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Multi-Mode Resonance Inversion of Viscoelastic Loss in Polymer-PZT Actuators

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Abstract:

Polymer-lead zirconate titanate composite actuators have emerged as critical components in precision engineering, soft robotics, and biomedical devices due to their unique combination of high mechanical flexibility and substantial electromechanical coupling. However, the inherent viscoelasticity of the polymer matrix introduces significant frequency-dependent energy dissipation, profoundly impacting the dynamic performance, phase margins, and resonance characteristics of these actuators. This paper presents a comprehensive investigation into the multi-mode resonance inversion of viscoelastic loss in polymer-lead zirconate titanate actuators. By characterizing the complex modulus across a wide frequency spectrum, the study aims to decouple the structural damping from the intrinsic piezoelectric hysteresis. The research employs a strictly non-parametric, multi-mode analytical framework to map empirical resonance data back to the foundational viscoelastic parameters of the composite structure. Extensive experimental validations using laser Doppler vibrometry and wideband impedance spectroscopy demonstrate that traditional single-mode lumped-parameter models drastically underestimate the phase lag introduced at higher-order resonant frequencies. Through the proposed multi-mode inversion technique, a high-fidelity mapping of the dynamic loss tangent is achieved, reducing predictive dynamic response errors substantially. These findings provide a robust theoretical and practical foundation for designing next-generation compliant actuators with optimized energy transmission pathways and minimized thermal degradation.

1.INTRODUCTION

1.1 Background and Motivation

The rapid advancement of smart materials has catalyzed a paradigm shift in the design of precision electromechanical systems. Among the various smart materials available, lead zirconate titanate stands out as a highly efficient piezoelectric ceramic capable of converting electrical energy into mechanical strain with exceptional fidelity. Traditional solid lead zirconate titanate ceramics, while exhibiting high actuation forces and rapid response times, suffer from inherent brittleness and high mass density [1]. These mechanical limitations severely restrict their application in highly dynamic, conformal, or impact-prone environments, such as wearable robotics, artificial musculature, and flexible haptic feedback interfaces. To overcome these constraints, researchers have increasingly turned to polymer-matrix piezoelectric composites. By embedding active piezoelectric micro-particles, fibers, or structured scaffolds within a passive, compliant polymer matrix, engineers can tailor the macroscopic mechanical properties of the actuator while retaining a functional degree of electromechanical coupling [2]. This hybridization creates a composite that boasts both the high strain capabilities of the polymer and the rapid actuation potential of the ceramic phase. However, the integration of long-chain polymer macromolecules introduces a profound mechanical complication: pronounced viscoelasticity. As the composite is driven at varying frequencies, the polymer matrix exhibits time-dependent strain responses, leading to phase lags between the applied electrical field, the internal mechanical stress, and the resulting macroscopic displacement [3]. Understanding and mitigating this viscoelastic energy loss is paramount for the continued evolution of compliant actuation systems.

1.2 Problem Statement

Despite the structural advantages of polymer-lead zirconate titanate composites, their dynamic operational envelopes are frequently constrained by severe thermo-mechanical energy dissipation [4]. When an alternating electrical field is applied to the actuator, the active ceramic inclusions attempt to deform instantaneously. This localized deformation exerts stress upon the surrounding polymer matrix. Because polymers respond to stress through the gradual uncoiling and sliding of their macromolecular chains, a portion of the mechanical energy generated by the piezoelectric effect is irreversibly converted into thermal energy due to internal molecular friction. In dynamic applications, particularly those involving high-frequency cyclic loading or multi-frequency transient control, this viscoelastic loss manifests as a significant reduction in the quality factor of the mechanical resonances [5]. Traditional control and modeling paradigms typically rely on simple linear viscous damping assumptions or single degree of freedom lumped parameter models to account for this energy loss. However, these simplistic models fail entirely when the actuator is driven near higher-order structural resonances. A single damping coefficient cannot accurately capture the wideband, frequency-dependent nature of polymer chain relaxation. Furthermore, the viscoelastic loss is intrinsically coupled with the piezoelectric hysteresis of the ceramic phase, making it exceptionally difficult to isolate and quantify the mechanical damping purely through forward-modeling techniques. This inability to accurately predict dynamic dissipation limits the precision of open-loop control strategies and complicates the design of feedback compensators in high-speed scanning and micromanipulation tasks.

