Analysis of Mechanical Vibration and Energy Transfer in Low-Frequency Layered Magnetoelectric Composite Antennas

Leilei Wang[1], Wusheng Ji[1,*], Xingyong Jiang[2], Junzhe Lu[1], Boyuan Luo[1], Jie Gao[1]

[1]School of Electronic Engineering, Tianjin University of Technology and Education, Tianjin 300222, China
[2]Rofs Microsystem, Tianjin 300462, China

Abstract: Traditional low-frequency electromagnetic antennas typically face problems such as large structural dimensions, difficulties in impedance matching, and limited bandwidth under low-frequency operating conditions, making it difficult to meet the requirements of low-frequency communication systems for antenna miniaturization and integration. Layered magnetoelectric composites convert electrical energy, mechanical energy, and magnetic energy through mechanical resonance by coupling the piezoelectric effect with the magnetostrictive effect, providing a new technical approach for the miniaturized design of low-frequency antennas.This study investigates the FeGaB/PZT-5H/FeGaB layered magnetoelectric composite antenna and establishes an electric field–mechanical field coupled finite element model using COMSOL Multiphysics to analyze the mechanical vibration response and energy transfer behavior within the structure. The resonance response, displacement distribution, admittance characteristics, quality factor, and stress distribution of the structure are investigated through simulation to analyze the vibration and energy transfer behavior of the composite structure under electrical excitation. The simulation results show that the FeGaB/PZT-5H/FeGaB layered magnetoelectric composite antenna exhibits significant mechanical vibration response characteristics near the target frequency. The mechanical vibration distribution in the working region and the interlayer stress transfer behavior were analyzed, revealing the mechanical vibration and energy transfer processes within the composite structure and providing a theoretical reference for the structural design and mechanical coupling behavior analysis of low-frequency layered magnetoelectric composite antennas.

Keywords: Low-frequency; Layered Magnetoelectric Composite Antenna; Mechanical Vibration Transfer; Energy Conversion; Multiphysics Coupling

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1 Introduction

With the development of wireless communication, underground and underwater communication, and wireless sensing systems in the frequency range from tens of kilohertz to hundreds of kilohertz, the demand for low-frequency, miniaturized, and high-performance antenna devices is increasing. However, conventional electromagnetic antennas are limited by the operating wavelength and face problems such as increased size, reduced antenna performance, and difficulty in impedance matching under low-frequency conditions. Therefore, overcoming the size limitations of conventional electromagnetic antennas and achieving low-frequency miniaturized antenna design has become an important research direction in the current antenna field [1]. Mechanical antennas have significant size advantages compared with conventional electrical antennas

*Corresponding author: Wusheng Ji, jiwusheng@tute.edu.cn

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operating at the same frequency, but communication distance remains an important challenge for their practical application [2]. To address the size limitation of low-frequency antennas, magnetoelectric composite materials utilize the coupling between the magnetostrictive effect and the piezoelectric effect to achieve energy conversion among the electric field, mechanical strain, and magnetic field, providing a new technical approach for low-frequency electrically small antennas [3].

According to the combination modes of functional materials, magnetoelectric composite structures mainly include 0-3 particulate composite structures, 1-3 columnar composite structures, and 2-2 layered composite structures. Among them, layered magnetoelectric composite structures, owing to their continuous material interfaces and shorter strain transfer paths, can effectively promote the mechanical coupling between the piezoelectric phase and the magnetostrictive phase, and therefore have become an important structural form in the study of magnetoelectric devices [4]. In layered magnetoelectric composite structures, the magnetoelectric conversion process mainly depends on the strain transfer efficiency between the magnetostrictive material and the piezoelectric material. Existing studies have shown that the bonding state between functional layers, the matching of material mechanical parameters, and the characteristics of local stress distribution directly affect the mechanical energy transfer process and further influence the magnetoelectric response performance [5].

