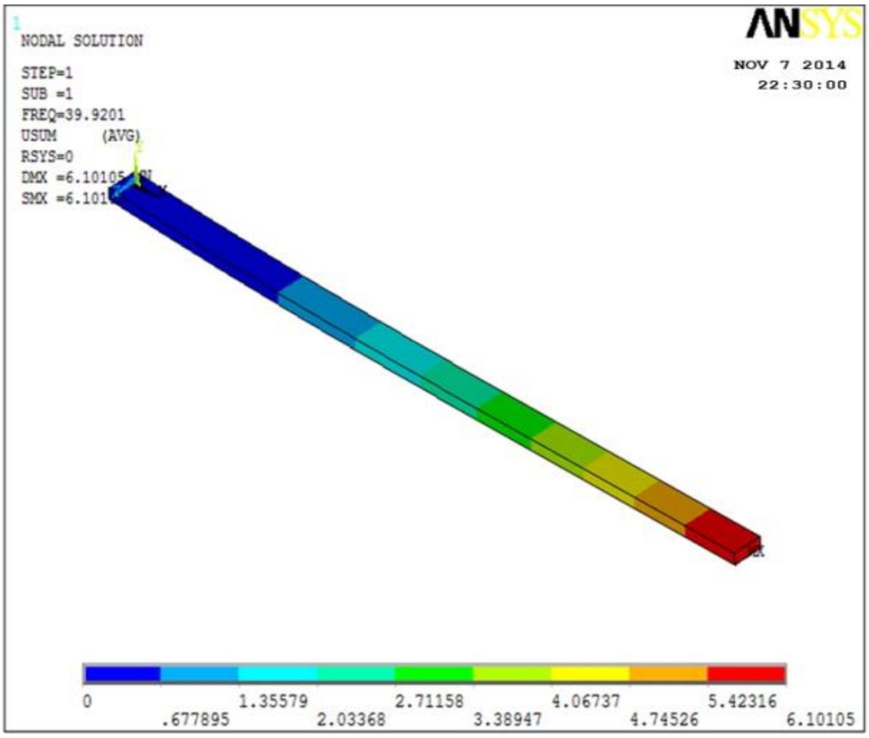


Figure 21 Non-cracked-First Mode

The frequency of non- cracked beam in first mode is 39.9201 Hz.

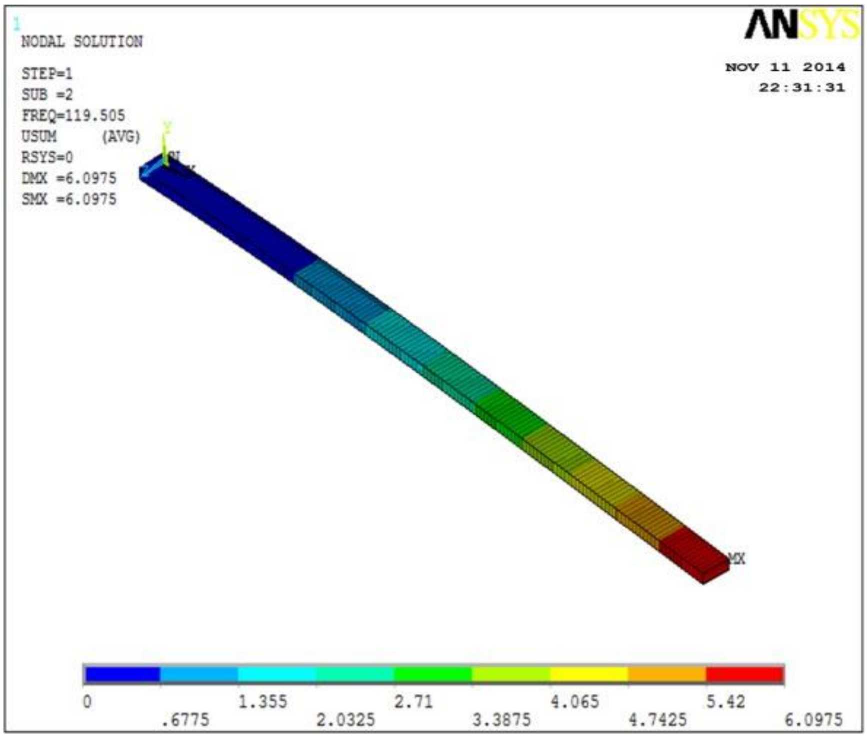


Figure 22 Non-cracked-Second Mode

The frequency of non- cracked beam in second mode is 119.505 Hz.

