

# Method for Enhancing Electromechanical Coupling Efficiency of Multistage Piezoelectric Ceramic Transducers

Yingxuan He

College of Science, China Jiliang University, Hangzhou, Zhejiang, 310018, China

## ABSTRACT

To address the issues of modal mismatch between different levels of multi-stage piezoelectric ceramic transducers, parasitic capacitance shunting, interface mechanical losses, and electro-mechanical fatigue that lead to low electromechanical coupling efficiency, three improvement methods are proposed: structural optimization, energy recovery type drive and material process collaboration. By using asymmetric electrodes and gradient polarization to reduce parasitic capacitance, and multi-stage series matching to achieve wide-band impedance self-adaptation; using strain energy feedback phase synchronization and duty cycle perturbation to suppress modal coupling, combined with bidirectional energy recovery circuits to reduce dielectric loss; developing gradient transition layer bonding, doping pre-polarization stress regulation, and active temperature control collaborative preload force technology. Experiments show that the electromechanical coupling efficiency has been increased to over 86%, interface losses have been reduced by approximately 65%, and fatigue life has been extended by 2.5 times.

## KEYWORDS

Multi-stage piezoelectric ceramic transducer; Electromechanical coupling efficiency; Asymmetric electrode; Energy recovery; Gradient transition layer

## 1 Introduction

Multistage piezoelectric ceramic transducers are widely used in high-power ultrasound and precision drive applications, but their electromechanical coupling efficiency is limited by inter-stage modal coupling, parasitic capacitance shunting, mechanical losses at the bonding interface, and electro-thermal fatigue effects. Traditional single-stage matching networks are unable to adapt to wide-band dynamic impedance variations, and fixed preload and passive heat dissipation cannot suppress performance degradation over long-term operation<sup>[1]</sup>. This paper focuses on these bottlenecks and proposes a collaborative enhancement approach from three levels: structural topology reconfiguration, drive control strategy, and material interface modification. It elaborates on the technical principles and experimental verification results of asymmetric electrodes and multi-stage matching, strain energy feedback and duty cycle perturbation, gradient transition layer and temperature-controlled preload, respectively.

## 2 Structural Optimization and Impedance Matching Design of Multistage Piezoelectric Ceramic Transducers

### 2.1 Collaborative Optimization of Geometric Parameters based on Modal Analysis for Multistage Laminated Structures

The electromechanical coupling efficiency of multistage piezoelectric ceramic transducers is limited by the mismatch of vibration modes and stress transfer losses among each layer. Traditional designs often adopt equal thickness laminations or empirical proportional layering, ignoring the longitudinal and transverse vibration mode couplings between each level<sup>[2]</sup>. This paper proposes a geometric parameter collaborative optimization method based on combined finite element modal analysis and sensitivity topology. Firstly, a fully parameterized model including electrode layers, piezoelectric layers, and structural bonding layers is established, and the separation degree of axial resonant frequencies and radial parasitic modes of each level is extracted. It is found that when the thickness ratio of each level along the propagation direction is non-uniformly distributed in a gradient form, i.e., the thickness of the first level is controlled at 0.12-0.15 and increases by 3%-5% for each subsequent level, it can effectively suppress the energy theft of high-order radial modes from the longitudinal vibration. Further optimization of the transition chamfer radius between each level and the electrode coverage area reduces the reflection coefficient of stress waves at the interface by approximately 27%<sup>[3]</sup>. Additionally, a multi-objective genetic algorithm is introduced, with the product of the electromechanical coupling coefficient and the mechanical quality factor as the fitness function, constraining the diameter and thickness ratio of each level within the stability boundary. Experiments show that the optimized three-layer structure has an effective electromechanical coupling coefficient  $k_{eff}$  from 0.58 to 0.71 near the resonant frequency, and the parasitic peak amplitude decreases by more than 60%. This collaborative optimization strategy does not increase additional circuit or material costs, but only through structural geometric reconfiguration can achieve significant efficiency enhancement, suitable for high-power ultrasound transducers and precision drive platforms.

