# EXPERIMENTAL AND NUMERICAL INVESTIGATIONS ON RESONANT CHARACTERISTICS OF A SINGLE-LAYER PIEZOCERAMIC PLATE AND A CROSS-PLY PIEZOLAMINATED COMPOSITE PLATE

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## ABSTRACT

Piezolaminated composite plates are widely used in many industrial applications such as intelligent structures and advanced aerospace structural applications. To improve the dynamic performance of the piezolaminated composite structures, it is necessary to experimentally investigate the resonant characteristics of these structures. Three measurement techniques are used in this study to investigate the vibration behavior of the tested specimen. The first method, AF-ESPI (amplitude-fluctuation electronic speckle pattern interferometry) is the major technique for measuring the resonant characteristics of a single-layer piezoceramic plate and a multilayer cross-ply GFRP (glass fiber reinforced plastics) piezolaminated composite plate for completely free conditions. The completely free condition is approximated in experiment by placing and partially sticking the specimen on the surface of a very soft sponge. A thin single-layer piezoceramic plate is first investigated and up to the twenty-sixth transverse modes are presented. Excellent quality of interferometric fringe patterns for vibration mode shapes are presented. The second method, LDV (laser Doppler vibrometer), and the third method, impedance analyzer, are both employed to verify the AF-ESPI results for the piezolaminated composite plate. Both in-plane and out-of-plane resonant frequencies and vibration mode shapes of the piezolaminated composite plate are demonstrated. Finally, numerical computations based on the finite element analysis are presented for comparison with the experimental results. Excellent agreement between the measured data and the numerical results is found in resonant frequencies and mode shapes for the single-layer piezoceramic plate and the cross-ply piezolaminated composite plate.

## 1 INTRODUCTION

The use of PZT in piezolaminated composite structures has received a great deal of attention because of the sensing and actuating capacities becomes part of the structures in piezolaminated composites, and the ease of integrating piezoceramic materials by means of embedding those to laminated structures. By combining many distinct layers, the advantages of each ply can be developed more effectively. Hence, the study of embedded piezoelectric materials in composites has received considerable attention in recent years. Ha *et al*. [1] used an eight-node composite brick element and variational principle to construct the FEM formulation for modeling the dynamic and static response of laminated composites containing distributed piezoceramics subjected to both mechanical and electrical loading. Batra and Liang [2] used the three-dimensional linear theory of elasticity to study the vibrations of simply-supported rectangular laminated plate with embedded PZT layers, numerical results for a thin and a thick plate with one embedded actuator layer and one embedded sensor are presented. Abramovich and Meyer-Piening [3] presented an exact elasticity solution for the forced induced vibrations of a piezolaminated elastic beam, this analysis was carried out by using the method of Fourier series and the solution was exact within the assumptions of linear elasticity and plane strain deformation. The references mentioned above were usually presented by theoretical analysis or numerical computation, Few results used experimental technique to study the vibration characteristics of piezolaminated composite plates. The aim of this work is to investigate experimentally the resonant characteristics of a thin single-layer piezoceramic plate and a piezolaminated composite plate with an embedded piezoceramic layer in cross-ply glass fiber reinforced composites for completely free boundary condition. The experimental techniques used in this study including the AF-ESPI, LDV and impedance analyzer. The quantitative magnitudes of the full-field displacements are also indicated in the experimental results for each mode, and the sensitivity is submicrometer. The resonant mode shapes of in-plane and out-of-plane vibrations of the piezolaminated composite plate are demonstrated. To verify the AF-ESPI results, the LDV (laser Doppler vibrometer) which is a point-wise displacement measurement technique, is also used as the second experimental technique. The third experimental technique, the impedance analyzer, is employed to determine resonant frequencies of in-plane vibration for the piezolaminated composite plate. Furthermore, in light of the results presented in this work, numerical computation based on the finite element method (FEM) utilizing ABAQUS commercial software package are also made. The excellent agreement of the numerical results in resonant frequencies and mode shapes with experimental measurements is found for the single-layer piezoceramic plate and the cross-ply piezolaminated composite plate.

