# *Machine Tool Damage Prediction Using Modal Characteristics*

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***Abstract*—Crack damage is the one of the main reasons for the machine tool structure failure. Machine tool damage prediction (MTDP) helps to make sure that there is no damage in the tool during machining and to predict the possible breakage of tool by identifying the appearance of small cracks in the tool during machining. Machine tool state monitoring is critical for controlling the work piece quality and production continuity in the case of mass production. For assessing tool wear and tool breakage MTDP is a suitable means. In this study finite element based damage prediction model employing piezoelectric is developed for determining the depth as well as the position of tool cracks. The variation of modal characteristics like natural frequency and mode shape with tool damage is analyzed. Parametric study is conducted by varying the number, depth and position of cracks. Piezoelectric sensor is also modelled using ANSYS to prove the effectiveness of the same in MTDP. Modal and harmonic vibration analysis are performed to determine the natural frequency of the system.**

***Keywords—crack; damage prediction; piezoelectric sensor; ANSYS; harmonic vibration***

## I. INTRODUCTION

The use of varying dynamic characteristics in the detection of cracks has been a hot research topic now a days and is a source of attraction for civil, aerospace, and mechanical engineering communities in recent years. Crack in vibrating components causes a change in physical properties of a structure which in turn affects dynamic response characteristics [1], [2], 3]. Therefore dynamic response characteristics can be made use in order 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 failure. In recent years the study on monitoring and identifying the size, location and number of crack has caused wide attention [4]. Ultrasonic, eddy current, magnetic powder and infrared detection method have made certain level of success on crack detection, but these methods are only applicable to static conditions. Machine tool damage prediction (MTDP) 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 [5], [6], [7].

## II. MACHINE TOOL DAMAGE PREDICTION (MTDP)

The process of implementing a damage prediction and characterization strategy for machine tools is referred to as machine tool damage prediction system. Here damage is defined as changes to the material and/or geometric properties of a structural system, including changes to the boundary conditions and system connectivity, which adversely affect the system's performance. The machine tool damage prediction process involves the observation of a system over time using periodically sampled dynamic response measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of the tool.

### *A. Statistical Pattern Recognition Paradigm Approach*

The damage monitoring can be addressed in the context of a statistical pattern recognition paradigm. This paradigm can be broken down into four parts: (a) Operational Evaluation, (b) Data Acquisition and Cleansing, (c) Feature Extraction and Data Compression, and (d) Statistical Model Development for Feature Discrimination. These processes can be implemented through hardware or software and, in general, some combination of these two approaches will be used.

#### *a) .Operational Evaluation:*

Operational evaluation attempts to answer the four questions regarding the implementation of a damage identification capability:

i) What are the life-safety and/or economic justification for performing the damage monitoring?

ii) How is damage defined for the system being investigated and, for multiple damage possibilities, which cases are of the most concern?

iii) What are the conditions, both operational and environmental, under which the system to be monitored functions?

iv) What are the limitations on acquiring data in the operational environment?

Operational evaluation begins to set the limitations on what will be monitored and how the monitoring will be accomplished. This evaluation starts to tailor the damage identification process to features that are unique to the system being monitored and tries to take advantage of unique features of the damage that is to be detected.

b*). Data Acquisition, Normalization And Cleansing:*

The data acquisition portion of the damage monitoring process involves selecting the excitation methods, the sensor types, number and locations, and the data acquisition/storage/transmittal hardware. Again, this process will be application specific. Economic considerations will play a major role in making these decisions. The intervals at which data should be collected are another consideration that must be addressed.

Because data can be measured under varying conditions, the ability to normalize the data becomes very important to the damage identification process. As it applies to damage monitoring, data normalization is the process of separating changes in sensor reading caused by damage from those caused by varying operational and environmental conditions. One of the most common procedures is to normalize the measured responses by the measured inputs. When environmental or operational variability is an issue, the need can arise to normalize the data in some temporal fashion to facilitate the comparison of data measured at similar times of an environmental or operational cycle. Sources of variability in the data acquisition process and with the system being monitored need to be identified and minimized to the extent possible. In general, not all sources of variability can be eliminated. Therefore, it is necessary to make the appropriate measurements such that these sources can be statistically quantified. Variability can arise from changing environmental and test conditions, changes in the data reduction process, and unit-to-unit inconsistencies. Data cleansing is the process of selectively choosing data to pass on to or reject from the feature selection process.