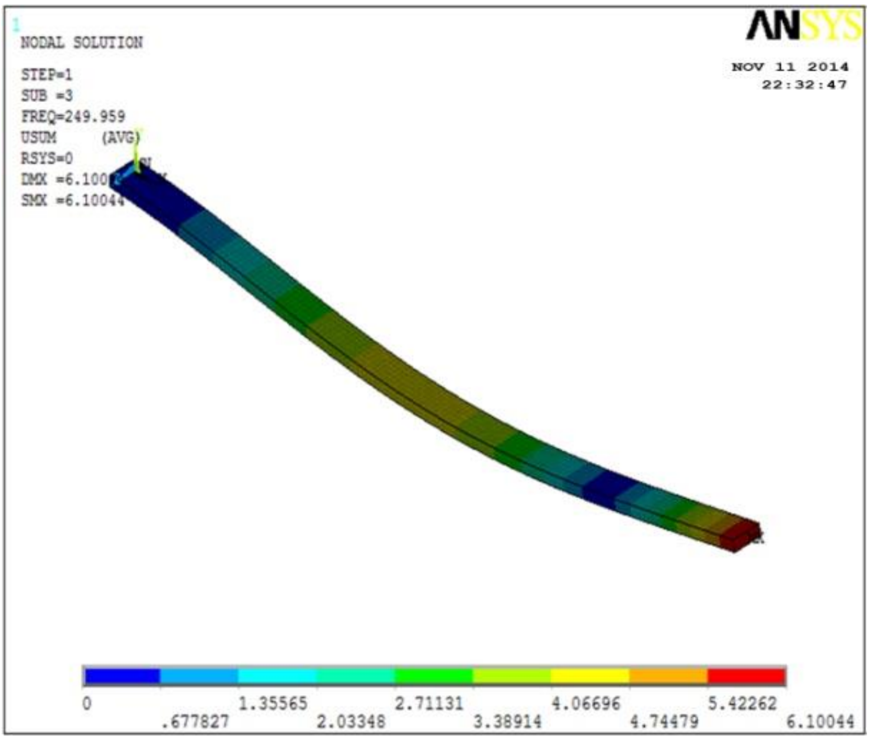


Figure 23 Non-cracked-Third Mode

The frequency of non- cracked beam in third mode is 249.959 Hz.

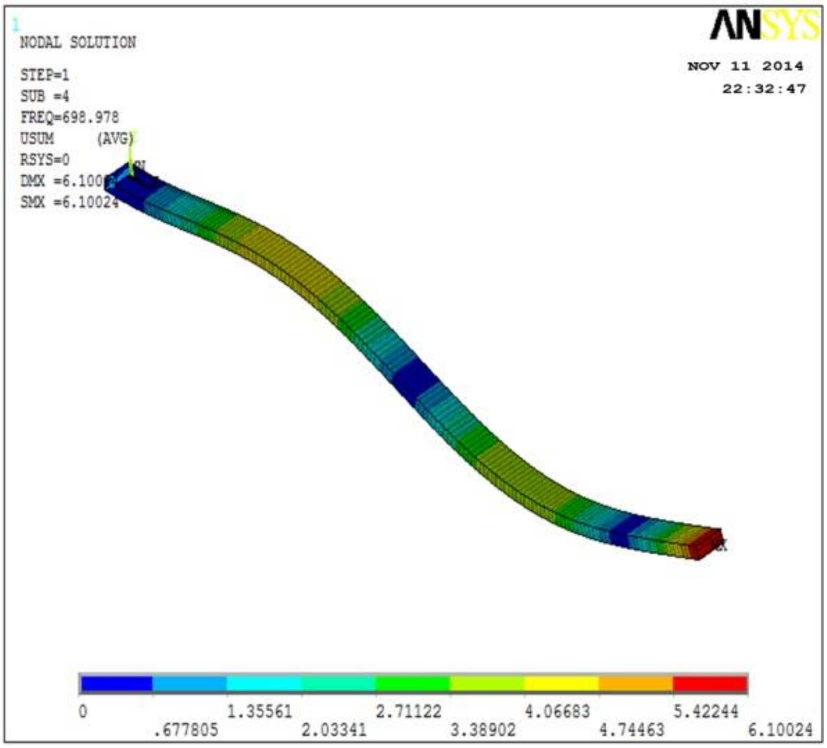


Figure 24 Non-cracked-Fourth Mode

The frequency of non- cracked beam in forth mode is 698.978 Hz.

Table 4 ANSYS results of Non-cracked beam

Crack configuration	Mode	Natural frequency(Hz)
Non-cracked	First	39.920
	Second	119.50
	Third	249.95
	Fourth	698.97

The natural frequency of non-cracked beam is in Table 4. From the graph, the natural frequency of the beam comes in between 39 to 40 Hertz. There will be a slight change since the piezoelectric has an effect on the stiffness of the beam; this will affect the frequency of the beam also. It is prove that the natural frequency can find by using a piezoelectric. It is possible because of the ability of piezoelectric to give the peak value at its maximum stress. That point is at the resonance i.e. at the natural frequency of the beam.

The peak value of the voltage gives the natural frequency of the beam also it is possible to obtain the natural frequency by finding the maximum displacement point. From the above results it can conclude that for experimental purpose, a piezo film sensor can use for finding the natural frequency.

3.3 Modeling of cracked beam

For this a cantilever beam of following parameters are considered with a crack on it and without crack. The configuration of dimensions are given as Fig. 25.

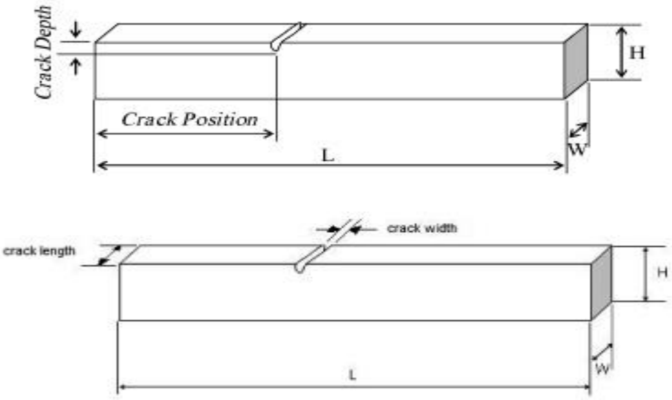


Figure 25 Dimensions of Cracked Beam

Modeling procedures are same as that of a non-cracked beam instead a crack has to be made on the beam. Different types of cracks that can be modeled in the beam are shown in the Fig. 26-28

