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HEALTH MONITORING OF PLATE STRUCTURE USING PIEZO ELECTRIC PATCHES AND CURVATURE MODE SHAPE

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ABSTRACT

A reliable and effective damage detection technique is important to maintain the safety and integrity of structures. This study is based on dynamic analysis, uses an integrated methodology for detection, location and severity of damage in a plate like structure. Finite element analysis is used for simulating the crack model. In the first approach, piezoelectric patches are used as sensors and actuators, being bonded on both sides of the structure which execute flexural oscillations. They measure differential bending strain in terms of voltage difference to detect presence of cracks very effectively without the need to compare with a healthy sample. The second method is based on curvature mode shape parameter and is used for structural health monitoring. In this method in addition to detection, location and severity estimation is also possible by comparing an intact structure. Both the methods are carried out in frequency domain analysis and it is limited to lower modes. Results shows that proposed multi method incorporating piezoelectric patch and curvature mode shape is effective in damage assessment in plate structure

Keywords: Structural Health monitoring; Piezoelectric Sensors and actuators; Dynamic analysis; Curvature Mode Shape; frequency Domain Analysis.

1.INTRODUCTION

The structural integrity of any structure is of paramount importance since any failure could be highly catastrophic, in some cases possibly life threatening. Damage occurs during service because of many factors such as operational cyclic loading ,aging, mechanical vibration, changing of ambient conditions, shocks and corrosion. Hence early detection of damage, location and severity is very important. The basic way of damage detection is to remove the structure from a service and check for its damage zones; however this is a time consuming and expensive. Therefore online detection of damage i.e. checking the structure while in-service is preferred which is generally called Structural Health Monitoring (SHM). The dynamics-based damage detection is an effective method due to its simplicity of implementation and ability of acquiring both the global and the local information of the structure. The development of real-time, in-service structural health monitoring and damage detection techniques using smart material has recently attracted a large number of academic and industrial researchers. Application of a combination of two different damage detection techniques such as electromechanical coupling property of piezoelectric material and tracking the changes in the frequency response function data is shown in [1]. [2] Has presented the method which uses pairs of piezoelectric sensors bonded on both sides of a structure executing flexural oscillations in order to determine the changes in the strain distribution due to the presence of a crack. The advantage of using PZT sensors is that by passing a voltage in the PZT elements, strains are induced, even in the absence of external forces [3]. Experimental PZT based damage detection in steel bridge components is investigated [4]. A comprehensive survey of various vibrations based damage detection methods including curvature mode shape is presented in [5].A curvature mode shape based damage detection in composite structure is shown in [6]. The curvature mode is shown to be an excellent parameter in damage detection of structure while in case that certain curvature mode curve cannot show existence of damage. A curvature mode changing rate (CMCR) method for the damage detection is shown in [7]. In this study the effective combined utilization of Piezo Electric patches and Curvature mode shape for vibration based structural health monitoring is explored. It is not only detecting the damage but to estimate the damage location and severity.

NOMENCLATURE

σ	Stress Tensor in Gpa
Rf	Amplifier Constant
ε	Strain tensor
E_p	Young'sModulas piezo electric Material
D	Electrical Displacement vector(c/m^2)
2h	Thickness of plate in mm
d	Piezo electric Coupling coefficient (C/N)
h_p	Thickness of piezo patches in mm
k	Dielectric Permittivity (Vm/c)
w	Bending displacement in mm
E	Electric Field (V/m)
C	Compliance matrices m^2/N

2.HEALTH MONITORING USING PIEZO ELECTRIC PATCH

Piezo zirconium titanium material (PZT) is a type of smart material which involves interactions between two fields such as mechanical and electrical, which allow the material to be used as a sensor and or an actuator in some manner. PZT generate electrical potential when subjected to mechanical loading (direct effect) and acts as sensor. It can generate mechanical displacements when subjected to electrical loading and act as actuator (converse effect). The materials used for this study are aluminium (host structure) and PZT (actuator and sensor).