*c) Feature Extraction And Data Compression*

The area of the damage monitoring process that receives the most attention in the technical literature is the identification of data features that allows one to distinguish between the undamaged and damaged structure. Inherent in this feature selection process is the condensation of the data. The best features for damage identification are, again, application specific.

One of the most common feature extraction methods is based on correlating measured system response quantities, such a vibration amplitude or frequency, with the first-hand observations of the degrading system. Another method of developing features for damage identification is to apply engineered flaws, similar to ones expected in actual operating conditions, to systems and develop an initial understanding of the parameters that are sensitive to the expected damage. The flawed system can also be used to validate that the diagnostic measurements are sensitive enough to distinguish between features identified from the undamaged and damaged system. The use of analytical tools such as experimentally-validated finite element models can be a great asset in this process. In many cases the analytical tools are used to perform numerical experiments where the flaws are introduced through computer simulation. Damage accumulation testing, during which significant structural components of the system under study are degraded by subjecting them to realistic loading conditions, can also be used to identify appropriate features.

This process may involve induced-damage testing, fatigue testing, corrosion growth, or temperature cycling to accumulate certain types of damage in an accelerated fashion. Insight into the appropriate features can be gained from several types of analytical and experimental studies as described above and is usually the result of information obtained from some combination of these studies.

*d) Statistical Model Development*

The portion of the damage monitoring process that has received the least attention in the technical literature is the development of statistical models for discrimination between features from the undamaged and damaged structures. Statistical model development is concerned with the implementation of the algorithms that operate on the extracted features to quantify the damage state of the structure. The algorithms used in statistical model development usually fall into three categories. When data are available from both the undamaged and damaged structure, the statistical pattern recognition algorithms fall into the general classification referred to as supervised learning. Group classification and regression analysis are categories of supervised learning algorithms. Unsupervised learning refers to algorithms that are applied to data not containing examples from the damaged structure. Outlier or novelty detection is the primary class of algorithms applied in unsupervised learning applications. All of the algorithms analyze statistical distributions of the measured or derived features to enhance the damage identification process.

### B. *Present Work:*

Machine tool damage is one of the important problem during machining, tools may get break due to fatigue. Cracks are among the most encountered damage types in the machine tools that weakens the same. When the crack size increases in course of time, the tools becomes weaker than its previous condition. Finally, the tool may breakdown due to a minute pressure. Therefore, crack detection plays an important role for machine tool applications.

Most of the machine tools are cantilever beam configuration. The most common structural defect is the existence of a crack. Cracks are present in structures due to various reasons. The presence of a crack could not only cause a local variation in the stiffness but it could affect the mechanical behaviour of the entire structure to a considerable extent. Cracks may be caused by fatigue under service conditions as a result of the limited fatigue strength. They may also occur due to mechanical defects. Another group of cracks are 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 to detect cracks.

Dynamic characteristics of damaged and undamaged materials are very different. For this reason, material faults can be detected, especially in beams, which are very important construction elements because of their widespread usage in steel construction and machinery. Crack formation due to cycling loads leads to fatigue of the structure and to discontinuities in the interior configuration. 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. 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. 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.

## III. CRACK THEORY

### *A. Physical parameters affecting Dynamic characteristics of cracked structures*

The dynamic response of a structure is normally determined by the physical properties, boundary conditions and the material properties. The changes in dynamic characteristics of structures are caused by their variations. The presence of a crack in structures also modifies its dynamic behavior. The following properties of the crack influence the dynamic response of the structure.

- The depth of crack
- The location of crack
- The orientation of crack
- The number of cracks

### *B. Classification of Cracks*

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 weaken 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.

Longitudinal cracks: These cracks are parallel to the beam axis. It is dangerous when tensile load is applied at right angles to the crack direction i.e. perpendicular to beam axis or perpendicular to crack.