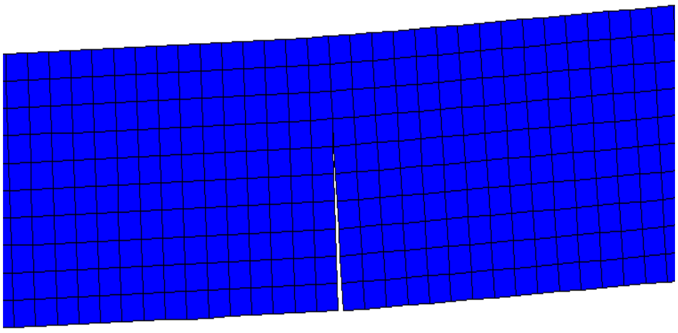


Figure 26 Line Crack

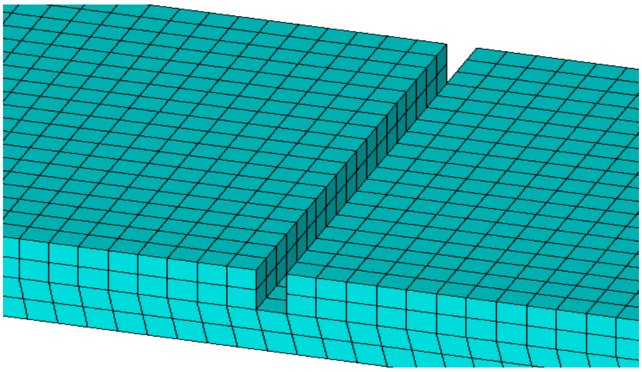


Figure 27 Square Notch Crack

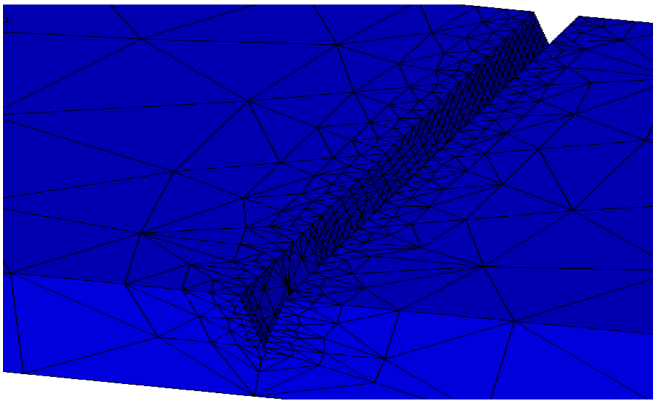


Figure 28 V Crack

Numerical analysis is done with ANSYS 13 program. Meshing should be done to make the infinite number of particles to finite numbers. The beam is meshed with proper aspect ratio, each side is divided and a quadrilateral mesh is made. Each brick element is in quadrilateral form. The modal analysis of a three dimensional beam with piezoelectric is done. For that a beam is modeled with the following dimensions and is shown in the Table 2.

The line crack is the suitable because cracks generally formed in the machine tool is line cracks. Crack depth, crack location and number of cracks is varied and modal analysis should be done. The beam is modelling as per the data shown in Table 2 and different crack configurations are shown in the Table 5.

Table 5 Various crack configurations used

No.	Crack Configuration	Crack length (mm)	Crack positions from the constrained end (mm)	Crack depth (mm)
1	Single Crack	12	27	1
		12	27	2
		12	27	3
2	Double Crack	12	27	3
			137	1
		12	27	3
			137	2

Modeling of crack is done by merging method. For modeling a single crack the beam should be modeled as two separate volumes and for double crack it should be modeled as three separate volumes. The nodes which are not merged will act as crack in the beam and is of line crack type. Displaying of break is finished by blending technique. For demonstrating a solitary break the pillar ought to be displayed as two different volumes and for twofold split it ought to be demonstrated as three different volumes. Break is made by consolidating the hubs at that specific area and at the specific profundity. The hubs which are not blended will go about as break in the shaft and is of line split sort. After making crack in the beam remaining procedures are almost same as that of the non-cracked beam. Solution is done and different mode shapes are obtained.

The first mode is considered for experimental validation because the experiment is done only in first mode. First mode of the cracked cantilever beam with cracks of different depth at a distance 2.7cm for single cracked beam and at a distance of 13.7cm for double cracked from the fixed end is shown in the following figures. All the models are made separately and crack depth of 1mm, 2mm, 3mm is made in the case of single cracked beam but in the case of double cracked beam crack depth up to 2mm is made because the beam will lose its total rigidity. The result of the cracked beam asper the dimension is developed by numerical method is going to compare with the experimental result. Analysis results of cracked beam are shown in the below Fig. 29-33.

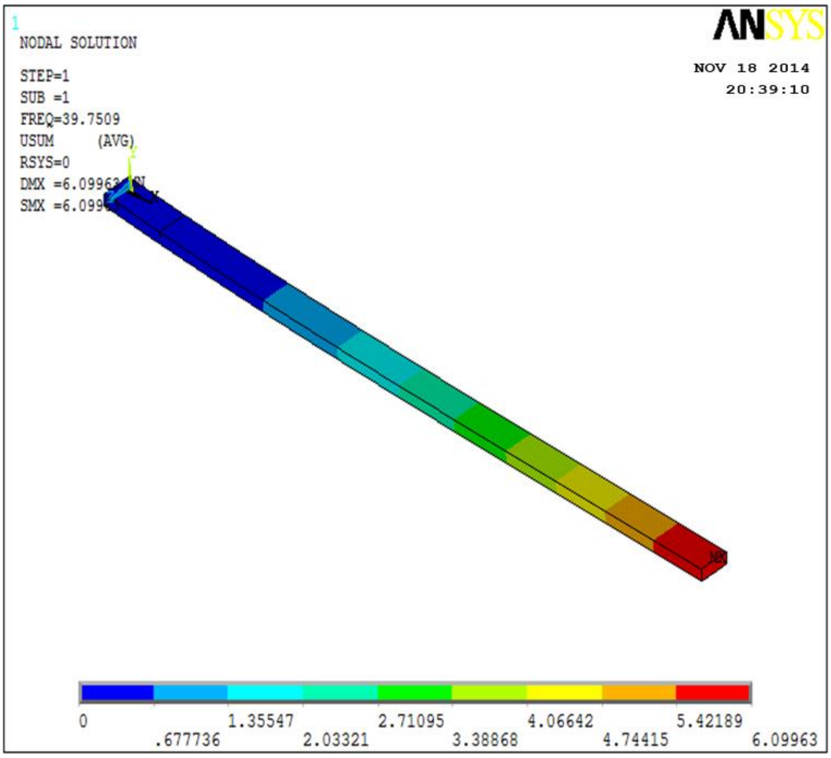


Figure 29 Cracked beam of 1mm depth – Mode1

The natural frequency of beam with crack at 27 mm from constrained end with the depth of 1mm is calculated by numerical method. Fig.29 shows the natural frequency of the cracked beam with 1 mm depth is 39.7509 Hz. The natural frequency of the rest of cracked beam also calculating through the same way. The first mode of frequencies are only calculating because the experiment is done only in first mode. And finally the results are going to compare with the experimental result to validate the experiment.

