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Predicting the effect of fiber orientations and boundary conditions on the optimal placement of PZT sensor on the composite structures

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Abstract

In this paper, the modal-model of the composite structure is predicted and viewed to decide the optimal position of the PZT sensors on the composite structures. The novelty of this work is to systematically study the effect of fiber orientations and boundary conditions on the modal-model and the optimal location of the PZT sensors on the composite structures. The glass fibers are reinforced in a polyester matrix at different fiber orientations such as 0°, 30°, 45°, 60° and 90°. It is used for various engineering applications, especially in the aerospace and automobile sector, and it is very important to measure its dynamical response. The PZT patches can be embedded on the composite structures to measure their vibrational response. In this paper, ABAQUS software is used to build the finite element model of the PZT-composite structure. The composite structure is modeled with different boundary conditions. It is observed that the orientation of the fibers as well as the boundary condition directly put their effect on the modal-model of the composite structure and also on the selection of the optimal position of the PZT patches. It is found that the optimal position of the PZT directly depends upon the fiber orientation.

1. Introduction

Composite materials have distinct properties from other conventional and metallic materials such as high fatigue life, corrosion resistance, specific strength, specific stiffness, wear resistance, acoustical insulation, and many more. Inherent properties like high specific strength and durability have immense the use of composite material in various naval, aerospace and automobile applications [1, 2]. The extensive use of composite materials opens a wide range of failures caused in a static and dynamic mode. In this regard, both static and dynamic analysis of the composite structures is essential to study to avoid failure of the structure. The composite structure may fail because of its resonance condition, so it is very important to predict or measure the modal characteristics (spatial model, modal-model, and response model) of the structure. Researchers studied the vibrational analysis of the composite structures in which they analyzed the importance of prediction of the modal-model (natural frequencies, mode shapes and viscous damping coefficients) for effective dynamic analysis. The study of natural frequencies and their corresponding mode shapes of the structure are combined to term as modal analysis. Modal analysis of any structure depends upon the physical properties of the material, structure-dimensions, and boundary conditions. In the case of composite materials, there are two or more different materials combined at the homogenous level that may affect the modal analysis separately. In composite materials, mostly fibers are embedded at different orientations in the matrix or resin. The orientation of reinforced fibers into the matrix may affect the modal-model of the system.

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In the year 1972, an experimental study was proposed to determine the modal-model (natural frequencies and mode shapes) of graphite-epoxy and boron-epoxy composite materials. In this study, graphite fibers were reinforced into epoxy resin at different fiber orientations such as 0°, 15°, 30°, and 90° with the axis of the beam. The beam is in clamped-free conditions. The experimental results show good agreement with the numerical results for the orientation of 15° and 30° when compared [3]. Ha et al [4] analyzed the behavior of piezo-ceramics sensor and actuator on the composite structures using the finite element method. The structure was subjected into both mechanical and electrical loading. The damping factor is a parameter that defines vibrational behavior of the structure under different loading conditions. Adams and Maheri [5] predicted the damping factor in advanced polymer-matrix composites. The change in damping behavior was observed with the change in stress concentration on composite structure experimentally. Hwang et al [6] developed the finite element mode for PZT sensors and actuators on laminated composite plate. The purpose of the study to control the laminated composite structure by both active and passive vibration control system.

Teboub and Hajela [7] used first-order deformation theory to analyze the vibrational behavior of composite beams. The model which was used in this study considers for both rotary and in-plane inertias. The proposed results were validated with previously published experimental and numerical results.

To analysis the deep fiber composite structure, the first-order theory is facing certain bugs and errors. Marur and Kant [8] proposed a higher-order theory for deep reinforced composite structure. It was observed that composite materials can also be used for active vibration control (AVC) applications because of having distinct properties from other materials.

Peng et al [9] investigated the effect of the changing of the position of the PZT patches on the vibrational response of the composite material beam. A modal superposition technique and the Newmark-β method were used in the numerical analysis to compute the dynamic response of composite beams. The effects of the locations of the sensors/actuators on the control system were also determined. Tita et al [10] determined the damped performance of fiber-reinforced composite material beam. The authors studied the dynamic damped actions of fiber-reinforced composite beams in flexural vibrations.