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. 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.

Gaping cracks: These cracks always remain open. They are more accurately known as notches.

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.

Subsurface cracks- These are the cracks that are not on the surface. Special techniques such as ultrasonic, magnetic particle, radiography or shaft voltage drop are needed to detect them.

### *C. Cantilevered Machine Tools*

Machine tools are generally cantilevered type because they are fixed at one end and force is applied on the other end. Metal cutting broadly constitutes turning, boring, drilling, facing, forming and parting-off, milling and shaping/planning. Cutting tools generally can be classified into two categories: single point tools (turning, shaping, and planning) which have one cutting edge and a shank, while multiple tool points (drilling, milling, broaching) have more than one cutting edges. 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. Two kinds of metal cutting operations in turning can be encountered; oblique and orthogonal cutting. Orthogonal cutting represents a reasonable approximation of cutting on the major cutting edges and therefore is the most prevalent form of cutting. In orthogonal cutting the cutting tool approaches the work piece at right angles to the direction of cutting, with the cutting edge parallel to the uncut surface. A full understanding of the mechanics of the orthogonal cutting process is not intended to be discussed in this paper. It is, however, fair to assume that high stresses and strain rates develop as the cutting tool ploughs through the work piece giving rise to complicated forces, high temperatures and dynamic behaviour across a broad spectrum of frequencies and this can be compared with a cantilever beam [8] .

### *D.Practical methods for detecting tool wear and cracks*

Most indirectly measured sensor signals are generally affected by work piece material variation, geometry and material of the cutting tool and the cutting conditions. An on-line monitoring system designed to take all the before mentioned factors into consideration would be extremely demanding. Machine tool damage prediction (MTDP) employs FFT analyses to predict the breakage during machining. [9][10].

## IV. ANALYSIS OF THREE DIMENSIONAL BEAM WITH CRACK AND WITHOUT CRACK

### *A. Piezoelectric Constitutive Equations*

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. Furthermore, if electrodes are attached to the surfaces of the material, the generated electric charge can be collected and used. This property is particularly utilized in piezoelectric shunt damping applications.

Piezoelectric or magnetostrictive materials have two constitutive laws, one of which is used for sensing and the other for actuation purposes. For 2-D problems, the constitutive model for a piezoelectric material is of the form:

$$\{\sigma\}_{3x1} = [C]^{(E)}_{3x3}\{\varepsilon\}_{3x1} - [e]_{3x2}\{E\}_{2x1} \quad (1)$$

$$\{D\}_{2x1} = [e]^{T}_{2x3}\{\varepsilon\}_{3x1} + [\mu]^{(\sigma)}_{2x2}\{E\}_{2x1} \quad (2)$$

`The first of this constitutive law is called the actuation law, while the second is called the sensing law. Here,

$\{\sigma\}^T = \{\sigma_{xx} \;\; \sigma_{yy} \;\; \tau_{xy}\}$ is the stress vector,

$\{\varepsilon\}^T = \{\varepsilon_{xx} \;\; \varepsilon_{yy} \;\; \gamma_{xy}\}$ is the strain vector,

$[e]$ is the matrix of piezoelectric coefficients of size 3 x 2, which has units of N/(Vmm),

$\{E\}^T = \{E_x \;\; E_y\} = \{V_x/t \;\; V_y/t\}$ is the applied field in two coordinate directions

$V_x$ and $V_y$ are the applied voltages in the two coordinate directions

$t$ is the thickness parameter

$[\mu]$ is the permittivity matrix of size 2 x 2, measured at constant stress and has units of N/V/V and

$\{D\}^T = \{D_x \;\; D_y\}$ is the vector of electric displacement in two coordinate directions. This has units of N(V mm)

$[C]$ is the mechanical constitutive matrix measure at constant electric field.

