Analysis of Piezoelectric Actuator for Vibration Control of Composite plate

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Abstract. Vibration analysis is studied numerically in this paper for a simply supported composite plate subjected to external loadings. Vibrations are controlled by using piezoelectric patches. Finite element method (ANSYS) is used for obtaining finite element model of the smart plate structure, a layered composite plate is manufactured experimentally and tested to obtain the structure mechanical properties. Different piezoelectric patch areas and different applied gain voltage effects on vibration attenuation is studied. The numerical solution is compared with the experimental work, a good agreement achieved.

1. Introduction
The use of layered composite materials in the aeronautics and astronautics industry have been increased, plate and shell structures are most widely used elements. It had been showed that the piezoelectric materials are useful and used for smart adaptive structures [1-4]. Control and suppression of structural vibrations are necessary and also important. Recently, smart materials and structures especially piezoelectric elements are preferred and widely used for vibration control and suppression [5-7]. FEM is used to reduce the iterations done experimentally and to evaluate the behaviour of the smart structures subjected to electromechanical loads [8-10]. ANSYS is used in this work to study the vibrations of a fully simply supported composite plate subjected to external force. Vibration is controlled and suppressed successfully using the PZT piezoelectric patches bonded to the plate surface. The effect of different PZT patch area is examined experimentally and the results compared with the numerical solution, a good agreement is achieved. Also the effect of different applied voltage to the piezoelectric film is studied. 8-ply E-glass epoxy composite plate is manufactured and its mechanical properties is obtained using tensile tests, then vibration tests is applied on the plate with the PZT patches.

2. Production of the laminate specimens
E-Glass woven fiber was used as a bidirectional fabric as shown in Figure1. And laminating epoxy resin as matrix for the composite material of the laminates specimens. Industry has evolved a dozen separate manufacturing processes for fabricating composites each one offers advantages and specific benefits. Hand lay-up is a basic moulding process which is used in this work.

Figure 1.
E-Glass woven fabric.
3. Experimental determination of mechanical properties

The first set of tests in the experimental work was performed for the mechanical characterization of the used composite laminate plates. Characterization was used to determine the mechanical properties of the composite laminate (Glass/epoxy). These mechanical properties were required as inputs to the finite element model for natural frequency detection by free vibration. The test program and specimen’s configuration for laminate and specimen’s configuration for laminate characterization are shown in Table 1. In order to obtain any material property, three specimens were tested and the average value was considered.

Table 1. Characterization test program

| Elastic constants | No. of specimens | Length | Width | Layers | Orientation |
|-------------------|------------------|--------|-------|--------|-------------|
| $E_{11}$          | 3                | 250    | 15    | 8      | 0°          |
| $E_{22}$          | 3                | 175    | 25    | 8      | 90°         |
| $\nu_{12}$        |                  |        |       |        | The same specimens from $E_{11}$ test. |
| $\nu_{21}$        |                  |        |       |        | The same specimens from $E_{22}$ test. |
| $G_{12}$          | 3                | 250    | 25    | 8      | $\pm 45^\circ$ |

The testing machine used in the present experimental work was a computerized universal testing machine (Shimadzu) of capacity 50 kN.

3.1. Tensile test procedure

Nine specimens were prepared for tensile test using material test system machine as relevant to ASTM standard code (D3039) as shown in Figure 2. The mechanical properties of 8-layered woven fiber Glass/Epoxy were determined using 5 mm electrical strain gages. Unidirectional tensile tests were performed on specimens cut in longitudinal and transverse directions to obtain $E_{11}$, $E_{22}$, $\nu_{12}$ and $\nu_{21}$. Specimens cut at angle $\pm 45^\circ$ to the longitudinal direction were prepared to find the shear modulus $G_{12}$ according to Jones.

![Figure 2. Tensile test machine and the strain gauges mounted to specimen.](image)

3.2. Results of tensile test

3.2.1. Determination of $E_{11}$ and $\nu_{12}$. The longitudinal Young's modulus $E_{11}$ and the major Poisson's ratio $\nu_{12}$ were determined from a simple tension test. The longitudinal Young's modulus $E_{11}$ was determined from the slope of the stress-strain curve, the major Poisson's ratio $\nu_{12}$ was determined from the slope of the transverse and axial strain diagram during the same experiment as shown in Figure 3.

![Figure 3. Stress strain curve & Transverse and axial strain curve (direction 1).](image)
3.2.2. Determination of $E_{22}$, $\nu_{21}$, and $G_{12}$

Similarly, the transverse Young’s modulus $E_{22}$, Poisson’s ratio $\nu_{21}$, and in-plane shear modulus $G_{12}$ was determined from slope of stress strain diagrams.

From the previous experimental tensile tests, the average values of material properties of the 8-layered woven fiber Glass/Epoxy laminate are given in Table 2.

Table 2. Experimentally measured mechanical properties of 8-layered woven fiber Glass/Epoxy laminate

| $E_{11}$ | $E_{22}$ | $\nu_{12}$ | $\nu_{21}$ | $G_{12}$ |
|----------|----------|------------|------------|----------|
| 19 GPa   | 19 GPa   | 0.256      | 0.249      | 2.8 GPa  |

4. Vibration Test

The second set of tests is performed on square composite laminate with simply supported boundary conditions is the vibration test. The natural frequencies of the composite plate with different piezoelectric patch areas is measured and compared with the numerical results from ANSYS, then the effect of changing of applied volt on the PZT film is studied.