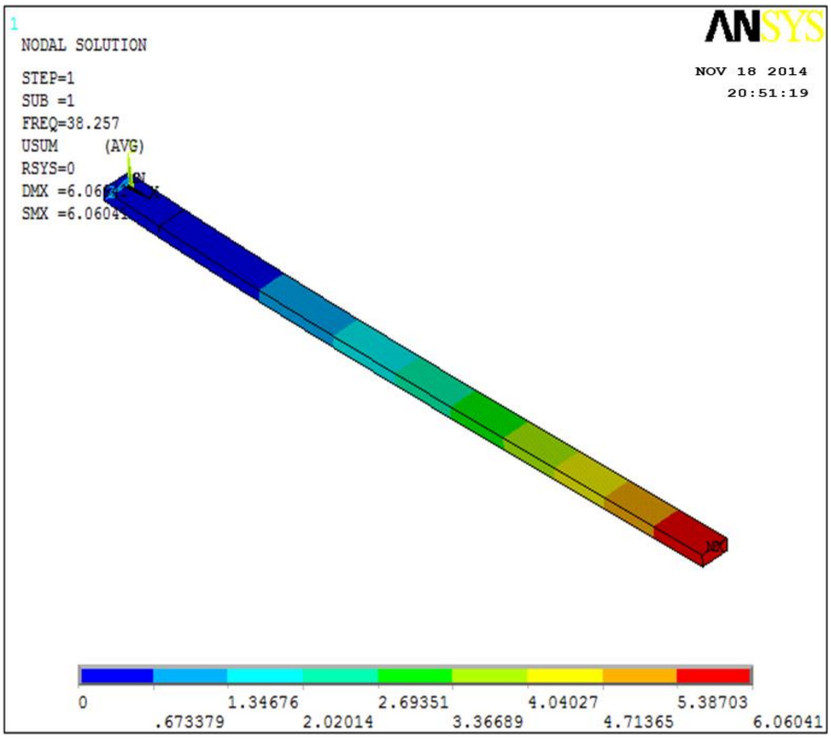


Figure 30 Cracked beam of 2mm depth – Mode1

The Fig. 30 shows the natural frequency of beam with crack at 27 mm from constrained end with the depth of 1mm is 38.257 Hz.

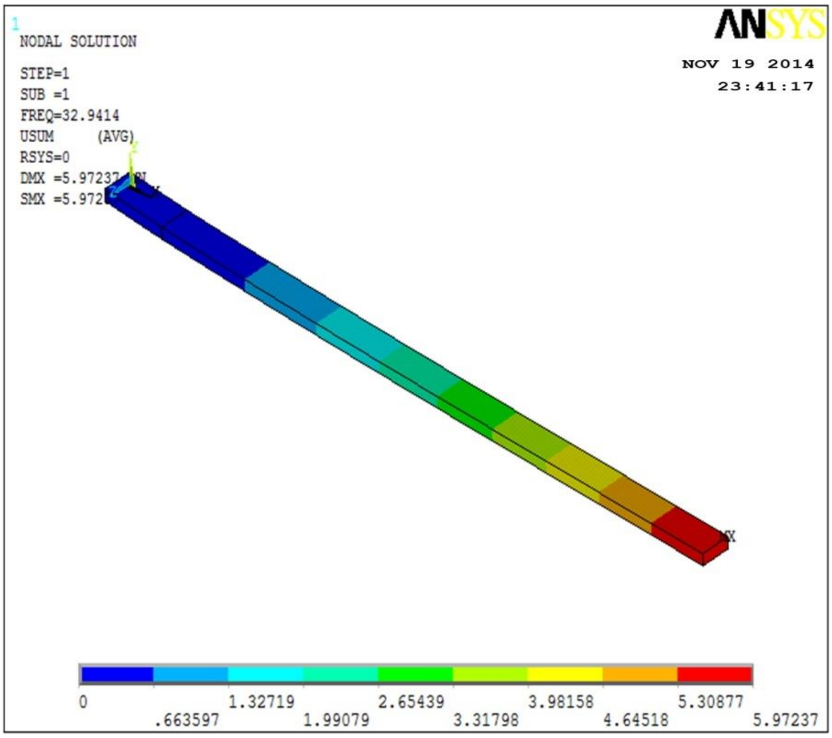


Figure 31 Cracked beam of 3mm depth – Mode1

The Fig. 31 shows the natural frequency of beam with crack at 27 mm from constrained end with the depth of 3 mm is 32.9414 Hz.