To further improve the operating capability of low-frequency magnetoelectric devices, researchers have gradually introduced mechanical resonance mechanisms into magnetoelectric antenna design. Compared with conventional electromagnetic resonance methods, mechanical resonance can utilize elastic wave vibrations inside materials to achieve energy conversion, allowing the device size to be much smaller than the corresponding electromagnetic wavelength, thereby overcoming the size limitation of low-frequency antennas.Mukherjee et al [6]. proposed a self-biased low-frequency miniaturized magnetoelectric antenna structure, which achieved mechanical resonance driving through magnetoelastic coupling between the magnetostrictive layer and the piezoelectric layer, demonstrating the application potential of magnetoelectric antennas in low-frequency wireless communication and implantable devices. Shi et al [7]. proposed a novel magnetoelectric antenna that utilizes nonlinear magnetic force coupling to achieve a dual-resonance state. By enhancing ultra-low-frequency magnetoelectric conversion performance through a multistable mechanical structure, a new structural design method was provided for frequency expansion and performance improvement of low-frequency magnetoelectric antennas. Vanderveken et al [8]. further analyzed the operation process of magnetoelectric antennas from the perspective of energy transfer, pointing out that mechanical vibration is an important intermediate link connecting input electrical energy and magnetic field output, and emphasizing that the mechanical resonance state has an important influence on energy conversion efficiency.Luo et al [9]. reviewed the research progress of magnetoelectric bulk acoustic wave and surface acoustic wave devices and analyzed the role of acoustic resonance in the miniaturization of magnetoelectric antennas and the improvement of device performance.

With the development of magnetoelectric antenna research, researchers have begun to focus on the effects of structural parameters, material combinations, and magnetoelastic coupling mechanisms on device performance. Zaeimbashi et al [10]. investigated an ultraminiaturized low-frequency magnetoelectric antenna based on the magnetoelastic coupling mechanism, further demonstrating the advantages of mechanical coupling approaches in the miniaturization of low-frequency antennas.Ma et al [11]. designed multilayer magnetoelectric antennas with mechanical-parallel and electrical-parallel configurations, achieving ultra-low-frequency ASK/FSK wireless communication by enhancing the mechanical driving force and improving the electrical response. Xin et al [12]. introduced a bridge support structure into Metglas/PMN-PT magnetoelectric laminates, lowering the electromechanical resonance frequency and achieving ultra-low-frequency ASK/FSK signal reception. However, current research on layered magnetoelectric composite antennas mainly focuses on resonance frequency tuning, structural dimension optimization, and performance metric validation, while systematic analysis of the generation, propagation, and energy transfer of mechanical vibrations within composite structures under low-frequency conditions remains lacking. In particular, in FeGaB/PZT layered structures, how the mechanical vibration generated by the piezoelectric layer is transferred to the magnetostrictive layer and how the

stress distribution affects the mechanical energy transfer process still require further investigation [13].

Mao et al [14] systematically summarized the direct and converse magnetoelectric coupling mechanisms of magnetoelectric composite materials and their device applications, and pointed out that magnetoelectric composite structures have good application potential in sensing, energy harvesting, and magnetoelectric antennas. Ma et al [15]. further pointed out that the development of multiferroic composite materials has gradually shifted from material preparation toward device applications, in which the electromechanical coupling mechanism and multiphysics synergistic effects have become key issues affecting device performance.

Therefore, this study takes the FeGaB/PZT-5H/FeGaB layered magnetoelectric composite antenna as the research object and establishes a multiphysics coupling model of the "electric field–mechanical field–magnetic field." From the perspectives of mechanical vibration transfer and energy conversion, the mechanical vibration propagation and energy transfer mechanisms within the composite structure under low-frequency conditions are investigated by analyzing the structural displacement response, admittance characteristics, quality factor, and stress distribution, providing a theoretical basis for the structural optimization of layered magnetoelectric composite antennas.

2 Design of the Layered Magnetoelectric Composite Antenna

2.1 Antenna Structural Model

The structure of the layered magnetoelectric composite antenna is shown in Figure 1, and the material properties are listed in Table 1. The structure consists of an upper magnetostrictive layer, upper electrode layer, piezoelectric layer, lower electrode layer, lower magnetostrictive layer, and silicon substrate. Among them, the central piezoelectric layer adopts high-performance PZT-5H material, which converts electrical energy into mechanical vibration through the inverse piezoelectric effect; the upper and lower magnetostrictive layers adopt FeGaB material, which converts mechanical vibration into magnetization oscillation through the inverse magnetostrictive effect; the copper electrode layer is used to apply electrical field excitation.