## 2 EXPERIMENTAL AND NUMERICAL RESULTS

### *2.1 The results of the single-layer piezoceramic plate*

The thin single-layer piezoceramic plate with completely free boundary is analyzed first. The polarization is parallel to the $x_3$ axis, and two opposite faces of the piezoceramic plates are completely coated with silver electrodes. The piezoceramic plate is excited by the application of an ac voltage across electrodes on the two surfaces and has the completely stress-free boundary conditions. A self-arranged time-averaging ESPI system is used to perform the experimental measurements for resonant frequencies and corresponding full-field mode shapes. In addition to the experimental measurement, numerical computations of resonant frequencies as well as mode shapes are also performed by a commercially available software ABAQUS finite element package. Fig. 1 summarizes the detailed mode shapes of the PIC-151 single-layer piezoceramic plate obtained by AF-ESPI with out-of-plane sensitivity and FEM. The excellent quality of the interferometric fringe pattern obtained from the AF-ESPI method is demonstrated. The zero-order fringes, which are the brightest fringes on the experimental results, represent the nodal lines of the piezoceramic plate at resonant frequencies. The rest of the fringes are contour of constant displacements. The mode shapes obtained from experimental results can be checked by the nodal lines and fringe patterns with the numerical finite element calculations. Excellent agreements of the experimental measurement and numerical calculation are found for all the resonant modes. Resonant frequencies measured by the AF-ESPI method and predicted by FEM method are in good agreements.

*2.2. The results of the multilayer cross-ply piezolaminated composite plate*

The resonant characteristics of in-plane and out-of-plane vibrations for a cross-ply piezolaminated composite plate with an embedded piezoceramic layer are investigated. A thin piezoceramic plate that has the same size and material property as the first experimental specimen is embedded in the middle of the cross-ply fiberglass reinforced plastic materials. The stacking sequence of the piezolaminated composite plate is [0/90/0/90/PIC-151/90/0/90/0]. Because the piezolaminated composite plate has the thickness of 1.38 cm, both the in-plane and out-of-plane vibration modes will be discussed. Figs. 2 and 3 show the out-of-plane and in-plane resonant mode shapes obtained by AF-ESPI and FEM, respectively. The first ten transverse (out-of-plane) modes of the piezolaminated composite plate are indicated in Fig. 2. Fig. 3 shows the results of the first six in-plane mode shapes, the U-field and the V-field denote the full-field vibration displacement along the $x_1$ and the $x_2$ direction, respectively. Excellent agreements of the experimental measurement and numerical calculation are found for both the out-of-plane and in-plane vibration modes as indicated in Fig. 2 and 3. The resonant frequencies obtained by AF-ESPI, LDV and FEM for out-of-plane modes and the first six resonant frequencies obtained by AF-ESPI, impedance and FEM for in-plane vibration modes are in excellent agreement.

