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Finite element analysis of the electro-mechanical coupling effects in piezoelectric laminated structures

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Abstract. This study utilized the COMSOL Multiphysics software to conduct finite element analysis on the piezoelectric coupling effect of the composite layer structure. The article begins by introducing the basic principles and history of the piezoelectric effect, emphasizing the importance and widespread application of piezoelectric materials in the field of smart materials. Subsequently, it defines in detail the models of bimorph piezoelectric beams and multilayer composite piezoelectric plates, and conducts potential verification. The bimorph piezoelectric beam model uses PVDF material, and the potential distribution is monitored by boundary probes, confirming the influence of the quantity and distribution of sensor electrodes on voltage distribution. The multilayer composite piezoelectric plate model combines a Si non-piezoelectric semiconductor layer with a PZT-4 piezoelectric material layer, demonstrating the in-plane distribution of potential under lateral mechanical loads. This study not only verifies the reliability of COMSOL software in piezoelectric coupling analysis but also provides an in-depth understanding of the behavior and performance of piezoelectric materials in complex environments.

Keywords: piezoelectric effect, finite element analysis, piezoelectric coupling, COMSOL Multiphysics, composite plates.

1. Introduction

The piezoelectric effect refers to the ability of certain crystalline materials to generate electric charges proportional to the mechanical stress applied[1],it can be divided into positive piezoelectric effect and inverse piezoelectric effect. When subjected to an external force in a certain direction, the material will deform. At the same time, it will generate polarization phenomena within itself, and oppositely charged ions will appear on its two relative surfaces. However, when the external force is removed, it will return to the state of being electrically neutral. This phenomenon is known as the positive piezoelectric effect. When the direction of the applied force changes, the polarity of the charge also changes accordingly. Conversely, when an electric field is applied in the direction of polarization of these dielectrics, these dielectrics also undergo deformation. When the electric field is removed, the deformation of the dielectrics also disappears. This phenomenon is referred to as the reverse piezoelectric effect. In 1880, French scientists Pierre Curie and Jacques Curie investigated the relationship between the piezoelectric effect and crystal symmetry, discovering that natural quartz (α-SiO_2) exhibits piezoelectric properties, the first-time piezoelectricity has been observed in quartz bodies[2].

In recent years, in the field of intelligent materials, piezoelectric materials have been extensively applied in the fields of science and engineering due to their unique motor coupling characteristics. As structural elements, it has demonstrated significant potential and unique advantages in the fields of vibration control, energy conversion, precision measurement, and sensor design. In structural applications, these actuators can be surface bonded or embedded[3].Researchers (Bailey and Hubbard 1985, Lee 1990, Wang and Rogers 1991) proposed an analytical model for piezoelectric materials in beam. These models have recently been extended to include composite laminates with piezoelectric beams and plates for active vibration control used in sensor and actuator layers. With the advancement of technology, the study of these materials has continued to deepen, prompting people to explore the behavior and performance of piezoelectric materials under more complex conditions such as variable temperature and heat load.

Finite element analysis is a numerical simulation method that is more suitable for solving complex models[4].Currently, the main commercial finite element software ANSYS, Abaqus, and COMSOL all support the analysis of piezoelectric coupling in structures. This study utilized the COMSOL Multiphysics software to conduct a mechanical-electrical coupling analysis on piezoelectric dual-chip cantilever beams, composite piezoelectric plates, and thermoelectric beams/plates. Through the replication of existing literature, data analysis and comparison, the reliability of COMSOL finite element analysis and the distribution of electrical potential on beams and plates due to piezoelectric effects was validated.

2. Introduction

The piezoelectric double-chip beam is formed by stacking two piezoelectric layers with opposite polarization directions, yielding a beam that can be used as a bending actuator or sensor[5]. In this case, it is utilized for strain sensing. The deflection of the beam leads to the generation of induced voltage, which is the consequence of the positive piezoelectric effect (sensing).

2.1. Model definition

Two PVDF beams, each with a length of 100 mm, width of 5 mm, and thickness of 0.5 mm, are evenly divided into 5 layers and tightly clamped together. The arrangement is illustrated in the figure 1 below. Most material properties in the PVDF domain are defined by materials models in the material library, and some require manual changes, as shown in the table 1. The upper and lower surfaces of the cantilever piezoelectric beam were respectively covered by five pairs of identical sensor electrode, spanning the entire length of the beam.

Table 1. Material properties of PVDF[5].