Table 1 Material properties of FeGaB [16] and PZT-5H [17]

Property	FeGaB	PZT-5H
Density (kg/m^3)	7870	7600
Poisson ratio	0.45	0.36
Elastic modulus (GPa)	60	36
Initial susceptibility	200	-
Conductivity (S/m)	2×106	-
Dielectric constant	-	2300
Electrical Q-factor	-	50

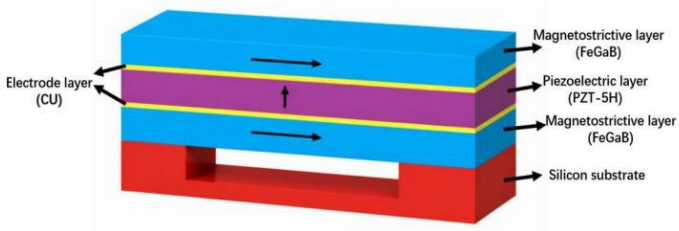


Figure 1 Layered Magnetoelectric Composite Antenna Structure

The operating frequency of the bulk acoustic wave magnetoelectric antenna is mainly determined by the acoustic resonance mode along the thickness direction of the piezoelectric layer. For the thickness longitudinal vibration mode, the resonance frequency can be approximately expressed as:

$$f\alpha\frac{1}{2S}\sqrt{\frac{E}{\rho}} \quad (1)$$

where f is the resonance frequency, S is the thickness of the piezoelectric layer, E is Young's modulus, and ρ is the density.

According to the target operating frequency of 313 kHz and the material parameters of PZT-5H, the theoretical thickness of the piezoelectric material required to meet the target acoustic resonance frequency was calculated to be 3.45 mm using Equation (1). Simulation with this thickness did not yield satisfactory results; when twice this thickness was attempted, satisfactory results were obtained at a thickness very close to 6.85 mm. Therefore, 6.85 mm was finally selected as the thickness of the piezoelectric layer.

BAW magnetoelectric antennas generally adopt layered structures with lateral dimensions greater than the thickness, and their resonance response is mainly determined by the bulk acoustic wave vibration mode in the thickness direction [18]. Therefore, in this study, the thickness of the functional layers was determined according to the target operating frequency, and the structural dimensions were designed by comprehensively considering the influence of the lateral dimensions on the vibration mode to reduce the influence of parasitic vibrations on the resonance response. Meanwhile, considering the influence of electrode thickness on the electric field excitation capability and structural vibration characteristics, a relatively thin electrode layer was selected to reduce its influence on the resonance process. In addition, the silicon substrate serves as the structural support layer, and its thickness needs to ensure the mechanical stability of the device while avoiding excessive constraints on the vibration of the functional layers. Therefore, a 22 mm-thick silicon substrate was selected as the support structure to meet the requirements of model stability and vibration response analysis. Reference [19] indicates that the thickness ratio between the piezoelectric phase and the magnetostrictive phase is an important structural parameter affecting the magnetoelectric coupling performance. When the two functional layers have similar thicknesses, the transfer of mechanical strain at the interface can be improved. Therefore, an equal-thickness design was adopted for the piezoelectric layer and magnetostrictive layer, and the final antenna dimensional parameters are shown in Table 2.

Table 2 Dimensions of the Layered Magnetoelectric Composite Antenna

layer	Thickness (mm)	Length (mm)	Width (mm)
Piezoelectric layer	6.85	400	40
Magnetostrictive layer	6.85	400	40
Electrode layer	0.1	400	40
Silicon substrate layer	22	400	40