## 2.2 Non-symmetric Electrode Configuration and Local Polarization Control to Reduce Parasitic Capacitance

In multistage piezoelectric ceramic transducers, the parasitic capacitance formed between each level and between the electrode and the ground terminal will shunt the driving current and reduce the proportion of effective electrical energy to mechanical energy. Although traditional symmetrical electrodes have simple processing, they result in uniform electric field distribution and cannot avoid the concentrated parasitic effect at the interface edge. This paper proposes a new method of non-symmetric electrode configuration combined with local polarization intensity gradient. Specifically, the upper and lower electrodes of each layer of piezoelectric ceramic sheet are designed with different coverage areas. The coverage rate of the driving end electrode is 85%, while the coverage rate of the output end is adjusted to 65%, and a width of approximately 0.3 mm de-electrode isolation band is set in the edge area<sup>[4]</sup>. This non-symmetric structure forces the electric field lines to bend in the thickness direction, effectively reducing the contribution of edge capacitance. At the same time, selective polarization technology is used, applying a voltage higher than the conventional polarization field strength by approximately 20% in the central area of the ceramic sheet, while reducing the polarization field strength to 70% of the conventional value in the 1 mm ring band near the edge, forming a gradient distribution of polarization intensity from the center to the edge<sup>[5]</sup>. This gradient polarization reduces the piezoelectric activity in the edge area, further suppressing the charge accumulation effect of parasitic capacitance. The actual measurement shows that compared with the traditional symmetrical electrode full-polarization transducer, the equivalent parallel capacitance  $C_0$  has decreased from 3.8 nF to 2.1 nF, while the dynamic capacitance  $C_d$  has changed little, resulting in a reduction of approximately 45% in the ratio of static capacitance to dynamic capacitance. The smoothness of the impedance spectrum within the range of 1 kHz to 100 kHz has significantly improved, and the average value of the electromechanical coupling efficiency has increased by 18.6%. This method does not require changing the overall laminate size and is easy to be implemented in the existing casting and screen printing processes.

## 2.3 Multi-stage Series Matching Circuit for Wideband Dynamic Impedance Adaptation

The dynamic impedance of multi-stage piezoelectric ceramic transducers varies significantly with frequency, load, and temperature. Fixed parameter matching networks are difficult to maintain the optimal electromechanical coupling state throughout the entire working frequency range. This paper designs a multi-stage series reconfigurable matching circuit, each stage consisting of a capacitor array controlled by a switch and an adjustable inductor, and embedding a voltage-current phase detection module to be fed back to the microcontroller in real time. Different from the traditional single-stage LCC matching, this scheme disperses the matching function among each stage of piezoelectric ceramics, and each matching unit compensates for the local dynamic capacitance of that stage, achieving impedance block adaptation<sup>[6]</sup>. The control strategy adopts recursive least squares method to online identify the equivalent resistance, dynamic inductance, and series capacitance of each stage, and then adjusts the parallel compensation amount by binary switch capacitor array with a 0.1 nF step, while using the variable core inductor to continuously adjust the series inductance within  $\pm 30\%$ <sup>[7]</sup>. The multi-stage combined adjustment mechanism avoids lowering the overall active power due to drastic changes in the impedance of a certain stage. The experiment uses a three-stage series matching, with the driving frequency swept in the range of 20 to 30 kHz. The results show that compared with the traditional single-stage matching, which has a power factor of up to 0.92 at the center frequency point and drops to 0.65 at the edge frequency, this method maintains a power factor above 0.94 throughout the entire frequency band, and the fluctuation amplitude of the input apparent power is reduced from the original 32% to within 8%. More importantly, due to each stage's independent tracking of the local resonance point, the overall electromechanical coupling efficiency of the transducer has increased from 72% to 86%, and the thermal accumulation has decreased by approximately 40%. This adaptive matching circuit is particularly suitable for efficient energy transmission under multi-frequency mixed excitation or load change conditions.

## 3 Energy Recovery Drive Strategy and Nonlinear Control

### 3.1 Phase Synchronous Drive Waveform Synthesis Based on Strain Energy Feedback

The traditional multi-stage piezoelectric ceramic transducer uses a single waveform for driving, ignoring the phase difference of strain energy transfer between stages, resulting in the reverse conversion of mechanical energy into heat. This paper proposes a phase synchronous drive waveform synthesis method based on real-time strain energy estimation. Strain sensing optical fibers are attached to each stage surface, and vibration displacement and velocity signals are extracted and sent to the FPGA to construct a dynamic energy model, calculating the instantaneous strain energy value as the difference between elastic potential energy and kinetic energy. The adaptive phase regulator fine-tunes the fundamental phase of the driving voltage, making the voltage waveform lead the strain waveform by  $5^\circ$  to  $10^\circ$  electrical angle, achieving synchronous increase in input electrical energy and strain energy rate changes<sup>[8]</sup>. When multiple stages are connected in series, a phase coordination algorithm between stages is introduced to maximize the mechanical power output of the final stage, using time-division multiplexing to lock the optimal phase level step by step. Experiments show that after phase synchronous driving, the force transmission loss between stages decreases by 34%, the effective value of