Eqn. (1) can also be written in the form:

$$\{\varepsilon\} = [S]\{\sigma\} + [d]\{E\} \quad (3)$$

In the above expression, *[S]* is the compliance matrix, which is the inverse of the mechanical material matrix *[C]* and $[d] = [C]^{-1}[e]$ is the electromechanical coupling matrix, where the elements of this matrix have units of mm/V and the elements of this matrix are 'direction dependent'. In most analyses, it will be assumed that the mechanical properties will change very little with the change in electric field and as a result, the actuation law (Eqn. (1)) can be assumed to behave linearly with the electric field, while the sensing law (Eqn. (2)) can be assumed to behave linearly with stress. This assumption will considerably simplify the analysis process.

The first part of Eqn.(1) represents the stresses developed due to mechanical load, while the second part of the same equation gives the stresses due to voltage input. From Eqn. (1) and (2), it is clear that the structure will be stressed due to the application of electric field, even in the absence of a mechanical load. Alternatively, when the mechanical structure is loaded, it generates an electric field.

In other words, the above constitutive law demonstrates electromechanical coupling, which is exploited for a variety of structural applications, such as vibration control, noise control, shape control and structural health monitoring. Actuation using piezoelectric materials can be demonstrated by using a plate of dimensions $L$ x $W$ x $t$, where $L$ and $W$ are the length and width of the plate and $t$ is its thickness. Thin piezoelectric electrodes are placed on the top and bottom surfaces of the plate, as shown in Fig 1.

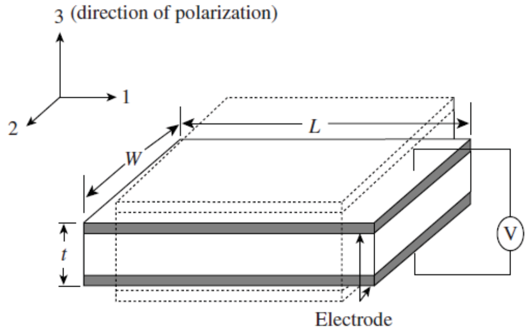

Figure 1: Illustration of the actuation effect in a piezoelectric plate

### B. *Solid186 and Solid 220 Element Description*

SOLID186 is a higher order 3-D 20-node solid element that exhibits quadratic displacement behavior. The element is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. This structural Solid is well suited to modeling irregular meshes (such as those produced by various CAD/CAM systems). The element may have any spatial orientation. Generally the number of nodes used in the analysis was approximately (1250-1300) and the number of elements was (550-600).

Solid220 has twenty nodes with up to five degrees of freedom per node including electric potential which may be employed for modeling piezoelectrics.

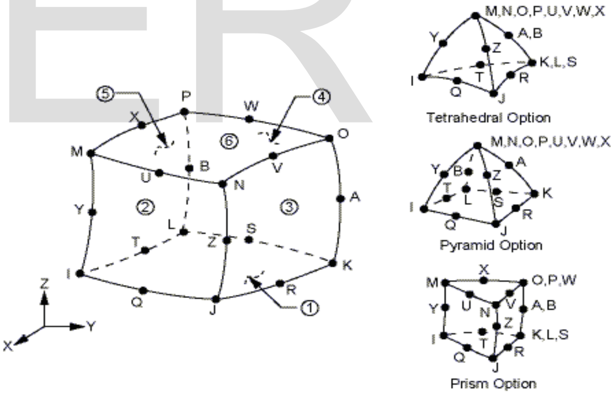

Figure 2: SOLID 186/226 Geometry

### C. *Uncracked And Cracked Beam Analysis*

The uncracked 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. The meshed model of 3D beam model is shown in Fig. 3 below.

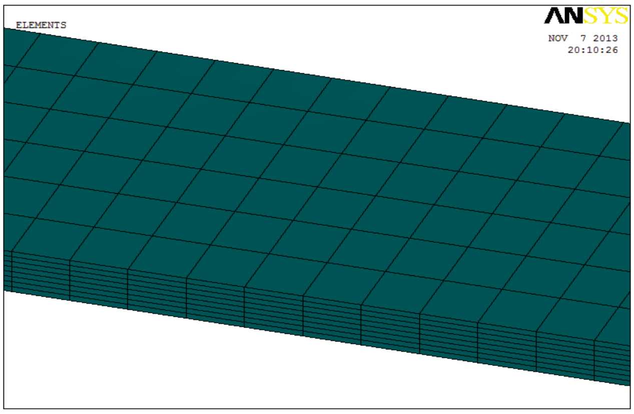

Figure 3: Meshed 3D Beam Model

### D. *Modal Analysis Of Three Dimensional Beam Without Crack*

The mode shapes of uncracked beam are obtained as shown in figures below.