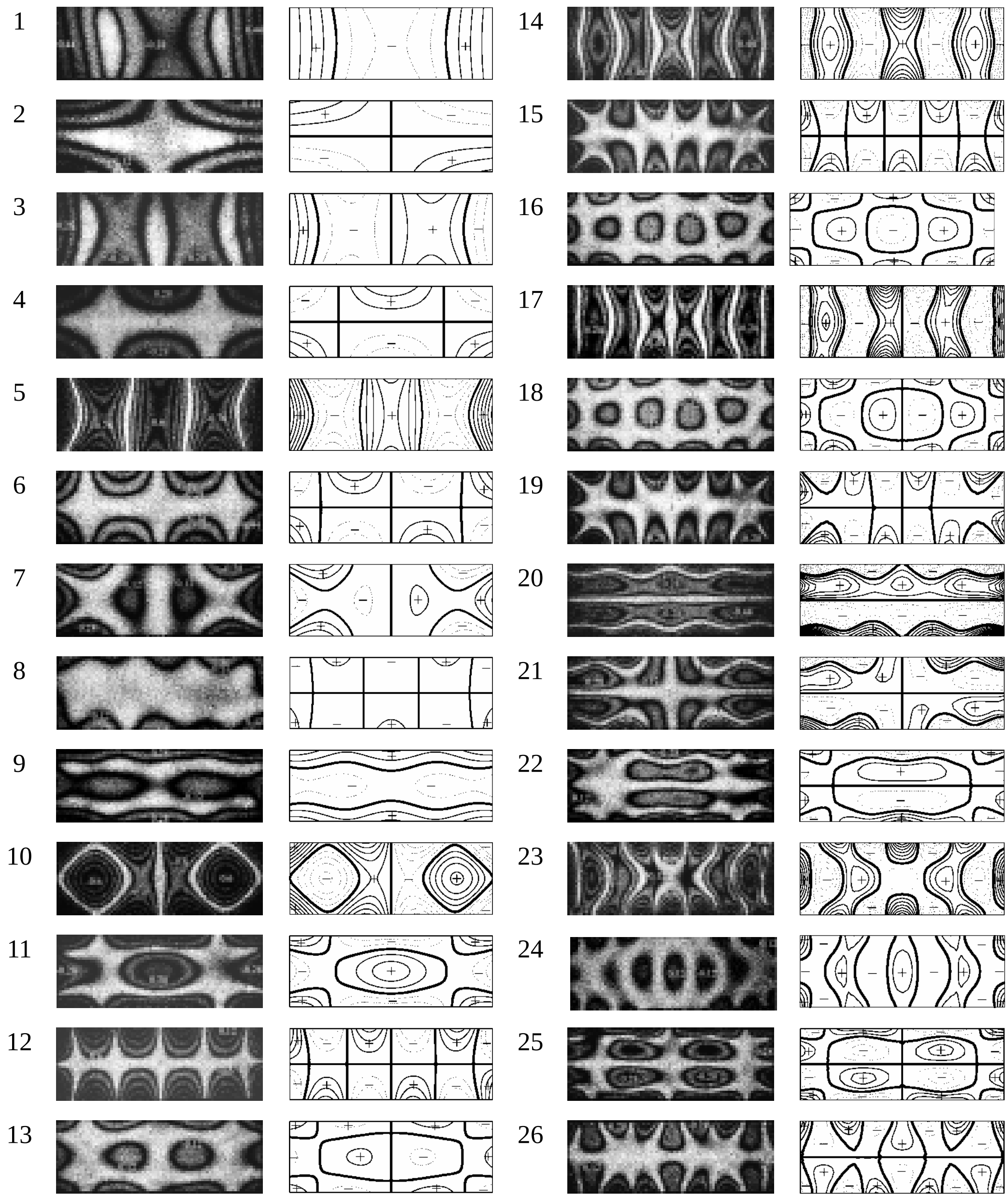

Figure 1 :The out-of-plane mode shapes of the thin piezoceramic plate obtained by AF-ESPI and FEM