1.3 Objectives and Scope

This research seeks to resolve the inadequacies of current dynamic models by developing a comprehensive multi-mode resonance inversion framework specifically tailored for viscoelastic polymer-lead zirconate titanate actuators. The primary objective is to formulate an inverse analytical methodology that utilizes experimentally derived multi-frequency resonance data to accurately reconstruct the frequency-dependent complex elastic moduli of the composite material [6]. By analyzing the shifts in resonant frequencies and the attenuation of peak amplitudes across

multiple structural vibration modes simultaneously, this approach aims to uncouple the macroscopic viscoelastic loss from the intrinsic properties of the constituents. The scope of this paper encompasses the theoretical derivation of the multi-mode dynamic response, the preparation of specialized composite test specimens, the execution of high-resolution vibrometric data acquisition, and the implementation of numerical inversion algorithms. The methodology relies exclusively on descriptive formulations of the structural dynamics, avoiding isolated mathematical formulas in favor of a holistic explanation of the system transfer functions and energy dissipation mechanics. Ultimately, this work provides a rigorous diagnostic tool that enables materials scientists and control engineers to accurately quantify the dynamic loss tangent of piezoelectric composites, thereby facilitating the design of highly efficient, low-loss soft actuators for advanced technological applications.

2. Literature Review and Theoretical Background

2.1 Evolution of Polymer-PZT Actuators

The conceptualization and subsequent development of piezoelectric composites can be traced back to the fundamental need for transducers that possess acoustic impedances matching those of human tissue and water [7]. Early iterations primarily focused on connectivity models, describing how the active ceramic phase and the passive polymer phase were spatially arranged within three-dimensional space. The zero-three connectivity model, characterized by isolated ceramic particles randomly dispersed within a continuous polymer matrix, offered supreme flexibility and ease of fabrication but suffered from remarkably poor electromechanical coupling due to the low dielectric constant of the surrounding polymer shielding the active particles from the applied electric field. To address this, engineers developed one-three composites, wherein continuous ceramic rods align through the thickness of the polymer matrix, providing direct load transfer paths and significantly higher actuation authority [8]. Recent advancements have leveraged additive manufacturing and complex micro-molding techniques to create interpenetrating networks and architected three-three composites [9]. These modern structures aim to maximize the strain energy transfer while minimizing the volume fraction of the heavy, brittle ceramic. However, regardless of the topological connectivity employed, the inclusion of a polymer matrix intrinsically anchors the macroscopic behavior of the actuator to the time-temperature superposition principles governing polymeric mechanics. As the operational demands on these actuators have shifted from quasi-static positioning to high-frequency dynamic excitation, the historical focus on static piezoelectric coefficients has proven inadequate, necessitating a deeper investigation into the dynamic rheology of the composite structures [10].

2.2 Mechanisms of Viscoelastic Loss

Energy dissipation within piezoelectric composites is a multifaceted phenomenon, arising from a complex interplay of physical mechanisms at multiple length scales. To accurately model these actuators, it is critical to distinguish between the various sources of loss. The first source is dielectric loss, which occurs within the ceramic inclusions as electrical dipoles attempt to align with an alternating electric field, generating heat due to domain wall friction [11]. The second source is intrinsic mechanical loss within the ceramic itself, though this is generally orders of magnitude smaller than the losses observed in the bulk composite. The dominant source of energy dissipation, and the primary focus of this investigation, is the viscoelastic mechanical loss originating within the polymer matrix. Polymers exhibit a unique combination of elastic solid and viscous fluid behaviors. When subjected to an oscillatory stress field generated by the expanding and contracting piezoelectric inclusions, the polymer network undergoes dynamic deformation. The resulting strain response is not instantaneous but lags behind the applied stress by a measurable phase angle. This phase lag is a direct consequence of the internal friction between polymer chains as they undergo conformational changes [12]. In the frequency domain, this behavior is best

described by a complex dynamic modulus, comprising a storage modulus that represents the elastically recoverable energy, and a loss modulus that represents the energy irreversibly dissipated as heat per deformation cycle. Furthermore, the magnitude of these moduli is heavily dependent on the excitation frequency. At low frequencies, the polymer chains have ample time to relax and conform to the applied stress, resulting in higher compliance and lower relative dissipation. At exceptionally high frequencies, the chains cannot respond quickly enough, leading to a glassy state characterized by high stiffness and low dissipation [13]. It is within the intermediate transition frequencies, where the excitation rate aligns with the natural relaxation times of the polymer network, that the viscoelastic loss reaches its absolute maximum. In a multi-mode actuation scenario, where an actuator might be driven simultaneously at a low-frequency bending mode and a high-frequency longitudinal mode, the effective damping acting upon each mode will be drastically different.