2.1. **Mathematical Modeling of plate structure**

In plate, generally flexural vibration is taking place simultaneously in the x and y direction and general equation of plate is given below

$$Dp\left(\frac{\partial^4 w}{\partial x^4}+2\frac{\partial 4w}{\partial x^2\partial y^2}+\frac{\partial^4 w}{\partial y^4}\right)+\rho h\ddot{w}=0 \qquad (1)$$

Where,w= transverse displacement, ρ =density of structure, Dp= flexural stiffness is defined as

$$\mathrm{Dp} = \frac{\mathrm{Eh}^3}{12(1-\upsilon^3)} \qquad (2)$$

Where E = young's modulus υ = poisson ratio

$w(x,\bar{y},t) \longrightarrow w(x,t)$, thus equation is simplified to get

$$Dw''' + \rho h\ddot{w} = 0 \qquad (3)$$

The constitutive Equation for the piezo electric material is

$$\begin{Bmatrix} \in \\ D \end{Bmatrix} = \begin{bmatrix} c & d^T \\ d & k \end{bmatrix} \begin{Bmatrix} \sigma \\ E \end{Bmatrix} \qquad (4)$$

When certain conditions are imposed, the problems can be simplified in such that it yields an invariant with y and depends only on x such vibrations are called straight-crested flexural vibrations

2.2 Actuator Equation

In this numerical analysis, design of actuator is a laminar design i.e. the PZT layer is bonded on the host structure as shown in figure 1. The geometrical arrangements such that the useful direction of expansion is normal to that of the electric field and thus the activation capability are governed by the piezoelectric constant d_{31}. Here it is assumed that the thickness of PEP (Piezo Electric Patch) is very small compared to the thickness of plate structure hp << h. The PEP is used as actuator by controlling the voltage V applied to the electrodes creating a constant electric field v/hp and here it is assumed that electrodes having uniform width and thickness

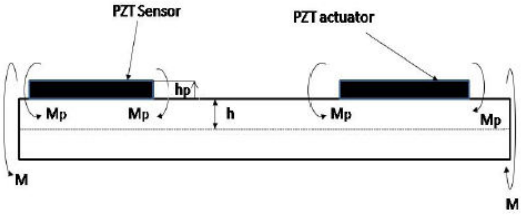

FIGURE 1

The moment acting at the actuator is $M_p = -E_p\, d_{31} V b_p h$ (4)
Above equations are based on the assumption that thickness of PEP patch is very smaller than that of plate ie hp << h

2.3 **Sensor Equation**

Consider a thin piezoelectric strip of width b_p and length l_p which is bonded on the upper (or lower) surface of a plate of height 2h and w(x,t) is the flexural displacement of the plate. The contact between the piezoelectric strips and the surface is assumed to be ideal. The piezoelectric strip can be used as a sensor, in which case the output voltage $\emptyset_{out}$ can be expressed in the form . The output voltage of the current amplifier is

$$\emptyset_{out}(t)=R_f E_p d_{31}\int_{x1}^{x2} bp(x)\dot{w}''dx$$
$$\rightarrow \emptyset_{out}(t)=R_f\, E_p d_{31} hbp\,[\dot{w}'(x_2)-\dot{w}'(x_1)\,] \qquad (5)$$

Where R_f = amplifier constant, b_p= width of plate and

$$w'(x_1) = \left[\frac{\partial w}{\partial x}\right]_{x=x1} \text{ and } \dot{w}'(x_1) = \frac{dw'}{dt}(x_1)$$

The dynamic analysis of the structure with piezoelectric strips is performed in this study using a finite element formulation. Finite element analysis is carried out with Ansys[8]. In the FEM analysis SOLID 45 element is used for modelling of host structure. The element is defined by eight nodes having three degrees of freedom at each node:i.e. ,translations in the nodal x, y, and z directions. And SOLID5 element is used to model the sensor and actuator (piezo electric strips), the element has eight nodes with up to six degrees of freedom at each node and it has 3-D magnetic, thermal, electric, piezoelectric, and structural field capability with limited coupling between the fields.

3 **CRACK DETECTION METHEDOLOGY**

The strategy used here involves two piezoelectric sensors glued on the opposite sides of a bending plate type structure. When there is no crack, the voltage difference between the two sides is zero, since strain on both sides will be same. If there is a crack, the strains on the two sides of the structure will be different, and hence the induced voltage generated in the piezoelectric strips will also be different. By measuring the voltage difference between the two piezoelectric strip sensors, the presence of cracks can be predicted. The strains caused by the influence of crack were found to be very small, when the static load acting on the structure. Therefore in this study the structure is subjected to flexural (bending) oscillation and thus the differential strain caused by the crack is large enough to measure with piezo electric patches.