Li Jun et al [11] studied a free vibration analysis of a laminated composite plate by using a finite element method (FEM). The authors studied the influence of torsion deformation, share deformation, coupling among extensional and rotary inertia on the dynamic analysis of the structure. Mallardo et al [12] used genetic algorithms to predict the optimal position of the PZT sensor on the composite structures. The main objective was to predict the impact identification on the composite structures. The optimal location of the piezoelectric patch is not only important to identify the impact but also very useful for active vibration control (AVC) applications. Zhang et al [13] presented the first known study of the optimal shape control of carbon nanotube-reinforced functionally graded composite plates. The authors studied the effect of CNTs distributions and plate aspect ratio on the optimal shape. Padoin et al [14] optimally locate the piezoelectric macro-fiber composite patches on the composite plate. The main objective of the work was to attenuate the vibrations of the plate. Ganesh et al [15] discussed the finite element method of a delaminated composite plate to analyze its free vibration measurements.

Oliveira et al [16] determined the modal-model of the composite flat plate embedded with a PZT patch using the experimental modal analysis (EMA) technique. The carbon fibers were reinforced in the epoxy resin. The orientation of the fibers is 0°, 30°, 45°, 60°, and 90° respectively. Rao et al [17] embedded a PZT sensor to the composite material plate and used the finite element method to model it. Rama [18] studied the dynamic analysis of the different layered laminate composite material under different boundary conditions. The ABAQUS software was used to model the laminate material. The excitation applied to the material was harmonic in nature.

The control of fiber location inside the matrix directly put their effect on the properties of the composite structures. Authors also found that the effective stiffness of the fiber-reinforced composite structures is responsible for noise, vibration, and ride harshness in automobile applications. Kumar and Kumar [19] applied finite element analysis (FEA) based modal analysis on glass-epoxy laminated composite panels with and without the PZT patches. The ANSYS software was used to develop a FE model of the PZT-composite beam to predict the mode shapes for only 0° fiber orientation. Later, the optimal location of the PZT patch on the cantilever composite beam (glass-epoxy laminated) was also predicted. However, the optimal location is limited to the first two–mode shapes only.

Quoc et al [20] developed a finite element (FE) model based first-order shear deformation theory for optimal placement of PZT sensor. The optimal position of the PZT patches was used for the active vibration control of laminated composite plates with a suitable controller. Bendine et al [21] predicted the optimal position of the discrete PZT patches on the composite plates by using an optimization technique. The predicted optimal position was used to actively control the vibrations of the plate by using a linear quadratic regulator (LQR) controller. Prakash et al [22] investigated the problem of optimal placement of piezoelectric sensors to improve the active vibration control performance of smart laminated beam. The optimal location of the PZT patches was
determined using the ANOVA method. The modal analysis of different materials has already been carried out in past successfully [23–28].

It is observed from the above literature review that, in the earlier study the PZT sensors were used to measure and control the vibrational response of the composite material structure at different excitations. In this regard, mostly optimization-based algorithms are used to predict the optimal location of the PZT patches to accurately sense and control the vibrations of the composite structures. But, there is no study available with a prime objective to determine the effect of fiber orientations and boundary conditions on the optimal location of the PZT sensors on the composite structures. The optimal location of the PZT sensor is a key parameter for various applications such as active vibration and noise control of structures. However, the effective study to determine the effect of fiber orientations on the optimal location of the PZT sensor on the composite plate is missing in the literature. In this regard, the prime objective of this present paper is to predict the optimal location of the PZT sensor on the composite plate by considering the fiber orientation and the boundary conditions are two uncertain parameters. This is only possible by analyzing the behavior of natural frequencies and mode shapes of the structure at different fiber orientations and boundary conditions. It is found that the proposed method (viewing method) is very systematic, easy, and robust to apply on simple to complex-shaped composite materials, to predict the optimal location of PZT sensors on it. The main achievement of the proposed method is the quick prediction of the optimal location of the PZT sensors without using any optimization technique.