Elasticity modulus Y	$0.2\text{x}10^{10}$ N/m^2
Piezoelectric constant e_{31}	0.046 C/m^2
Piezoelectric constant e_{32}	0.046 C/m^2
Dielectric constant d_{33}	$0.1062\text{x}10^{-9}$ F/m

The proposed model incorporates piezoelectric, solid multi-physical interface, and introduces constitutive relations required for piezoelectric material modeling to simulate the positive piezoelectric effect. It represents the piezoelectric coupling in stress-charge form. In the field of mechanical solidity, the charge conservation and the use of piezoelectric materials models for PVDF domains are assigned, and a fixed constraint is imposed at the left end face of the beam to simulate the conditions of a cantilever beam. A displacement of 0.01 m in the direction of thickness is applied to the right end face of the beam. The upper and lower beam utilize opposite-polarized coordinate systems (with polarization direction along the x-axis).In the electrostatic interface, the charge conservation model is assigned to the PVDF domain, and the grounded condition is assigned to the right end face of the beam to ensure that the potential of the right end face of the beam is 0 V.

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In order to obtain the distribution of surface potential on the top and bottom of the beam, we respectively added boundary probes to each of the ten areas on the top and bottom of the beam, to monitor the average potential of each sensor coverage area. Grid partitioning requires as much refinement as possible to achieve a more refined result.

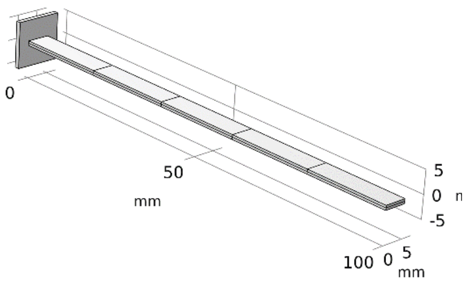

Figure 1. Geometric model of piezo-electric beam with twin plates.

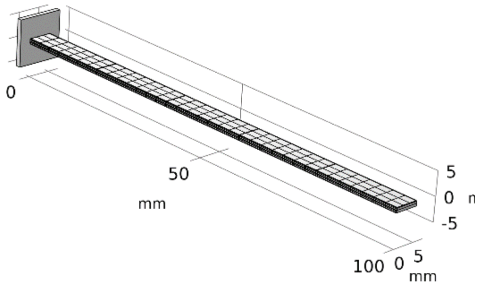

Figure 2. Meshing of twin piezoelectric beams and beams.

2.2. Result analysis

The number and distribution of sensor electrodes directly affect the voltage distribution along the length of the beam obtained. Each pair of sensor electrodes generates a mean voltage value, with the increment between successive sensors being equally distributed. In Figures 3 and 4, it is clearly evident that this distribution exhibits equal increments. Under the extreme condition of an infinite number of sensors along the length direction, the increase in the number of sensors evenly distributed along the length will result in a linear distribution of voltage.

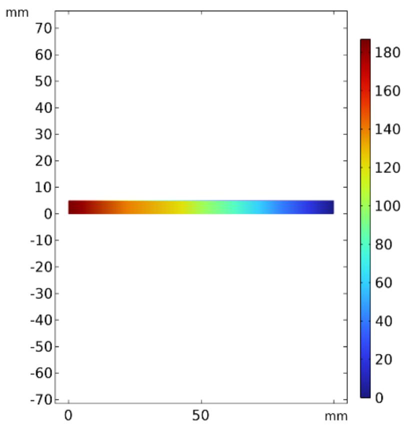

Figure 3. Potential distribution along beam length.

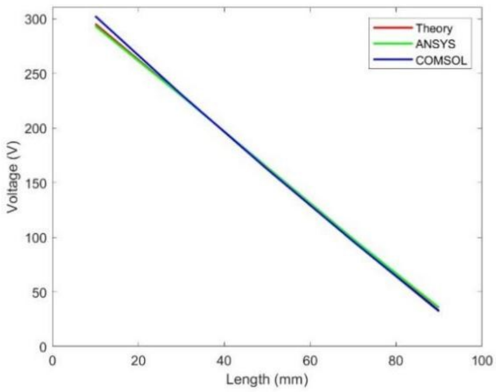

Figure 4. Comparison of potential distribution data along beam length.

3. Potential verification of multilayer composite voltages

Piezoelectric panels are typically planar structures, suitable for applications that require planar strain, while piezoelectric beams are linear structures, suitable for applications that require bending or vibration. When validating electrostatics, piezoelectric plates are typically more common than piezoelectric beams due to their simpler structure, ease of manufacturing, and integration. Moreover, the potential response of piezoelectric plates can be more easily quantified, making it the preferred choice in a variety of sensing and energy harvesting applications.

3.1. Model definition

A piezoelectric plate measuring 400 nm in length, 300 nm in width, and 50 nm in thickness is divided into three layers. The upper and lower layers are Si non-piezoelectric semiconductor layers (each layer

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thickness is 15 nm), while the middle layer is a PZT-4 piezoelectric material layer. The material properties of Si and PZT-4 domains are listed in Table 2.

Table 2. Material properties related to PZT-4 and Si[6].