the driving current reduces by 22%, and the output amplitude increases by 18%; the electrical heat dissipation power decreases from 9.2 W to 4.5 W. This method only optimizes the control layer efficiency and is suitable for precise positioning and active vibration control.

### 3.2 Bidirectional Energy Recovery Circuit Reduces Dielectric Loss and Heat Generation

During the operation of multi-stage piezoelectric ceramic transducers, mechanical damping and dielectric lag generate reactive power cycles, which are usually absorbed by the driving resistor and converted into temperature rise. This paper designs a bidirectional energy recovery circuit, which returns the reactive energy in the equivalent parasitic capacitance and leakage inductance to the DC bus after each driving half-cycle. The circuit uses a H-bridge and a bidirectional Buck-Boost converter with synchronous rectification, dynamically adjusting the recovery timing according to the phase difference between voltage and current in each stage. It conducts the low-resistance circuit in the current continuous mode to smoothly recover<sup>[9]</sup>. The independent energy recovery units through the common DC bus achieve energy redistribution. In the three-stage stacked transducer prototype (with a peak-to-peak voltage of 400 V and a frequency of 24 kHz), after connecting this circuit, the DC input power decreased from 152 W to 108 W, the output mechanical power decreased only from 98 W to 96 W, and the overall electrical-mechanical-electrical efficiency increased from 64.5% to 88.9%. The maximum temperature of the transducer shell decreased from 82 °C to 51 °C, and the dielectric loss tangent  $\tan\delta$  decreased from 0.024 to 0.013. This circuit has soft-switching characteristics, suppressing voltage spikes, prolonging the ceramic life, and is particularly suitable for large-power continuous operation.

### 3.3 Duty Cycle Disturbance Control Based on Resonance Tracking Suppresses Modal Coupling

Due to temperature drift or load changes, multi-stage piezoelectric transducers experience resonance frequency shifts and modal coupling oscillations, causing a sudden drop in the electromechanical coupling efficiency. Existing resonance tracking only adjusts the frequency, ignoring the suppression of modal coupling by the duty cycle<sup>[10]</sup>. This paper proposes a combined duty cycle-disturbance control strategy for resonance frequency and duty cycle: using a phase-locked loop to lock the fundamental resonant frequency, actively applying a small duty cycle disturbance (amplitude  $\pm 2\%$  to  $\pm 5\%$ , frequency lower than 1/10 of the resonant frequency), detecting the amplitude change rate and phase fluctuation to construct a modal coupling sensitivity function. When the sensitivity exceeds the threshold, the duty cycle is adjusted stepwise towards the sensitivity reduction direction, and an inertia weight is introduced to avoid frequent jumps. In the three-modal coupling multi-stage piezoelectric transformer experiment, without control, the temperature rose from 20 °C to 60 °C, and the efficiency dropped from 83% to 57%. With this control, the duty cycle automatically adjusted from 50% to 38.5%, and the gain of the secondary and tertiary coupling modes was reduced by approximately 12 dB, with the efficiency remaining stable at 79% to 82% throughout the temperature range. The disturbance has negligible impact on output accuracy and does not change the transducer structure or the main circuit topology, making it easy to be embedded in digital drive software.

## 4 Composite Interface Materials and Thermal-thermal-electrical co-regulation

### 4.1 Gradient Transition Layer Bonding Process Reduces Interface Mechanical Losses

The rigid epoxy bonding between successive levels of multi-stage piezoelectric ceramic transducers causes interface reflection and scattering losses due to acoustic impedance mismatch. This paper developed a gradient transition layer bonding process: three layers of nano-titanium dioxide and modified acrylic resin were coated and cured at ratios of 1:3, 1:2, and 1:1, each layer being 5-8  $\mu\text{m}$  thick, forming a gradual transition channel from high impedance of the ceramic to low impedance of the adhesive layer. The acoustic reflection coefficient decreased from 0.32 to 0.09. Combined with vacuum-assisted immersion and hot pressing curing, a dense and bubble-free structure was ensured. The ultrasonic transmission experiments of the three-layer laminated transducer showed that the insertion loss decreased from 4.8 dB to 1.9 dB, and the interface loss ratio decreased from 65% to 22%. Scanning electron microscopy indicated that there were no boundary cracks in the transition layer, forming mechanical interlocking with the ceramic and electrodes, and the shear strength increased by 30%. The mechanical quality factor  $Q_m$  increased from 560 to 820. This process maintained low losses after 500 cycles at -40 to 85°C, requiring only multiple steps of screen printing and segmented curing, and is suitable for mass production.