2. Finite element modeling

In this section, the finite element (FE) modeling of a neat polyester plate and polyester plate (composite plate) reinforced with glass fiber is carried out. The objective is to predict the modal-model of the composite plate.

2.1. Finite element modeling of a composite structure

In this section, the finite element (FE) modeling of neat polyester and the composite panel is performed by using ABAQUS software. Finite element analysis is performed to determine the mechanical properties of the materials [29–33]. The Young’s modulus, Poisson’s ratio, and density of the polyester material are 26 MPa, 0.37, and 1390 Kgm$^{-3}$ respectively. The dimensions of the polyester material plate used for FE modeling are 0.3 m $\times$ 0.3 m $\times$ 0.001 m respectively. The mesh size is 12 $\times$ 12. The glass fibers are reinforced in the polyester matrix and called a composite plate. The fiber orientation angle in the polyester plate is 0°, 30°, 45°, 60°, and 90°. For the finite element modeling, the 3D shell feature is selected with planar type. The dimensions of the composite panel are 0.3 m $\times$ 0.3 m $\times$ 0.001 m respectively. The plate is discretized into a mesh size of 12 $\times$ 12 as shown in figures 1 and 2.

The different properties of glass and polyester composite plates used for FE modeling are taken as $E_1 = 37.41 \text{ GPa}, E_2 = G_{12} = G_{13} = 13.67 \text{ GPa}, G_{23} = 6.66 \text{ GPa}, v_{12} = 0.3$ and $P = 1768.9 \text{ Kg m}^{-3}$ [11]. The FE model of the composite material is carried out at different boundary conditions. The boundary conditions for the composite plate used in this study are clamped-clamped (CCCC), clamped-free (CFFF), free-free (FFFF), and simply supported-simply supported (SSSS) at all the edges. The modal analysis is carried out to predict the modal-model of the plate at different fiber orientations and different boundary conditions.
2.2. Finite element modeling of composite structure embedded with a piezoelectric sensor

Finite element modeling of a composite plate embedded with a PZT patch is carried out. To model the PZT patch on the composite plate certain constraints are used in ABAQUS software [34] without using those constraints piezoelectric patch dislocates from its position resulting in an error and aborted file. At the one side of the piezoelectric patch, a zero displacement boundary condition is applied. The dimensions of piezoelectric patch are 0.05 m \times 0.05 m \times 0.0005 m respectively. The FE mesh size of the PZT sensor is 2 \times 2. The different properties of the PZT sensor used for FE modeling are taken as \( E_{13} = E_{32} = -8.9678 \) GPa, \( E = 23.3 \) GPa, \( P = 7800 \) Kg m\(^{-3}\), \( v = 0.34 \) and dielectric constant = \( 6.6075 \times 10^{-9} \) [35].

3. Proposed methodology

In this section, the methodology to predict the optimal location (where all the vibrating modes of the composite plate can be sensed in the frequency range of interest) of the PZT sensor by viewing the mode shapes is explained in detail. Figure 3 represents the flow chart to predict the optimal location of the PZT sensor on the composite plate.

The FE model of the composite plate is carried out first at different boundary conditions and at different fiber orientations. Then the modal analysis is carried out, by using the ABAQUS software, to predict the natural frequencies and mode shapes of the composite plate. Now, by viewing the mode shapes of the plate, an optimal location of a PZT sensor on the plate is selected. The PZT sensor should not be placed at any nodal line of the plate. It is embedded at the particular optimal location according to the particular boundary condition. Again the modal analysis is performed on the PZT-composite plate to observe its mode shapes. To validate the optimal location of the PZT sensor on the plate, the overlay of the FRFs at optimal and non-optimal locations of the PZT can be plotted.

4. Numerical study

In this section, the modal analysis of the glass fiber reinforced polyester composite plate is carried out. In order to support the ABAQUS results and viewing method for location of the PZT patch, the validation study was already carried out [36, 37].