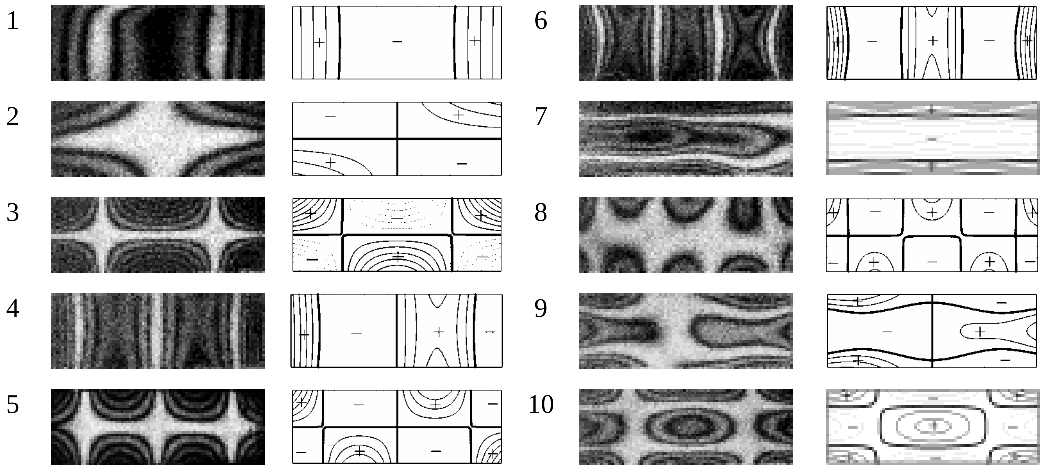


Figure 2: The out-of-plane mode shapes of the GFRP piezolaminated composite plate obtained by AF-ESPI and FEM.

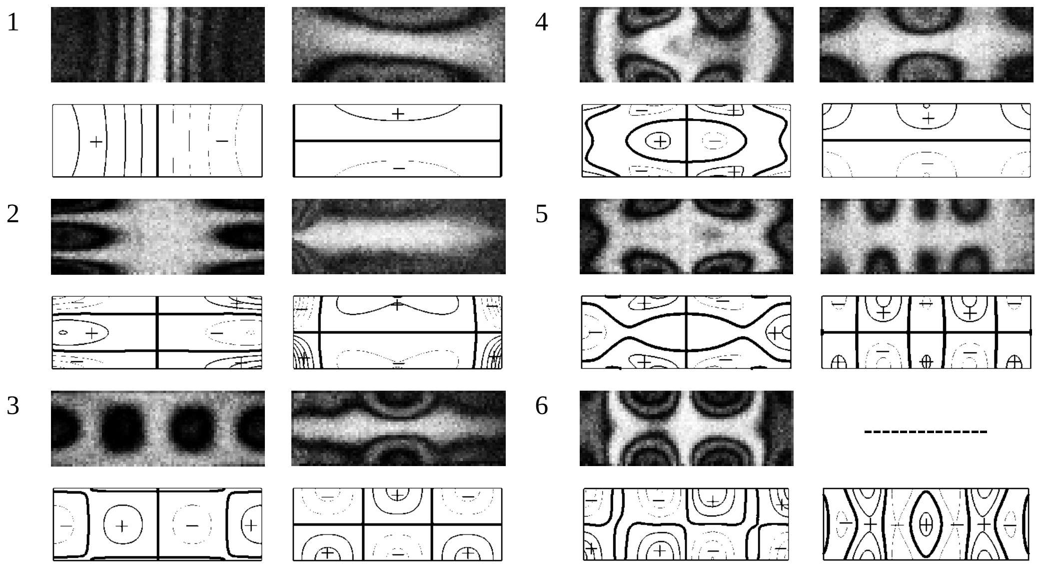


Figure 3:The in-plane mode shapes of the GFRP piezolaminated composite plate obtained by AF-ESPI and FEM.

## 3 CONCLUSIONS

This study investigates the resonant frequencies and mode shapes of piezolaminated composite plate for out-of-plane and in-plane vibrations by three experimental techniques (AF-ESPI, LDV, impedance) and FEM. It has shown that the AF-ESPI method has the advantages of non-contact, full-field, real-time and high-resolution measurement. Excellent quality of interferometric fringes for mode shapes are presented by a video recording system. For the thin piezoceramic plate, the resonant frequencies and full-field mode shapes up to twenty-sixth modes are measured by AF-ESPI and are excellently correlated with FEM results. For the case of piezolaminated composite plate, not only transverse modes but also in-plane modes are analyzed by three experimental techniques and FEM. Excellent agreements between the theoretical predictions and experimental measurements of resonant frequencies and mode shapes are obtained.

## REFERENCES


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