2.2 Multiphysics Model of the Antenna

This study uses COMSOL Multiphysics 6.3 to establish a two-dimensional finite element model of FeGaB/PZT-5H/FeGaB, and couples the three physical fields of solid mechanics, electrostatics, and magnetic fields. The coupling between the electric field and magnetic field is realized through the multiphysics interfaces of the piezoelectric effect and magnetostrictive effect. Fixed constraints are set on the left and right sides of the model, while the other relevant boundaries adopt free boundary conditions. In the electrostatic field, the upper and lower electrodes of PZT-5H are set as terminal and ground, respectively, and an AC voltage with an amplitude of 1 V is applied, with a frequency sweep range of 275–350 kHz. The magnetic field region is treated as an open computational domain, and perfectly matched layers (PMLs) with a thickness of 50 mm are set on both sides of the antenna to absorb outward-propagating electromagnetic fields and reduce boundary reflections caused by the finite computational domain. Considering the large difference in scale between the length and thickness directions of the layered antenna, the model adopts a mapped mesh, with local mesh refinement at the FeGaB/PZT-5H interface to accurately describe the bulk acoustic wave vibration and interlayer stress transfer. The mesh is shown in Figure. 2.

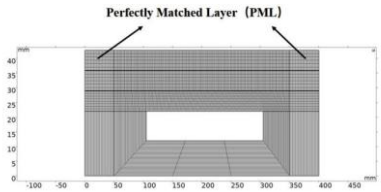


Figure 2 Mesh generation and perfectly matched layer design of the layered magnetoelectric composite antenna

3 Mechanical Vibration and Energy Transfer Analysis

The displacement distribution of the layered magnetoelectric composite antenna is shown in Figure 3. From the overall distribution, it can be seen that the composite structure exhibits a significant mechanical vibration response under the external alternating electric field, indicating that the PZT-5H piezoelectric layer can achieve the conversion of electrical energy into mechanical energy. The displacement field exhibits an approximately symmetrical distribution, with the larger displacement region mainly concentrated at the center of the structure and gradually decreasing along the length direction, reflecting the spatial distribution characteristics of the mechanical vibration response in the composite structure. Due to the mechanical coupling between PZT-5H and FeGaB, the periodic strain generated by the piezoelectric layer is transferred to the magnetostrictive layer, causing the structure to form a continuous vibration response. Meanwhile, the lower displacement amplitude in the edge region indicates that the boundary constraints impose a certain limitation on vibration propagation. Therefore, the displacement response results indicate that the layered magnetoelectric composite antenna can form a relatively clear mechanical vibration mode at the characteristic frequency, providing a basis for subsequent analysis of electromechanical coupling response, mechanical energy storage, and stress transfer.

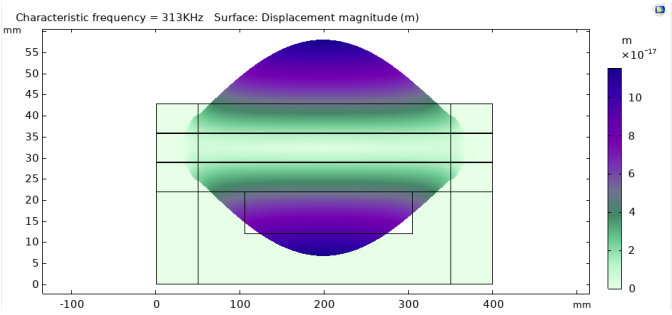


Figure 3 Displacement Distribution of the Layered Magnetoelectric Composite Antenna

The admittance response of the layered magnetoelectric composite antenna is shown in Figure 4. It can be seen from the Figure that the structural admittance exhibits obvious peak and valley variations with the excitation frequency, indicating that there is a coupling between the external electrical excitation and the internal mechanical vibration response of the composite structure. When the excitation frequency is 313 kHz, the admittance amplitude reaches its maximum, indicating that the piezoelectric layer can respond more effectively to the external electric field excitation and drive the structure to produce a stronger mechanical vibration response, indicating that significant electromechanical coupling characteristics exist near this frequency. As the frequency further increases, the admittance amplitude rapidly decreases and reaches a minimum, exhibiting typical resonance and antiresonance response characteristics. The frequency region corresponding to the admittance peak is consistent with the region of larger vibration response in the aforementioned displacement distribution, further indicating that the composite structure has a strong mechanical vibration response near this frequency.