4.1. Modal analysis of the neat polyester plate under different boundary conditions

The FE modal analysis of the neat plate is carried out at the different boundary conditions. Figure 4 represents the natural frequencies and the mode shapes of the neat polyester plate. It is observed that the mode shapes of the composite plate depend upon the boundary conditions of the structure. The natural frequency is maximum in the case of clamped (CCCC) and minimum for the cantilever (CFFF) boundary condition. This is due to the variation in the stiffness of the plate at the particular boundary condition. The location of the nodal line (minimum displacement value) varies for different boundary conditions. In the contour images, the blue color
represents zero displacements, whereas red represents the maximum displacement. Although these contour does not represent real displacement because for modal analysis no load is applied. Mode shapes and frequencies are formed because of their self-weight.

4.2. Modal analysis of the composite plate
In this section, the modal analysis of the composite plate at different fiber orientations and boundary conditions is carried out by using FE software.

(a) CCCC boundary condition

Figure 5 shows the mode shapes of the composite plate for all sides fixed boundary conditions. In the above figure, the first column represents the different fiber orientations and other columns correspondingly represent the different mode shapes (first six mode shapes). The second row represents the mode shapes of the neat matrix material. The fiber orientations (0°, 30°, 45°, 60° and 90°) is represented along the rows. By viewing the mode shapes, it is clear that mode shapes depend on the fiber orientation. Since it is a square plate, the modal-model of 0° and 90° and 30° and 60° fiber orientation are similar. By viewing the 1st mode shape, it is visible, for all fiber
| B.C. | Mode 1 | Mode 2 | Mode 3 | Mode 4 | Mode 5 | Mode 6 |
|------|-------|-------|-------|-------|-------|-------|
| SSSS | 1.49  | 3.80  | 3.80  | 6.07  | 7.92  | 7.92  |
| CCCC | 2.74  | 5.75  | 5.75  | 8.44  | 10.91 | 10.97 |
| FFFF | 0.96  | 1.42  | 1.87  | 2.54  | 2.54  | 4.68  |
| CFFF | 0.25  | 0.61  | 1.58  | 2.04  | 2.20  | 4.00  |

Figure 4. Natural frequencies (in Hz) and mode shapes of the neat polyester plate under the different boundary conditions.

| F.O. | Mode 1 | Mode 2 | Mode 3 | Mode 4 | Mode 5 | Mode 6 |
|------|-------|-------|-------|-------|-------|-------|
| Matrix | 2.74  | 5.75  | 5.75  | 8.44  | 10.91 | 10.97 |
| 0° & 90° | 65.003 | 113.31 | 157.98 | 194.55 | 204.33 | 271.31 |
| 30° & 60° | 63.082 | 118.60 | 144.46 | 189.39 | 223.60 | 277.78 |
| 45°   | 62.454 | 122.22 | 138.07 | 188.45 | 242.85 | 252.49 |

Figure 5. Natural frequencies (Hz) and mode shapes of the composite plate at different fiber orientations.

orientation (0°, 30°, 45°, 60° and 90°), the mode shape pattern is almost the same with no nodal line (column 2) present in the first mode. In a 2nd mode shape, there is a horizontal nodal line in the neat matrix but when fibers are embedded in 0° and 90°, a vertical nodal line is seen. Also, when the fiber orientation is 30° and 60° and 45° there is a slight shift in the vertical line. Similarly, for the 3rd mode shape, the direction of the nodal line changes from vertical to horizontal. In the 4th mode shape, there are two nodal lines—one is horizontal and the other one is vertical, which shows an inclination for 60° and 45° and has approximately the same mode shapes. For the 5th mode shape, there are two vertical nodal lines and having approximately the same mode shapes for 90° and 60°.
but for 45° it is completely different. For the 6th mode shape, there is one horizontal and two vertical nodal lines for 90° fiber orientation, whereas for 60° fiber orientation there are three inclined nodal lines. The presented results revealed that the fiber orientation directly affects the modal-model (natural frequencies & mode shapes) of the composite structure.