4.**CRACK SIMULATION.**

In this study a crack is simulated by disconnecting a pair of nodes at the desired crack locations at different depths in the structure. During dynamic loading, the crack is opened during tension and is closed during compression, thus it is a nonlinear model of crack opening. But in the compression phase there is a problem of disconnected pair of nodes can penetrate into each other . In order to avoid such phenomenon, contact elements are used in the two sides of the gap. These contact elements use a

“target surface’ for one side of the gap and a “contact surface” for the other gap side, which together form a contact pair. The numerical results presented in this study use TARGE170 element for target surface and CONTA174for contact surface.

5. **RESULT AND DISCUSSION** (**Cantilever Beam Structure)**

The crack is simulated on the host structure in a depth of 1.25mm at a distance 330 mm from fixed end , it is made upto middle of the plate(30mm) as shown in figure[2]

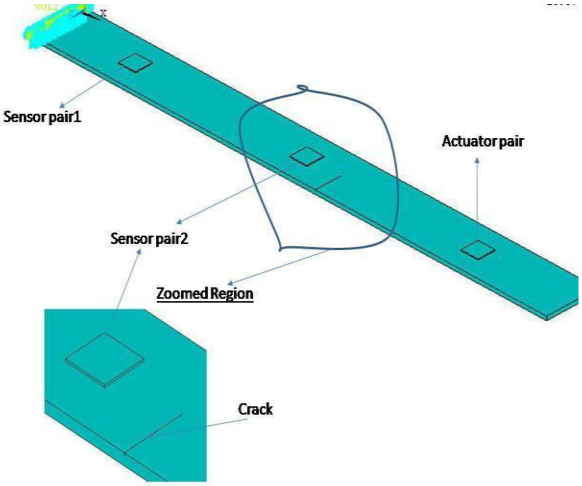

FIGURE 2

Modal analysis and harmonic analysis are separately done on the structure. Modal analysis is used to determine the vibration characteristics (natural frequencies and mode shapes) of a structure which is a starting point of any detailed dynamic analysis such as harmonic analysis. Block Lanczos mode extraction method is carried out in modal analysis, frequencies up to 800 Hz are extracted. Cantilever type structure is used in this analysis in which there are three pairs of piezoelectric patches, each pair consisting of two piezoelectric patches bonded at the same axial location on the upper and lower sides of a plate of length 600 mm, width 40 mm and thickness 5 mm, which is fixed at one end and free at the other end. The length, width and thickness of the piezoelectric patches are 40 mm, 20 mm and 1 mm, respectively. The first two pairs of piezoelectric patches, located at 280 mm and 80 mm distance from the fixed end, are used as sensors, and a third pair of piezoelectric strip, located at 480 mm distance from the fixed end, is used as actuator. It is shown that variation of frequency between healthy and damaged plate is very small which is not sufficient for detection of crack. Thus it undergoes harmonic response analysis upto 1000Hz frequency range using a electrical loading. The results of voltage difference is measured by using sensor pair 1 and sensor pair2 as shown in figure [3] . There is well defined three peaks (150, 650and 800Hz) can be seen in the figure [3] and all the peaks corresponds to the natural frequency of the structure. It is seen that sensor pair2 is showing higher peaks because in this case crack is near to the sensor pair2 and can also approximately locate the damage in addition to damage detection.

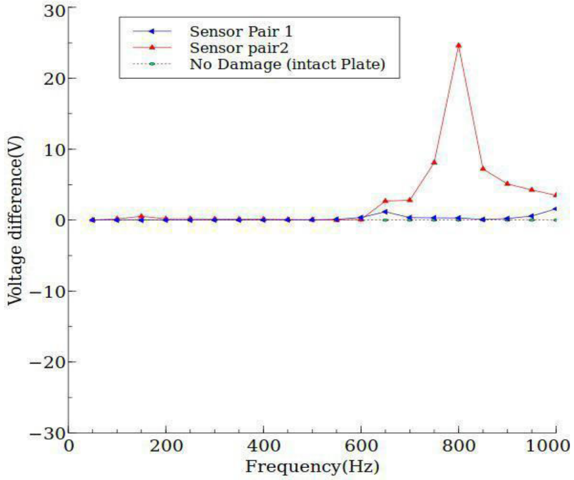

FIGURE 3

Health monitoring using Curvature Mode shape

This study shows that the change in curvature mode shape is a viable technique for Structural Health Monitoring. The change in the curvature mode shapes increase with increase in size of damage. The difference in curvature mode between the intact and the damaged case is utilized to detect the location and extent severity of the crack. If a crack or other damage is introduced in a structure, it reduces the flexural rigidity (EI) of the structure at the damaged region, which increases the magnitude of curvature at that section of the structure. The changes in curvature are local in nature and hence can be used to detect and locate a crack or damage in the structure.