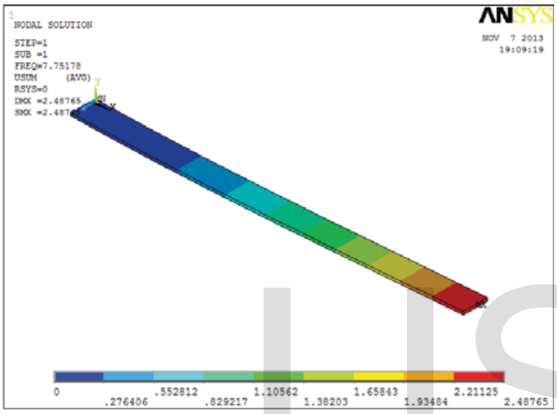

Figure 4: Un-cracked Cantilever Beam 3D – First Mode

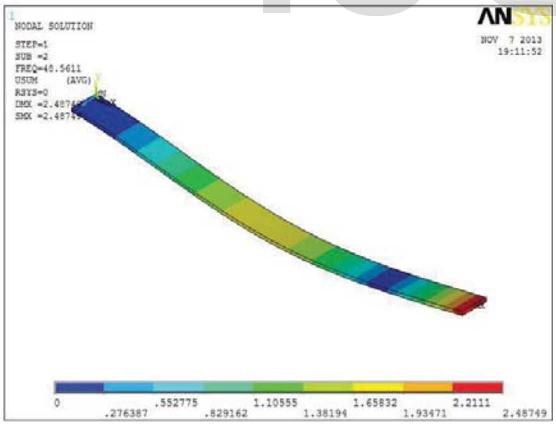

Figure 5: Un-cracked Cantilever Beam 3D – Second Mode

### E. *Modal Analysis Of Three Dimensional Beam With Crack*

The mode shapes of cracked beam are obtained as shown in figures below

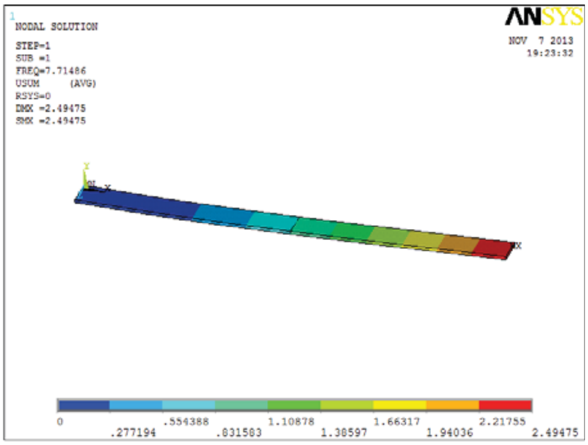

Figure 6: Cracked Cantilever Beam 3D – First Mode

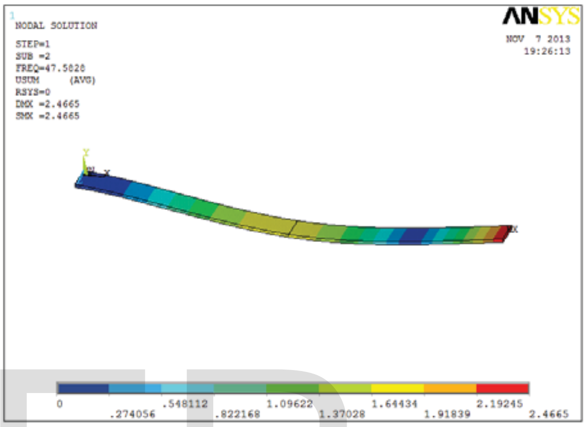

Figure 7: cracked Cantilever Beam 3D – Second Mode

Effect of crack location on natural frequencies for different crack location are shown in the graphs below