4.1. Effect of piezoelectric patches area on natural frequencies

The composite laminate plate specimens used in present experiment consist from 8 layers of (0/90) woven E-Glass fiber with epoxy matrix. After the cure process, four test specimens of size (200x200x2.5) mm$^3$ without piezoelectric patches and twelve test specimens of the same dimension with different areas of piezoelectric patches (50x50, 110x110, 150x150) mm$^2$ bonded on the top face of the composite plate with special wax were prepared to study the effect of increasing the piezoelectric actuator area on natural frequencies Figure 4.

The natural frequencies were measured for all specimens with four edges simply supported boundary conditions. Ten repeated tests were conducted for each plate. The force was measured using a force transducer with charge amplifier (B&K type 2626). This output was captured by one accelerometer to measure dynamic response and was amplified using a conditioning amplifier (B&K type 2626) as shown in Fig.4 and then read using the high resolution signal analyzer (B&K type 3562A), giving the frequency response function (FRF).

Figure 4. Vibration test measuring system with SS fixture of square laminate.

The first four measured experimental modes of vibration for different piezoelectric patch (actuator) area with 1 volt applied current on the top surface of structure are given in Table 3.

Table 3. Experimentally measured natural freq. (Hz) with different central piezoelectric patch areas

| Mode      | host plate only | Mid plane Piezoelectric film area (50x50) mm$^2$ | Mid plane Piezoelectric film area (110x110) mm$^2$ | Mid plane Piezoelectric film area (150x150) mm$^2$ |
|-----------|-----------------|-----------------------------------------------|-------------------------------------------------|-----------------------------------------------|
| First     | 172.2 Hz        | 176.3 Hz                                     | 191.2 Hz                                        | 199.4 Hz                                     |
| Second    | 459.5 Hz        | 462.8 Hz                                     | 550.5 Hz                                        | 615.2 Hz                                     |
| Third     | 466.3 Hz        | 467.5 Hz                                     | 560.4 Hz                                        | 620.2 Hz                                     |
| Fourth    | 686.4 Hz        | 695.3 Hz                                     | 798.2 Hz                                        | 870.1 Hz                                     |

From Figure 5, we can clearly observe that, the active control via the piezoelectric patches results in the increase of natural frequency, more predominantly for higher modes. The sensitivity of the primary frequency is high for the largest actuation area but lower for the small piezoelectric patch area,
while the sensitivity of the secondary, third and fourth frequency is high for both the small and large delamination areas.

Figure 5. Natural frequencies variation with normalized actuation area & % of increase in natural freq.

It can be seen that, as expected, for all modes the larger actuation area, the more significant increase in natural frequencies, also it can be deduced that different modes have different sensitivities to the actuation areas. For instance, the natural frequency of first mode has relatively small increase (16%) for actuation area (150x150) mm$^2$ whereas the increase in the higher mode is significant (37.7%) relative to host plate as shown in Figure 5.

4.2. Numerical results compared with experimental work

The results from present FEM validated with the experiments conducted on eight plies (0/90) of dimensions (200x200) mm$^2$ square laminate with four edges simply supported boundary conditions accomplished in our laboratory. Table 4 show the comparison between frequencies predicted for the first four modes by using the finite element model (ANSYS) and those measured experimentally. It arises that the results obtained from numerical calculations were in good agreement with the experimental investigation. The maximum error between FEM and experimental test results is less than 5.41%. The present verified finite element model can be used for further analysis.

Table 4. Experimental measured natural frequencies and numerical results for SS square laminates in Hz

| Actuation area mm$^2$ | First mode | Second mode | Third mode | Fourth mode |
|-----------------------|------------|-------------|------------|-------------|
| Host Plate            | EX 172.2   | FEM 171.73  | EX 459.5   | FEM 455.37  | EX 466.3   | FEM 455.37 | EX 692     | FEM 690.79 |
| 50x50                 | 176        | 173.78      | 462        | 470.48      | 467.5      | 470.48     | 695        | 698.83     |
| 100x100               | 191        | 186.16      | 551        | 546.86      | 560        | 546.86     | 798        | 788.31     |
| 150x150               | 199        | 195.94      | 615        | 607.85      | 620        | 607.85     | 870        | 889.28     |

Figure 6 shows the effect of increasing the piezoelectric patch area on reduction of the first frequency of composite plate. It’s very clear that vibration attenuation of 55.2%, 66.4%, and 79.7% are achieved as the patch area are set to (50x50), (110x110), and (150x150) mm$^2$ respectively.

Figure 6. Vibration attenuation with different piezoelectric areas.

4.3. Effect of piezoelectric actuator applied voltage on natural frequencies

The effect of changing the applied voltage on the one specified patch area is studied also numerically. By choosing the 150X150 mm$^2$ area patch and apply different voltage value on the upper face of the piezoelectric film (-50v, 1v, 50v) we noticed that the amplitude of mid-plane displacement of the plate...
reduces by increasing the voltage value. Figure 7 shows the displacement amplitude versus the frequency due to -50v, 1v, and 50v respectively.

It is also noticed that the 2nd mode frequency is not effected. It’s very clear that vibration attenuation of 54.8%, 79.7%, and 96.5% are achieved as the control voltage are set to -50, 1, and 50 volts respectively.

![Figure 7. Vibration attenuation with different applied voltage.](image)

### 5. Summary

ANSYS, FEM code, is used to investigate the response of the smart structure by control the vibration of E-Glass Epoxy composite plate. 8-ply (0/90) composite plate is manufactured and mechanically tested to measure its mechanical properties. Vibration test is performed experimentally for the plate with different piezoelectric patch areas bonded to measure the modal frequencies. The experimental results are compared with the numerical results and a good agreement is achieved. Also the effect of applied voltage on the piezoelectric patch is studied, and 96% of first mode frequency is attenuated.

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