(a) SSSS boundary condition

Figure 6 shows the mode shapes of the composite plate for simply supported boundary conditions. The number of rows represents the different fiber orientations and the number of the column represents the different mode shapes. After viewing the mode shapes, it is visible that mode shapes are affected by the fiber orientation, 1st row represents mode shapes till 6th mode shape and the remaining row represents different fiber orientations as 0°, 30°, 45°, 60°, and 90°. Figure 6 shows that the mode shape of the neat matrix plate changes as the fiber orientation varies.

(a) CFFF boundary condition

Figure 7 shows the mode shapes of the composite plate for cantilever boundary conditions. The plate is under the boundary condition fixed from one side and the remaining sides are free. By viewing the mode shapes, it is clear that mode shapes are affected by the fiber orientation. It can be seen that the 1st mode shape for each fiber orientation is similar with zero nodal lines, but natural frequency goes on increasing from 0° to 90°. The 2nd mode shape for each fiber orientation is again approximately similar with increased natural frequency from 0° to 90°. In the 2nd mode shape, there is one nodal line, which is horizontally centered. Now the 3rd mode shape is completely different for each fiber orientation, for 0° fiber orientation, there is only one nodal line which is much straight. The nodal line for 30° is slightly curvy but it is curved to a greater extent for 45° fiber orientation. For 60° and 90°, the nodal line tends to come closer to the edge which results in forming two nodal lines horizontally. Remaining all the mode shapes shows random order of nodal lines.

(a) FFFF boundary condition

Figure 8 shows the mode shapes of the composite plate for free-free boundary conditions. It is observed that in all mode shapes at least 2 nodal lines are present. The behavior of mode shapes are affected by the change in fiber orientation, the natural frequency for 0° and 90° remains the same but mode shapes are different, similarly for 30° and 60° natural frequencies remains the same but different mode shapes are obtained.

| F.O. | Mode 1 | Mode 2 | Mode 3 | Mode 4 | Mode 5 | Mode 6 |
|------|--------|--------|--------|--------|--------|--------|
| Matrix | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
| 0° & 90° | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) | ![Image](image10.png) | ![Image](image11.png) | ![Image](image12.png) |
| 30° & 60° | ![Image](image13.png) | ![Image](image14.png) | ![Image](image15.png) | ![Image](image16.png) | ![Image](image17.png) | ![Image](image18.png) |
| 45° | ![Image](image19.png) | ![Image](image20.png) | ![Image](image21.png) | ![Image](image22.png) | ![Image](image23.png) | ![Image](image24.png) |

Figure 6. Natural frequencies (in Hz) and mode shapes of the composite plate at different fiber orientations.
The following conclusions can be drawn from the above all plots:

- The natural frequencies of the composite plate vary as the fiber orientation changes from 0° to 90°.
- The boundary conditions also affect the modal-model of the composite structure.
- The mode shape of the composite material is also a function of fiber orientation.
- The natural frequency is increasing as the fiber orientation varies from 0° to 90°. It means that the orientation of fibers increases the stiffness of the plate.

5. Optimal location of a PZT sensor on the composite plate

The PZT sensors can be embedded on the composite plate to measure the response of the structure at different excitations. To accurately measure the response of the system, the location of the sensor is very-very important. The optimal location of the PZT sensor is the location where it can sense or observe all the modes of the system in the frequency range of interest. The following points are important while selecting the optimal location of the PZT sensors:

- The sensor should not be placed on the nodal line of the structure at a particular vibrating frequency; otherwise, it will not sense that vibrational mode.
- It should be on the optimum location where it can sense all the modes in the frequency range of interest.