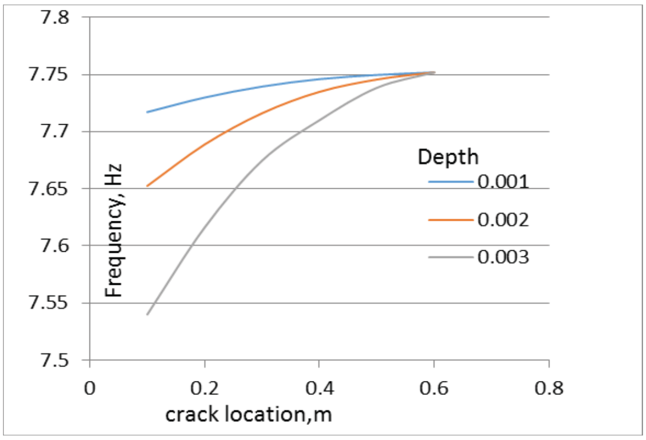

Figure 8: First mode at different crack location

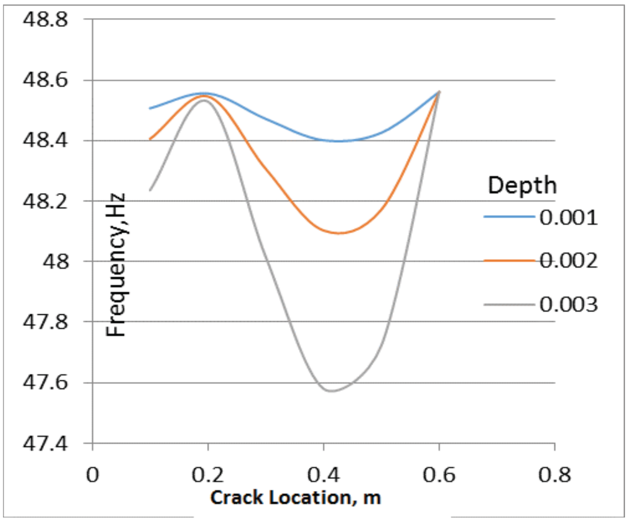

Figure 9: Second mode at different crack location

## V ANALYSIS OF THREE DIMENSIONAL BEAM EMPLOYED WITH PIEZOELECTRICS

### A. *Modelling Of Beam With Piezoelectric*

In this section, the modal analysis of a three dimensional beam with piezoelectric were analyzed. For that a beam is modeled with the following dimensions. The structural steel ($E=210x10^9$ N/m$^2$, p=7700 kg/m$^3$, $v$ =0.28) cantilever beam has the following dimensions.

Length of the Beam = 0.295 m
Width of the beam = 0.012 m
Height of the Beam = 0.004 m

After modeling of three dimensional beam the piezoelectric should be modeled, for that we are using solid 226 as the element type. Solid 226 is used as the element type because it is a mid-node element. Since we are using solid 186 a mid-node 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, piezo electric is modeled from that coordinate system with the following dimensions.

Length of the piezoelectric = 0.02 m
Width of the piezoelectric = 0.012 m
Height of the piezoelectric= 0.001 m

After modeling meshing is done, meshed model of piezoelectric on a solid beam is shown in the figure

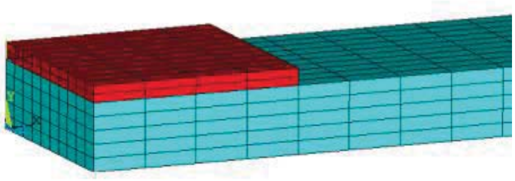

Figure 10: Meshed model of beam with piezoelectric

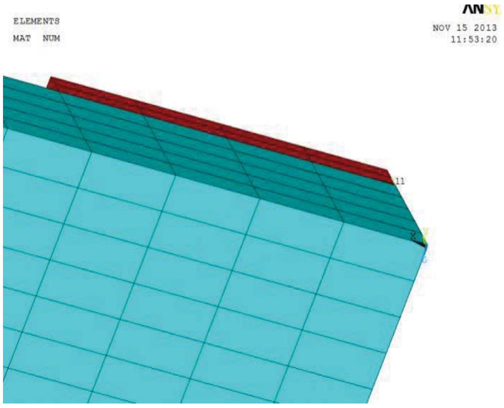

Figure 11: Piezoelectric coordinate system

The shifted coordinate system can be seen from the Fig 11, it is named as 11. After modelling merging of two volume 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, graph shown below gives the output of piezoelectric.