Material parameter	Symbol	Value
Elastic constant(GPa)	c_{11},c_{33},c_{12},	138.499,114.745,77.371
	c_{13},c_{44}	73.643, 25.6
	c'_{11},c'_{12},c'_{44}	165.7, 63.9, 79.56
Dielectric constant($10^{-9}Cm^{-1}v^{-1}$)	ε_{11}, ε_{33}	1.306, 1.115
	e'_{11}	0.1035
Piezoelectric constant(Cm^{-2})	e_{15},e_{31},e_{33}	12.72,- 5.2, 15.08

This model employs a piezoelectric, solid multi-physical interface. In the field of solid mechanics interfaces, we apply fixed constraints to the bottom of the silicon layer to fix the piezoelectric plate. In the central region of the silicon layer, with a size of 50 nm x 50 nm, a transverse load of 800 N/m^2 was applied. In a statically charged interface, the charge conservation is assigned to the Si domain, and the piezoelectric and charge conservation are assigned to the PZT-4 domain.

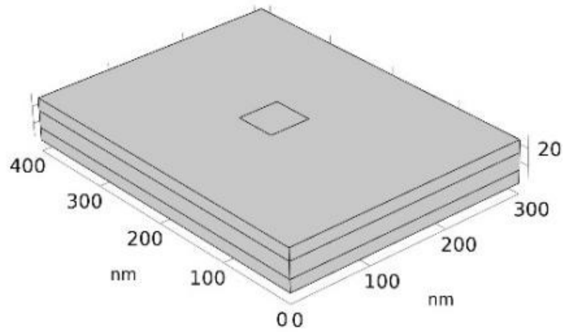

Figure 5. Geometric model of piezoelectric plate.

3.2. Result analysis

In the considered composite laminated plate comprised of PZT-4 and Si layers, the load is equivalent to the central force under static conditions. It generates an expected global deflection within a piezoelectric plate as shown in Figure 6. The in-plane distribution of potential can be manipulated by transverse mechanical load, dependent on shear deformation. By replicating existing cases, the distribution of surface potential on the piezoelectric plate when it is subjected to transverse load is well demonstrated.

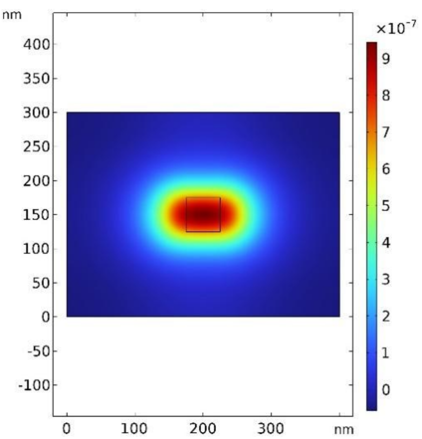

Figure 6. Potential distribution on the upper surface of a piezoelectric plate

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4. Conclusion

This study utilizes COMSOL Multiphysics software to conduct a finite element analysis of the piezoelectric composite structure, exploring in depth the electrical potential responses of piezoelectric materials under various loading conditions. The study findings indicate that the dual-crystal-plate piezoelectric beam model can accurately reflect the influence of the number and distribution of sensor electrodes on the voltage distribution, while the multi-layer composite piezoelectric plate model effectively demonstrates the in-plane distribution of potential under lateral mechanical load. These findings provide essential theoretical support for the design and optimization of piezoelectric sensors and actuators, laying the foundation for the application of piezoelectric materials in more complex multi-physics environments in the future. Furthermore, this study also confirmed the reliability and accuracy of finite element analysis in predicting the behavior of piezoelectric materials, providing a strong tool for the further development of intelligent material technology.

References

[1] Dong, H., Zhu, Z., Li, Z., Li, M., & Chen, J. (2024). Piezoelectric Composites: State-of-the-Art and Future Prospects. JOM, 76(1), 340-352.
[2] A.R. Hutson and D.L. White, J. Appl. Phys. 33, 40(1962)
[3] Wang, Q., & Quek, S. T. (2000). Flexural vibration analysis of sandwich beam coupled with piezoelectric actuator. Smart Materials and Structures, 9(1), 103.
[4] Wang, L., Zhao, L., Jiang, Z., Luo, G., Yang, P., Han, X., ... & Maeda, R. (2019). High accuracy comsol simulation method of bimorph cantilever for piezoelectric vibration energy harvesting. AIP Advances, 9(9).
[5] Nestorović, T., Marinković, D., Chandrashekar, G., Marinković, Z., & Trajkov,M. (2012). Implementation of a user defined piezoelectric shell element for analysis of active structures. Finite Elements in Analysis and Design, 52, 11-22.
[6] Qu, Y., Jin, F., & Yang, J. (2022). Electromechanical interactions in a composite plate with piezoelectric dielectric and nonpiezoelectric semiconductor layers. Acta Mechanica, 233(9), 3795-3812.