| F.O. | Mode  | Mode 2 | Mode 3 | Mode 4 | Mode 5 | Mode 6 |
|------|-------|--------|--------|--------|--------|--------|
| MATRIX | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
| 0°   | 0.25  | 0.61   | 1.58   | 2.04   | 2.20   | 4.00   |
|      | 4.78  | 12.14  | 30.34  | 44.38  | 55.41  | 86.57  |
| 30°  | 4.97  | 14.13  | 31.01  | 44.64  | 55.79  | 88.41  |
| 45°  | 5.48  | 15.25  | 33.93  | 43.97  | 56.28  | 90.28  |
| 60°  | 6.37  | 15.25  | 38.620 | 43.76  | 57.20  | 90.33  |
| 90°  | 7.93  | 14.13  | 38.58  | 50.71  | 59.66  | 88.49  |

*Figure 7. Natural frequencies (Hz) and mode shapes of the composite plate at different fiber orientations.*
The percentage of sensing (%S) the displacement at the particular mode is also very important. The main objective of this paper is to predict the optimal location of the PZT sensor on the composite structures for particular boundary conditions and orientation, by viewing the mode shapes. Figure 9 represents the optimal location of the PZT sensor for different boundary conditions and at different orientations. The white square represents the PZT sensor inside the composite plate. The fiber orientation varies from 0° to 90°. It is seen that the optimal location of the PZT sensor is different for different boundaries and also for varying fiber orientation. It means, if anybody wants to measure the response of the plate (especially composite), the optimal location should be chosen first. Otherwise, the contribution of the un-sensed mode will be missed in the overall behavior of the system.

5.1. Modal analysis of composite plate when PZT patch is located at its optimal location
In this section, the modal analysis of the composite plate along with the PZT sensor at its optimal location is carried out. Figure 10 represents the natural frequencies, mode shapes, and percentage of sensing (%S) of the displacement by the PZT sensor for the CCCC boundary condition. Percentage of sensing (%S) the displacement by the PZT sensor represents that at an optimal location which vibrational mode displacement is sensed more as compared to others. The black square represents the PZT sensor inside the composite plate. The percentage of sensing the displacement is calculated from the displacement at the centre of the PZT patch, considering the case of 0° & 90°, the most sensed mode is 6th mode because it has the maximum displacement of 0.845 m as compared to other modes (D₁ = 0.232 m, D₂ = 0.487 m, D₃ = 0.673 m, D₄ = 0.804 m, D₅ = 0.213 m). Therefore it has maximum percentage sensing of 100%. For other modes, percentage sensing is

| F.O. | Mode 1 | Mode 2 | Mode 3 | Mode 4 | Mode 5 | Mode 6 |
|------|--------|--------|--------|--------|--------|--------|
| MATRIX | 0.96 | 1.42 | 1.87 | 2.54 | 2.54 | 4.68 |
| 0° | 19.59 | 30.35 | 50.31 | 51.14 | 63.94 | 87.69 |
| 30° | 21.97 | 29.47 | 45.80 | 52.26 | 65.14 | 93.01 |
| 45° | 23.16 | 28.99 | 43.85 | 53.34 | 64.58 | 101.34 |
| 60° | 21.97 | 29.47 | 45.80 | 52.26 | 65.14 | 93.14 |
| 90° | 19.59 | 30.35 | 50.31 | 51.14 | 63.94 | 87.69 |

Figure 8. Natural frequencies (Hz) and mode shapes of the composite plate at different fiber orientations.
calculated by using the below formula:

\[
%S = \left( \frac{D_n}{D_n^0} \right) \times 100
\]

Where, \( n \) is the mode number and \( D_n \) is the displacement for a particular mode. In figure 10, the 1st column represents the different fiber orientations (F.O.) and the remaining columns represent the different mode shapes. Below every mode shape, there is percentage sensing (%S). It is corresponding to maximum sensing for a
particular mode shape. This percentage sensing proves that the proposed location of the piezoelectric sensor under the CCCC boundary condition is optimal location. However, the optimal location of the PZT sensor does not pass over any nodal line. Also, it is clear that for the same structure but according to the different fiber orientation, the optimal location is different to sense the vibrations of the structure at any kind of excitation.