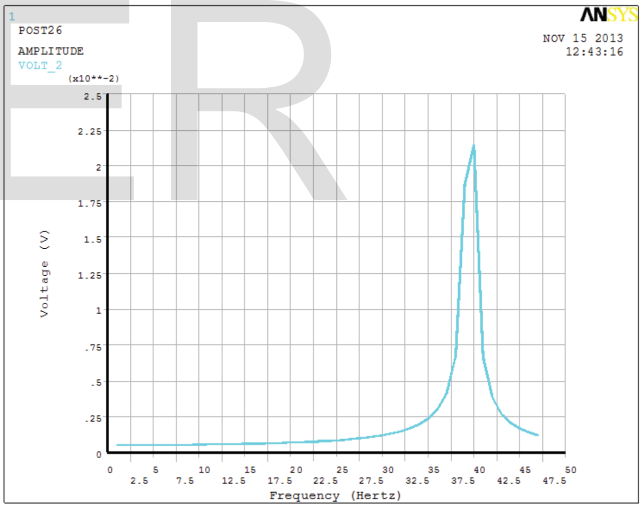

Figure 12: Graph showing peak voltage

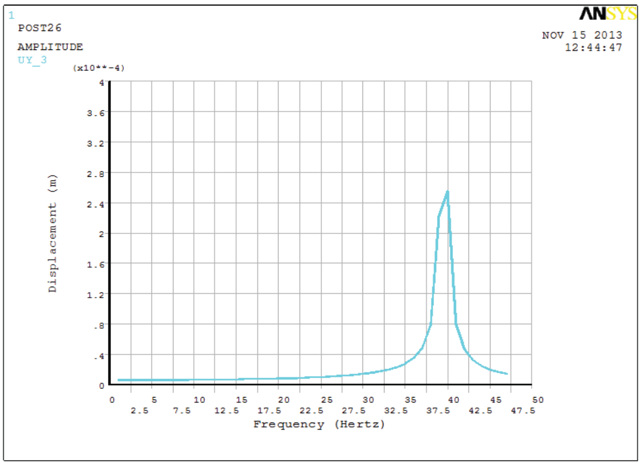

Figure 13: Graph showing maximum displacement

## VI. RESULTS AND DISCUSSIONS

From the above table and from the graph it could be noticed that the frequency variation is more near the constrained ends than at the free ends in the case of first and second set of natural frequencies, towards the free end of the beam, the frequency variation due to the cracks decreases.

In the case of second mode maximum frequency variation is at middle where the crack is present. It is because there is maximum crack opening during this set of motion.

From the Fig (12) and (13), it is evident that natural frequencies due to the presence of crack on the beam is reduced. Percentage of variation is very much less. It is also clear that the results we obtained from the analysis is in good agreement with the journal results than that of the 2D results [1].

Minute change in the result is due to the fine refinement that we have given. There is no much variation in the fourth mode because of the position of the crack. Crack opening for the particular mode shape is less so variation in the natural frequency is also less.

*Effect of Crack Location on Natural Frequencies*

For studying the effect of crack location on natural frequency, the modal analysis of cracked beam was done by keeping the depth of the crack a constant and the crack positions varied at different locations from the constrained end. Variation of frequencies at different crack depths when Relative Crack location at 0.1,0.2,0.3,0.4,0.5 and 0.6 m are as given in the figures. A constant crack depth is maintained throughout this different crack locations.

From the graph we can see the natural frequency of the beam comes in between 39 to 40 Hz. 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 also clear that by using a piezoelectric we can find the natural frequency. 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. From the above results we can conclude that for experimental purpose we can use a piezofilm sensor for finding the natural frequency.

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