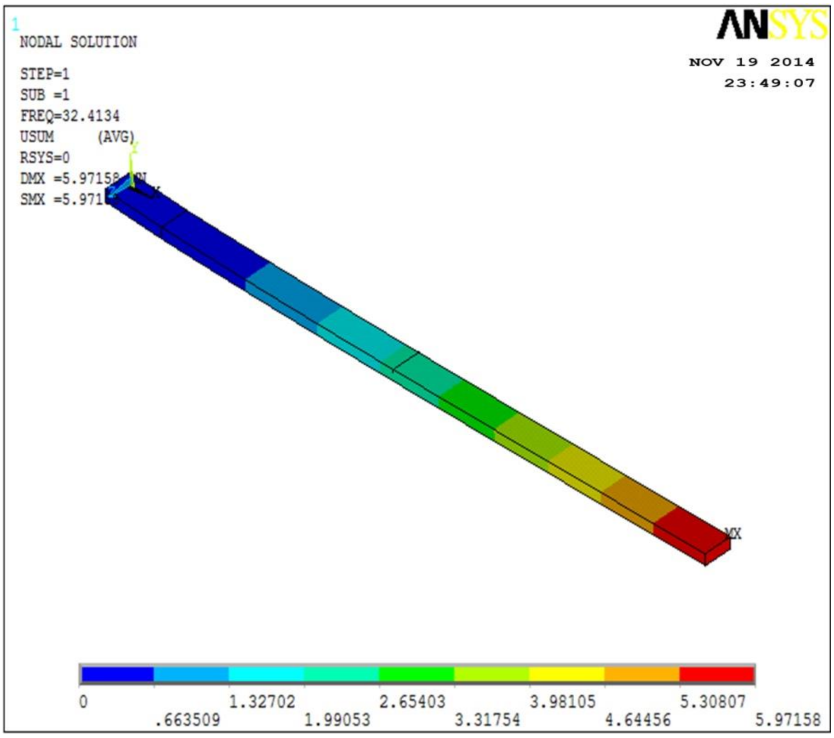


Figure 32 Double cracked beam of 3mm and 1mm depth – Mode1

The Fig. 32 shows the natural frequency of beam with double crack at 27 mm and 137mm from constrained end with the depth of 3 mm and 1mm is 32.4134 Hz.

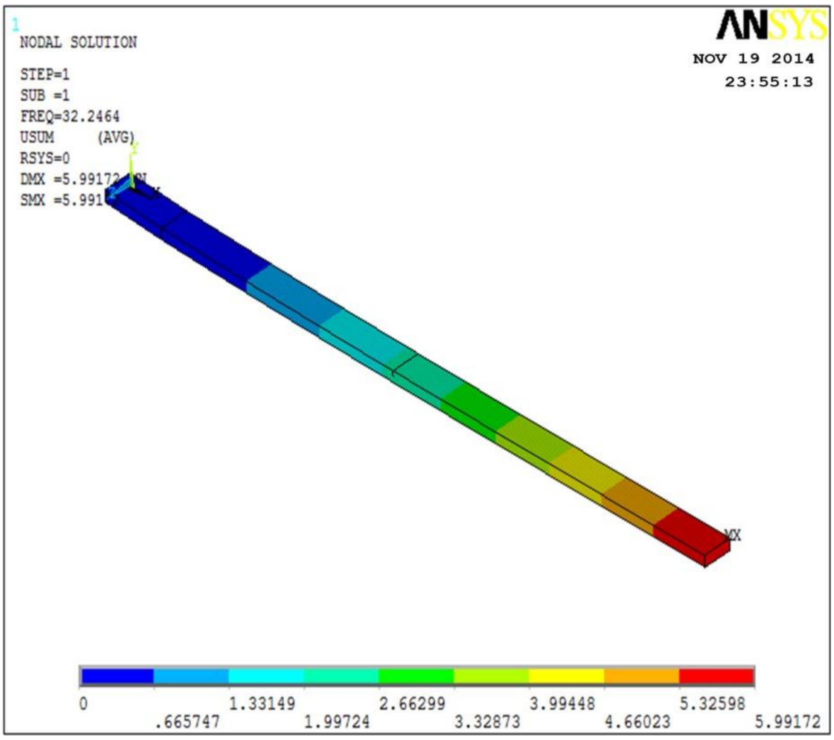


Figure 33 Double cracked beam of 3mm and 2mm depth – Mode1

The Fig. 3 shows the natural frequency of beam with double crack at 27 mm and 137mm from constrained end with the depth of 3 mm and 2 mm is 32.2464 Hz.

Table 6 ANSYS results of cracked and non-cracked beam

No.	Crack Configuration	Crack depth (mm)	First mode frequencies (Hz)
1	Non-cracked	-	39.920
2	Single Crack	1	39.750
		2	38.257
		3	32.941
3	Double Crack	3	32.413
		1	
		3	32.264
		2	

The natural frequency of non –cracked and cracked beam is in Table 6. The existence of a defect like a crack will leads to change in natural frequency of the beam and enlargement of the crack will also lead another change in natural frequency with the change of the size, position of the crack and with number of cracks. It is also clear that there is a drastic change in the frequency when crack depth changes from 2mm to 3mm. So by finding the magnitude of change in frequencies we can predict the crack location and depth of the crack also.

4. Comparison of experimental and numerical results and result analysis

The experimental result is comparing with numerical result for validating the experimental result. The Table 7 below compares the value of natural frequency of the cantilever beam obtained by experimental method and numerical method with different crack positions and crack depth. The numerical values obtained by using ANSYS will be always higher than the experimental values. The shapes of the curve for both experimental and numerical results are the same. The first point of both curves corresponds to the natural frequency of non-cracked beam which will be always higher than natural frequency of the cracked beam (i.e. all other points on the curves).

Table 7 Comparison of experimental and numerical results

No.	Crack Configuration	Crack depth (mm)	Crack length (mm)	Crack positions from the constrained end (mm)	Experimental frequency (Hz)	Numerical (ANSYS) frequency (Hz)	Difference in frequency (Hz)
1	Non-cracked	0	0	-	38.851	39.920	1.069
2	Single Crack	1	12	27	38.492	39.750	1.258
		2	12	27	37.638	38.257	0.619
		3	12	27	31.714	32.941	1.227
3	Double Crack	3	12	27	31.658	32.413	0.755
		1		137			
		3	12	27	31.677	32.264	0.587
		2		137			

A comparison made between analytical results from ANSYS with experimental results shows a good approximation where the biggest error percentage is about 3.2 % in the single crack position 27 mm from the constrained end with 1 mm depth. The crack in the beam has an effect on the stiffness of the beam; this will affect the frequency of the beam. So, with the increasing of the crack depth, the stiffness of beam will decrease and this will cause a decreasing in the natural frequency of the beam.