Figures 11–13 represent the natural frequency, mode shapes, and percentage of sensing (%S) for SSSS, FFFF, and CFFF boundary conditions.

It is concluded from figures 11–13 that for the particular boundary condition and particular fiber orientation the location of the PZT sensor is different either the structure is the same. In this regard, it is very essential to predict the optimal location of the PZT sensor at uncertain parameters, such as fiber orientation and boundary condition, before embedding it to the composite structure plate. Otherwise, its non-optimal location will directly influence the overall measurement of the system.

6. Overlay of FRFs

In this section, to validate the proposed method, the frequency response function (FRF) of the PZT-composite plate is plotted. The PZT sensor response is transformed into the frequency domain. Figure 14 shows the overlay of the FRFs at the optimal and non-optimal PZT location.

The fibers are oriented in 45° along with CCCC boundary condition of the plate. Without doing the modal analysis, suppose PZT sensor is embedded at a non-optimal location. It is clearly observed from the above plot, the non-optimally located PZT sensor (red line curve) is not sensing the third and the fifth mode of the plate. But when the PZT is located by viewing the mode shapes (as proposed in this paper), all the modes are completely sensed by the PZT sensor (black line curve). Also, as it is proved from the above Figure that the optimal location varies with fiber orientation. The 0° fiber orientation optimal location is not for 45° and other fiber orientation composite plate. The presented FRF curve proves that there must be different optimal locations for different fiber orientations under different boundary conditions. So, one cannot choose the optimal location without viewing the mode shapes of the system.

7. Conclusions

The following conclusions can be drawn from this work.

• The modal analysis of the composite panel for different fiber orientations and under the different boundary conditions is analyzed.
• It is observed that the mode shapes and natural frequencies are the dependent functions of fiber orientations.
The optimal location of the PZT sensor is proposed for each fiber orientation and under all the boundary conditions by viewing the mode shapes. The PZT sensor is placed on the proposed optimal location and percentage sensing of the displacement is determined.

The present study is very important to optimally decide the position of the PZT sensor for vibrational sensing on the composite plate. If the PZT sensor is placed on the nodal line (for a particular vibrating frequency), then it will not add or detect the contribution of that mode in the overall behavior of the system. The optimal location is secure for each orientation and each or definite boundary condition. It is very important to get prior knowledge of the optimal location of the sensor before embedding it into the structure. The proposed method (viewing the mode shapes) will assist the vibrational community to select the optimum position of the sensor on composite structures. However, some complicated composite structures (laminate) can be studied theoretically and experimentally in the future to predict the optimal location of the sensors on it.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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| F.O.  | Mode 1 | Mode 2 | Mode 3 | Mode 4 | Mode 5 | Mode 6 |
|-------|--------|--------|--------|--------|--------|--------|
| 0°    | 4.72   | 11.69  | 28.78  | 41.46  | 54.34  | 83.16  |
| %S    | 55.29% | 66.62% | 100%   | 60.94% | 24.57% | 47.86% |
| 30°   | 4.92   | 13.64  | 29.16  | 41.75  | 55.21  | 83.62  |
| %S    | 46.33% | 59.91% | 100%   | 44.08% | 19.08% | 41.51% |
| 45°   | 5.45   | 14.63  | 31.93  | 42.10  | 54.41  | 85.17  |
| %S    | 40.21% | 71.49% | 100%   | 37.83% | 36.38% | 37.45% |
| 60°   | 6.31   | 15.02  | 32.23  | 42.95  | 54.44  | 88.59  |
| %S    | 35.64% | 36.33% | 100%   | 20.52% | 37.44% | 26.08% |
| 90°   | 7.83   | 13.69  | 36.67  | 48.49  | 56.20  | 84.41  |
| %S    | 71.35% | 72.68% | 100%   | 67.35% | 75.78% | 45.53% |

Figure 13: Natural frequencies (Hz) and mode shapes of PZT-composite plate at different fiber orientations (F.O.) under the boundary condition one side clamped and remaining all sides free.

Figure 14: Overlay of FRFs at optimal and non-optimal locations.

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