Finite Element analysis

A cantilever plate of dimension (600X60X5) mm is used for this analysis. The plate is subjected to a straight crested flexural vibration as done in the Piezo Electric patch analysis and therefore curvature (kx) is calculated at each point using central difference formula as shown below.

$$w''=\frac{w_{i-1}-2w_i+w_{i+1}}{h^2} \qquad (6)$$

where w_i is the vertical displacement mode shape at node i and h is the length of element. The variation of ky is very small because in this case aspect ratio (L/B) was taken 10 and thus membrane effect is neglected and also lower mode is investigated in this numerical analysis

Initially FEM model of plate structure with above dimension were modeled by using shell63 element. The element has both bending and membrane capabilities and it has six degree of freedom at each node, translational in the nodal x, y, z directions and rotational nodal x, y and z directions. The plane stress analysis is done with mesh size of regular element (20X20) mm. First Modal analysis of healthy plate is carried out and frequency up to 5th mode extracted throughout the analysis. For each mode frequency and displacement mode shape are calculated, then damage are simulated at different location of the plate structure by reducing the stiffness of 7% and measured modal frequency and displacement mode shape of the corresponding damaged plate. Using the above central difference formula calculate curvature mode shape (CMS) of the corresponding displacement mode shape obtained from the Ansys and compared the values between damaged And intact plate.

6.RESULT AND DISCUSSION

Cantilever plate with damage at near the fixed region The size of the damage is (20x20) mm and plate structure is divided into 30 along length direction and 4 division along width direction as shown in figure[4]. The damage is simulated by reducing the stiffness at the rate of 7%.

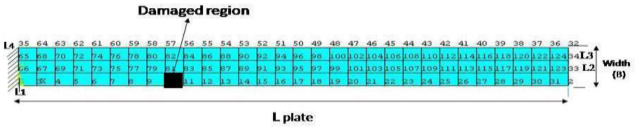

FIGURE 4

The table[1] shows the variation of modal frequency between damaged and healthy plate and here the variation is very small. This variation in modal frequency is not suitable for the damage detection.

TABLE1. COMPARISON OF MODAL FREQUENCY BETWEEN DAMAGED AND INTACT PLATE

Mode No:	Intact plate (frequency Hz)	Damaged Plate (frequency Hz)	% error
1	11.152	11.144	0.072
2	69.896	69.887	0.013
3	131.98	131.84	0.106
4	196.09	196.95	0.071
5	216.59	216.42	0.078

But consider the absolute curvature mode shape (difference of curvature mode shape of damaged and intact plate) as shown in figure [5] which gives the location of the damage and severity of the damage.

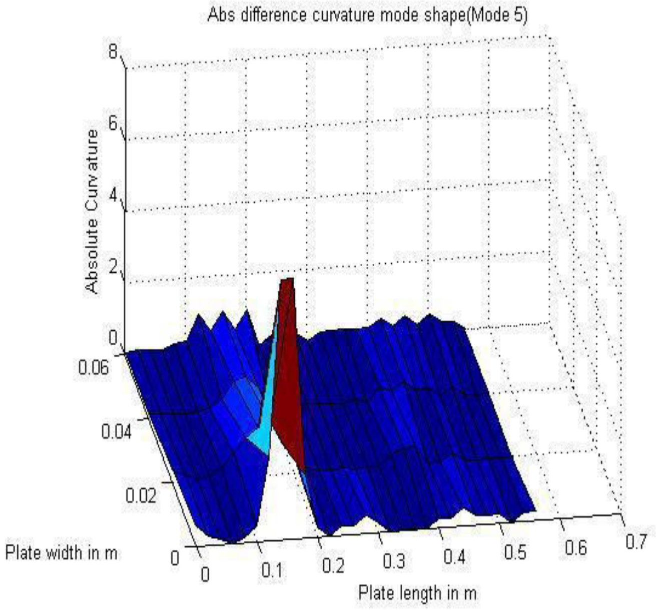

FIGURE 5

7.CONCLUSIONS

- Application of piezoelectric patches is promising for the damage detection of very fine cracks, without the need of comparing with a healthy sample. The damage location can be approximately fixed.
- Curvature method is best for damage location and quantification but required comparison with healthy sample
- Combining both techniques improves the detection, location and quantification of damage

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