The position of crack in the beam near to the ends of the beam has more effect on the stiffness and natural frequency of beam from the other positions (near the middle of the beam), i.e. frequency of the beam when the crack is near to the end position has a lower frequency of the beam with respect the cracks in the middle position. The shapes of the curve for both experimental and numerical results are the same.

A machine tool is compared to a cantilever beam and its model is made using ANSYS. Modal analysis of this finite element model is done and proved that natural frequency is reduced with the formation of crack.The influence of crack in the natural frequency of the structure had been checked experimentally and numerically on a cantilever beam and the results are compared. Comparison of both results shows a good approximation where the biggest error percentage is about 3.2 %.

The modal analysis of a three dimensional beam with piezoelectric were done and showed that using a piezoelectric we can find the natural frequency of the cantilever beam. This can be achieved because a piezoelectric will give it peak voltage output at its maximum stress and it will feel the maximum stress at its resonance. The graph comparing the experimental result and numerical result is obtained as shown in Fig. 34.

The following comparison has been made as per the analysis of the machine tool and the correlation of cracks in it and the frequency measured. The experimental and structural analysis made on the ANSYS mechanical software and the lab reading plotted graphically concurs with each other. From the Fig. 10 and 21, the result obtained by the ANSYS shows the frequency of 39.92Hz, whereas the natural frequency measured is 38.851Hz. Thus the output offered by the nodal solution in ANSYS confirms the graphical value of the machine tool.

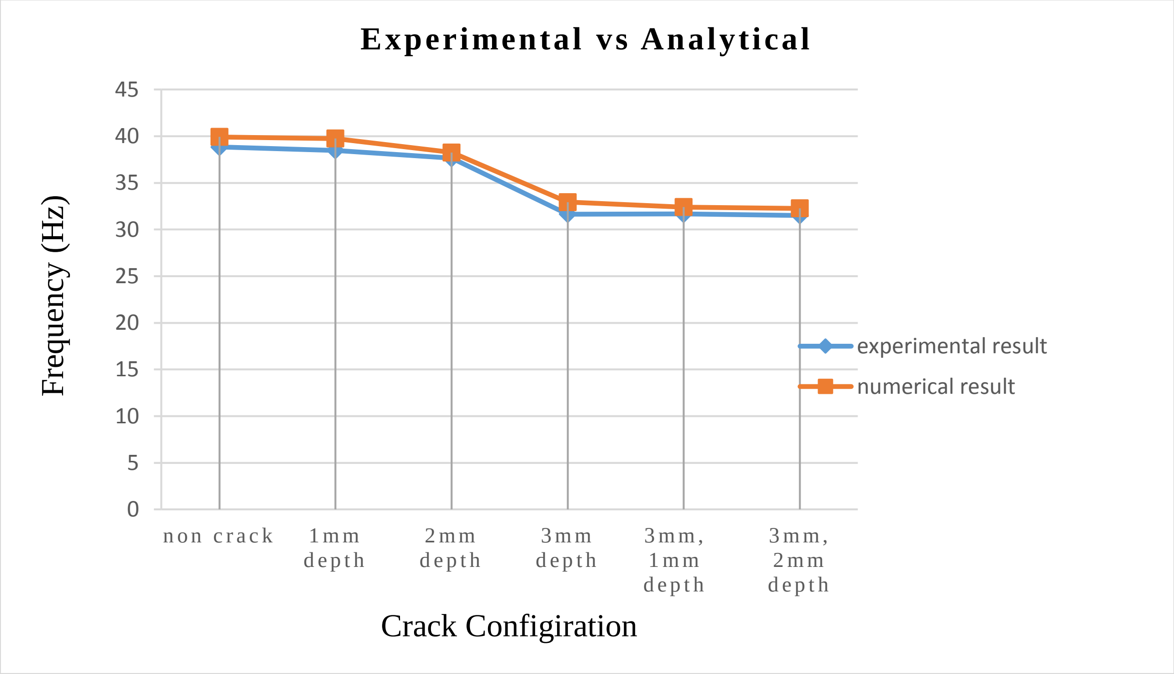


Figure 34 Comparison between experimental and analytical results

This is the comparison graph drawn using the experimental result and analytical result by testing the beam under different crack configuration. It is also noted that in all conditions analytical result is higher than experiment al result in a very small number and this may be due to precise result of analytic software's. For 1mm depth single crack at 27mm from fixed end shown in the Fig. 12 and 31, the result obtained by the ANSYS shows the frequency of 39.750Hz, whereas the natural frequency measured is 38.492Hz. Thus the output offered by the nodal solution in ANSYS confirms the graphical value of the machine tool. In the same way for 2mm depth single crack at position of 27mm from the fixed end shown in the Fig. 13 and 32, the result obtained by the ANSYS shows the frequency of 38.257Hz, whereas the natural frequency measured is 37.638Hz. For 3mm depth single crack at position of 27mm from the fixed end shown in the Fig. 14 and 33, the result obtained by the ANSYS shows the frequency of 32.941Hz, whereas the natural frequency measured is 31.714Hz. When comparing the experimental result of double crack beam with numerical result, the cracks are 27mm 137mm from the fixed end with 3mm and 1mm depth respectively. From Fig. 15 and 34, the result obtained by the ANSYS shows the frequency of 32.413Hz, whereas the natural frequency measured is 31.658Hz.when the second crack become 2mm, the result obtained by the ANSYS shows the frequency of 32.264Hz, whereas the natural frequency measured is 31677Hz.