### 4.2 Doping Modification and Pre-polarization Stress Regulation Enhance Longitudinal Piezoelectric Coefficient

The longitudinal piezoelectric coefficient  $d_{33}$  directly determines the electrical-mechanical conversion capability of the transducer. This paper introduced 0.2 wt%  $\text{MnCO}_3$  and 0.1 wt%  $\text{Sm}_2\text{O}_3$  into the PZT-5H base material, maintaining a high coercive field while enhancing the domain wall movement ability. During the green stage, a uniaxial pre-stress of 4-6 MPa was applied for directional pressing to pre-align the c-axis of the grains; during polarization, a continuous stress of 2 MPa in the same direction was maintained and pulse polarization (0.5 Hz, 3.5 kV/mm, 10 ms) was adopted. This co-

regulation strategy increased the 90° domain rotation rate to 1.7 times the conventional value. Tests showed that  $d_{33}$  increased from 420 pC/N to 615 pC/N, with dielectric loss  $\tan\delta < 0.008$ , and the coercive field decreased by only 5%. After assembling the three-layer transducer, the peak-to-peak output displacement increased from 18  $\mu\text{m}$  to 26  $\mu\text{m}$ , the electromechanical coupling efficiency increased from 62% to 77%, and the aging rate decreased from 4% per year to 1.5%. This method only requires adding stress devices in the press and polarization chamber, making it easy to industrialize.

### 4.3 Active Temperature Control and Pre-tightening Force Co-regulation Suppresses Electro-mechanical Fatigue Effect

Electro-mechanical fatigue caused by large amplitude continuous operation leads to polarization decline and dielectric loss increase. This paper proposed a co-regulation strategy of active temperature control and dynamic pre-tightening force: a TEC was embedded to control the ceramic laminates at a temperature 5–8° C higher than the environment to avoid low-temperature brittleness and high-temperature depolarization; a hydraulic variable pre-tightening device was used, adjusting according to the displacement amplitude feedback - when the amplitude decreased by more than 8%, the pre-tightening force was increased to 20 MPa to inhibit the expansion of microcracks, and when  $\tan\delta$  exceeded 0.022, the pre-tightening force was reduced to release stress concentration, coordinated control by fuzzy logic. After 500 hours of accelerated aging (400 V, 25 kHz, 60°C) for the three-layer transducer, it was shown that the passive cooling fixed pre-tightening group  $\tan\delta$  increased from 0.018 to 0.039,  $k_{\text{eff}}$  decreased by 32%; the co-regulation group  $\tan\delta$  only increased to 0.021, and  $k_{\text{eff}}$  decreased by less than 7%, with a 76% reduction in microcrack density, and the transducer life was increased by 2.5 times. This method significantly delays fatigue and is suitable for aerospace and deep well exploration scenarios where it is difficult to frequently replace transducers.

## 5 Conclusions

The proposed method for enhancing the mechanical-electrical coupling efficiency of multi-level piezoelectric ceramic transducers, as verified through both theory and experiments, leads to the following conclusions: The asymmetric electrodes combined with gradient polarization result in a 45% reduction in static capacitance. The multi-level series matching circuit maintains a power factor above 0.94 within a wide frequency band, with an efficiency of 86%. The strain energy feedback phase synchronization reduces heat dissipation by 34%, and the bidirectional energy recovery increases the overall electrical-mechanical-electrical efficiency of the system to 88.9%. The gradient transition layer reduces the interface reflection coefficient to 0.09. The samarium doping and pre-polarization stress regulation increase the longitudinal piezoelectric coefficient to 615 pC/N, and the active temperature control in conjunction with dynamic preload force extends the fatigue life by 2.5 times, providing a systematic solution for the design of high-performance piezoelectric transducers.

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