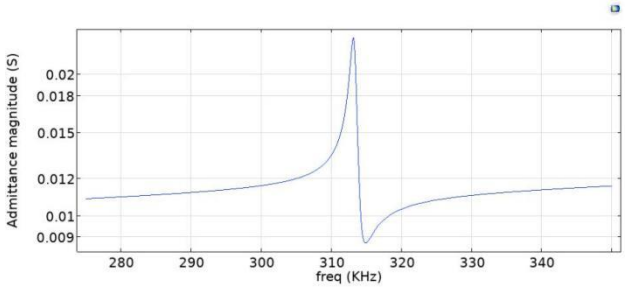


Figure 4 Admittance of the Layered Magnetoelectric Composite Antenna

The quality factor not only reflects the energy storage capability of the resonant structure but also characterizes the energy dissipation behavior during mechanical vibration. The quality factor of the layered magnetoelectric composite antenna is shown in Figure 5. It can be seen from the Figure that the structure has a relatively high quality factor in the low-frequency region. As the frequency increases, the quality factor gradually decreases and tends to be stable near the operating frequency band. Due to the presence of loss mechanisms such as boundary constraints in the layered composite structure, part of the mechanical energy is inevitably converted into dissipated energy, resulting in a decrease in the quality factor. This result indicates that mechanical vibration energy transfer is influenced not only by the resonance state but also closely related to the energy loss mechanisms within the composite structure, providing a basis for subsequent analysis of stress transfer and mechanical energy conversion processes.

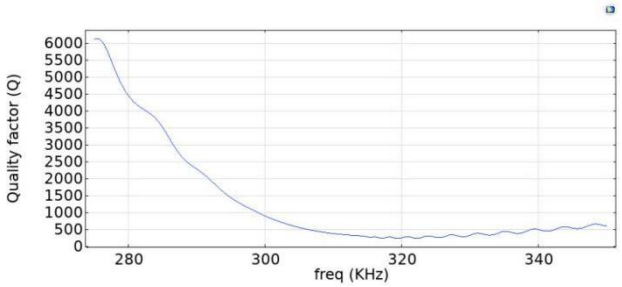


Figure 5 Quality factor of the layered magnetoelectric composite antenna

The stress distribution of the layered magnetoelectric composite antenna is shown in Figure 6. It can be seen from the Figure that the stress within the structure is mainly concentrated in the central region and gradually decreases toward both sides along the length direction, exhibiting an approximately symmetrical distribution, indicating that there is a coupling effect of mechanical vibration within the composite structure. Since PZT-5H and FeGaB have different elastic properties, the dynamic stress generated during vibration needs to be transferred through the interlayer interface. Combined with the displacement distribution results, it can be seen that the interfacial coupling state has an important influence on mechanical vibration transfer.

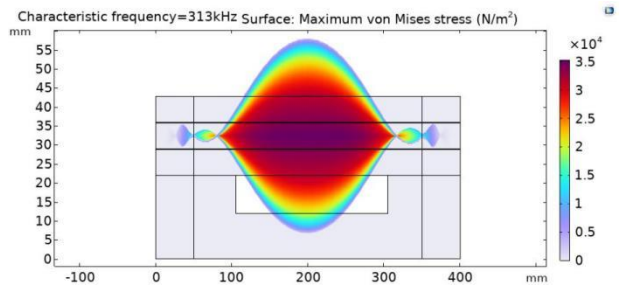


Figure 6 Stress distribution of the layered magnetoelectric composite antenna

4 Conclusion

This study investigates the mechanical vibration and energy transfer processes of a low-frequency layered magnetoelectric composite antenna, and establishes a multiphysics finite element model of the FeGaB/PZT-5H/FeGaB layered structure. By analyzing the structural displacement distribution, admittance response, quality factor, and equivalent stress distribution, the vibration characteristics and interfacial mechanical transfer behavior of the composite structure under electrical excitation are investigated. The results show that the PZT-5H piezoelectric layer can generate mechanical vibration under an alternating electric field and affect the mechanical response of the FeGaB layer through interfacial coupling; the structural resonance state is closely related to the mechanical energy storage and dissipation processes, and the stress distribution reflects the strain transfer characteristics between the functional layers. This study provides a reference for the structural design and mechanical coupling behavior analysis of low-frequency layered magnetoelectric composite antennas.Future work will involve antenna fabrication and stability testing, combined with three-dimensional simulations and structural optimization to improve radiation performance and bandwidth, and functional layer design to suppress parasitic vibrations and enhance energy confinement of the dominant mode.

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