The maximum difference when comparing experimental result with numerical result is 1.258Hz found in single crack with depth of 1mm. Comparison of both results shows a good approximation where the biggest error percentage is about 3.2 %. This is an experiment conducted to find out the occurrence of cracks in machine tool. The methodology implied here is to find out the cracks by analyze the variations in the frequency. The piezo film sensor is used for finding out the frequencies. For getting more accurate frequencies more than one film sensors can be used.

5. Conclusion

1. The various effect of crack at different locations and at different depth analysis is done for different crack configuration. Different trends for different modes are obtained. The above mention the experiment the frequency of the cracks have been estimated six times in order to understand and evaluate the intensity of changes in machine tool.

2. The modal analysis of a three dimensional beam with piezoelectric were done and showed that using a piezoelectric we can find the natural frequency of the cantilever beam. This can be achieved because a piezoelectric will give it peak voltage output at its maximum stress and it will feel the maximum stress at its resonance.

3. The influence of crack in the natural frequency of the structure had been checked experimentally and numerically on a cantilever beam and the results are compared. Comparison of both results shows a good approximation where the biggest error percentage is about 3.2 %.

4. A model or methodology for online machine tool damage prediction system by detecting the change in natural frequency is proposed. A machine tool is compared to a cantilever beam and its model is made using ANSYS. Modal analysis of this finite element model is done and proved that natural frequency is reduced with the formation of crack.

6. References

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Appendix

1. ANSYS codes for the experimental beam with piezo electric

```
/prep7
L=27.8e-2
W=4e-3
H=1.9e-2
B1=3.5e-2
A1=0
B2=7.1e-2
A2=0
B3=17.1e-2
A3=0
piezl=B1/2

ET,1,SOLID186

MP,EX,1,200e9
MP,PRXY,1,0.3
MP,DENS,1,7680

ET,3,SOLID5,3 ! 3-D COUPLED-FIELD SOLID, PIEZO OPTION
MP,DENS,3,7500 ! DENSITY
MP,PERX,3,804.6 ! PERMITTIVITY (X AND Y DIRECTION)
MP,PERZ,3,659.7 ! PERMITTIVITY (Z DIRECTION)
TB,PIEZ,3 ! DEFINE PIEZ. TABLE
TBDATA,16,10.5 ! E61 PIEZOELECTRIC CONSTANT
TBDATA,14,10.5 ! E52 PIEZOELECTRIC CONSTANT
TBDATA,3,-4.1 ! E13 PIEZOELECTRIC CONSTANT
TBDATA,6,-4.1 ! E23 PIEZOELECTRIC CONSTANT
TBDATA,9,14.1 ! E33 PIEZOELECTRIC CONSTANT
TB,ANEL,3 ! DEFINE STRUCTURAL TABLE
TBDATA,1,13.2E10,7.1E10,7.3E10 ! INPUT [C] MATRIX
TBDATA,7,13.2E10,7.3E10
TBDATA,12,11.5E10
TBDATA,16,3.0E10
```

```
TBDATA,19,2.6E10
TBDATA,21,2.6E10

BLC4, , ,B1,W,H
BLC4,B1 , ,B2-B1,W,H
BLC4,B2 , ,B3-B2,W,H
BLC4,B3 , ,L-B3,W,H


LPLOT
LSEL,S,LENGTH,,W
LESIZE,all, , ,16, , , , ,1
LSEL,S,LENGTH,,H
LESIZE,all, , ,10, , , , ,1
LSEL,S,LENGTH,,B1
LESIZE,all, , ,10, , , , ,1
LSEL,S,LENGTH,,B2-B1
LESIZE,all, , ,10, , , , ,1
LSEL,S,LENGTH,,B3-B2
LESIZE,all, , ,30, , , , ,1
LSEL,S,LENGTH,,L-B3
LESIZE,all, , ,30, , , , ,1

MSHAPE,0,3D
MSHKEY,1
!esize,0.001
VMESH,ALL
blc4,B1/5,W,piezl, W/10,H
vsel,s,,,5
LSEL,S,LENGTH,,piezl
LESIZE,all,3.5e-3, , , , , , ,1
allsel,all
LSEL,S,LENGTH,,W/10
LESIZE,all,W/10, , , , , , ,1
allsel,all
```

```
type, 3
mat, 3
 VMESH,ALL

seltol,1e-3
ASEL,S,LOC,X,B1
NSLA,R,1
NPLOT
NSEL,R,LOC,Y,0,W-A1
NPLOT
NUMMRG,NODE, , , ,LOW
ALLSEL,ALL


ASEL,S,LOC,X,B2
NSLA,R,1
NPLOT
NSEL,R,LOC,Y,0,W-A2
NPLOT
NUMMRG,NODE, , , ,LOW
ALLSEL,ALL


ASEL,S,LOC,X,B3
NSLA,R,1
NPLOT
NSEL,R,LOC,Y,0,W-A3
NPLOT
NUMMRG,NODE, , , ,LOW
ALLSEL,ALL

seltol,1e-3

NSEL,R,LOC,X,0
NPLOT
```

```
/SOLU
D,all, , , , , ,UX,UY,UZ, , , ,
allsel,all

/SOL
ANTYPE,2
MODOPT,LANB,10
EQSLV,SPAR
MXPAND,10, , ,0
LUMPM,0
PSTRES,0
MODOPT,LANB,10,0,10000, ,OFF
/STATUS,SOLU
SOLVE
/POST1
SET,LIST
```

2. ANSYS codes for the non-cracked beam

```
/CLEAR,NOSTART
/prep7
L=27.8e-2
W=4e-3
B1=3.5E-2
A1=2.5e-3

SIZE1=(B1/L)*500
SIZE2=(1-B1/L)*500
ET,1,PLANE183
KEYOPT,1,1,0
KEYOPT,1,3,0
KEYOPT,1,6,0
MP,EX,1,200e9
MP,PRXY,0.3
```

```
MP,DENS,1,7680
BLC4, , ,B1,W
BLC4,B1 , ,L-B1,W
LSEL,R,LENGTH,,W
LPLOT
LESIZE,ALL, , ,16, , , , ,1

ALLSEL,ALL
LSEL,S,LINE,,1,3,2
LESIZE,ALL, , ,SIZE1, , , , ,1

ALLSEL,ALL
LSEL,S,LINE,,5,7,2
LESIZE,ALL, , ,SIZE2, , , , ,1
ALLSEL,ALL

MSHAPE,0,2D
MSHKEY,1
AMESH,ALL

LSEL,S,LOC,X,B1
LPLOT
NSLL,S,1
NPLOT
NSEL,R,LOC,Y,A1,W
NPLOT
NUMMRG,NODE, , , ,LOW
ALLSEL,ALL
LSEL,S,LOC,X,0
LPLOT
NSLL,S,1
/SOLU
D,ALL, , , , , ,ALL, , , , ,

/PREP7
```

```
EPLOT
ALLSEL,ALL

/SOL
ANTYPE,2
MODOPT,LANB,10
EQSLV,SPAR
MXPAND,10, , ,0
LUMPM,0
PSTRES,0
MODOPT,LANB,10,0,10000, ,OFF
/STATUS,SOLU
SOLVE
/POST1
SET,LIST
```

3. ANSYS codes for the cracked beam

```
/prep7
L=28.7e-2
W=.4e-2
H=1.2e-2
B1=2.7e-2
A1=3e-3
B2=13.7e-2
A2=0
B3=15e-2
A3=0
lsize=120
wsize=8
hsize=6
size1=lsize*B1/L
size2=lsize*(B2-B1)/L
size3=lsize*(B3-B2)/L
size4=lsize*(L-B3)/L
```

```
ET,1,SOLID186

MP,EX,1,210e9
MP,PRXY,1,0.28
MP,DENS,1,7650

BLC4, , ,B1,W,H
BLC4,B1 , ,B2-B1,W,H
BLC4,B2 , ,B3-B2,W,H
BLC4,B3 , ,L-B3,W,H

LPLOT
LSEL,S,LENGTH,,W
LESIZE,all, , ,wsize, , , , ,1
LSEL,S,LENGTH,,H
LESIZE,all, , ,hsize, , , , ,1
LSEL,S,LENGTH,,B1
LESIZE,all, , ,size1, , , , ,1
LSEL,S,LENGTH,,B2-B1
LESIZE,all, , ,size2, , , , ,1
LSEL,S,LENGTH,,B3-B2
LESIZE,all, , ,size3, , , , ,1
LSEL,S,LENGTH,,L-B3
LESIZE,all, , ,size4, , , , ,1

MSHAPE,0,3D
MSHKEY,1
!esize,0.001
VMESH,ALL

seltol,1e-6
NSEL,S,LOC,X,B1
NSEL,R,LOC,Y,0,W-A1
NPLOT
```

```
NUMMRG,NODE, , , ,LOW
ALLSEL,ALL



NSEL,S,LOC,X,B2
NSEL,R,LOC,Y,0,W-A2
NPLOT
NUMMRG,NODE, , , ,LOW
ALLSEL,ALL

NSEL,S,LOC,X,B3
NSEL,R,LOC,Y,0,W-A3
NPLOT
NUMMRG,NODE, , , ,LOW
ALLSEL,ALL

seltol,1e-6

NSEL,R,LOC,X,0
NPLOT



/SOLU
D,all, , , , , ,UX,UY,UZ, , , ,
allsel,all





/SOL
ANTYPE,2
MODOPT,LANB,10
EQSLV,SPAR
MXPAND,10, , ,0
LUMPM,0
```

```
PSTRES,0
MODOPT,LANB,10,0,10000, ,OFF
/STATUS,SOLU
SOLVE
/POST1
SET,LIST

/CLEAR,NOSTART
/prep7
L=27.8e-2
W=4e-3
B1=3.5E-2
A1=2.5e-3

SIZE1=(B1/L)*500
SIZE2=(1-B1/L)*500
ET,1,PLANE183
KEYOPT,1,1,0
KEYOPT,1,3,0
KEYOPT,1,6,0
MP,EX,1,200e9
MP,PRXY,0.3
MP,DENS,1,7680
BLC4, , ,B1,W
BLC4,B1 , ,L-B1,W
LSEL,R,LENGTH,,W
LPLOT
LESIZE,ALL, , ,16, , , , ,1

ALLSEL,ALL
LSEL,S,LINE,,1,3,2
LESIZE,ALL, , ,SIZE1, , , , ,1

ALLSEL,ALL
LSEL,S,LINE,,5,7,2
```

```
LESIZE,ALL, , ,SIZE2, , , , ,1
ALLSEL,ALL

MSHAPE,0,2D
MSHKEY,1
AMESH,ALL

LSEL,S,LOC,X,B1
LPLOT
NSLL,S,1
NPLOT
NSEL,R,LOC,Y,A1,W
NPLOT
NUMMRG,NODE, , , ,LOW
ALLSEL,ALL
LSEL,S,LOC,X,0
LPLOT
NSLL,S,1
/SOLU
D,ALL, , , , , ,ALL, , , , ,

/PREP7
EPLOT
ALLSEL,ALL

/SOL
ANTYPE,2
MODOPT,LANB,10
EQSLV,SPAR
MXPAND,10, , ,0
LUMPM,0
PSTRES,0
MODOPT,LANB,10,0,10000, ,OFF
/STATUS,SOLU
SOLVE
```

```
/POST1
SET,LIST
```