Table 1Summary of historical dynamic modeling approaches for composite actuators and their inherent limitations

Modeling Approach	Core Assumption	Primary Advantage	Fundamental Limitation
Lumped Parameter	Single viscous dashpot	Low computational cost	Fails at higher order modes
Rayleigh Damping	Mass and stiffness proportional	Mathematically convenient	Non-physical frequency scaling
Fractional Calculus	Continuous relaxation spectra	High accuracy across bands	Requires extensive empirical tuning
Resonance Inversion	Modal decoupling	Directly tied to physical states	Highly sensitive to measurement noise

2.3 Multi-Mode Resonance Inversion Strategies

The challenge of accurately determining the frequency-dependent complex modulus of composite materials has led to the development of various parameter identification techniques. Traditional dynamic mechanical analysis is commonly employed; however, it requires the material to be tested in isolation under standardized geometries, which often fails to capture the complex in-situ stress states and boundary conditions experienced by a fully assembled actuator [14]. Consequently, researchers have turned to inverse problem-solving methodologies based on structural resonance data. The fundamental premise of resonance inversion is that the natural frequencies and modal damping ratios of a structure contain all the necessary information to reconstruct the underlying material properties. Early inversion attempts focused on single-mode analysis, measuring the half-power bandwidth of the primary fundamental resonance to estimate a global loss factor. While sufficient for narrow-band applications, this method is fundamentally flawed for broadband modeling because it assumes the loss factor remains constant across the entire frequency spectrum. To overcome this, advanced multi-mode inversion strategies have been proposed. These strategies involve exciting the actuator across a broad frequency sweep to capture multiple distinct resonance peaks, such as the fundamental bending mode, higher-order flexural modes, and fundamental torsional or extensional modes [15]. By utilizing non-linear optimization algorithms, the error between the experimentally measured frequency response function and an analytical or numerical model is minimized iteratively. The algorithm adjusts the postulated frequency-dependent storage and loss moduli until the simulated resonance peaks match the empirical data in both magnitude and phase [16]. The accuracy of this multi-mode inversion depends heavily on the fidelity of the forward model used to describe the composite structure, as well as the robustness of the chosen optimization routine against local minima.

3. Methodology and Analytical Framework

3.1 Material Synthesis and Preparation

The experimental phase of this research necessitates the careful fabrication of standardized polymer-lead zirconate titanate composite actuators designed to exhibit clear, measurable structural resonances. A one-three connectivity paradigm was selected for the test specimens to ensure strong electromechanical coupling along the primary axis of actuation while allowing the viscoelastic properties of the continuous polymer matrix to dominate the transverse and flexural dynamic responses. The active phase consists of commercially available lead zirconate titanate fibers, chosen for their high piezoelectric strain constant and consistent geometric tolerances. The passive matrix material is an aerospace-grade two-part epoxy resin, selected for its well-characterized baseline rheology and strong interfacial adhesion properties. The synthesis process begins with the alignment of the piezoelectric fibers within a custom-machined polytetrafluoroethylene mold, securing them such that they remain perfectly parallel and evenly distributed across the cross-section. The epoxy resin and hardener are mixed at a stoichiometric ratio and subjected to a vacuum degassing process to eliminate trapped air bubbles, which would otherwise act as localized stress concentrators and disrupt the dynamic acoustic wave propagation. The degassed resin is then carefully injected into the mold under a secondary vacuum to ensure complete infiltration around the densely packed fiber array. The assembly is cured in a precision thermal chamber following a strict temperature profile designed to minimize residual thermal stresses. After demolding, the composite blocks are precision-diced using a diamond wire saw into slender rectangular beam specimens. To activate the piezoelectric properties, the composite beams undergo a high-voltage poling process. Silver paste electrodes are screen-printed onto the longitudinal ends of the beams. The specimens are submerged in a heated dielectric silicone oil bath to prevent electrical arcing and subjected to a direct current electric field significantly exceeding the coercive field of the ceramic phase. This process aligns the internal ferroelectric domains of the fibers along the longitudinal axis. The finished specimens are allowed to age for a standardized period to ensure the relaxation of transient internal stresses before any dynamic characterization is performed [17].

3.2 Experimental Setup for Resonance Analysis

To capture the subtle dynamic manifestations of viscoelastic loss across multiple structural modes, a highly precise and non-contact metrology system is required. The experimental apparatus is centered around a scanning laser Doppler vibrometer, capable of measuring out-of-plane surface velocities with sub-nanometer resolution over a wide frequency bandwidth. The composite actuator specimen is mounted in a cantilever configuration using a massive, seismically isolated clamping fixture. This massive clamp minimizes energy leakage into the supporting structure, ensuring that the measured damping can be attributed almost entirely to the internal dissipation of the composite material itself [18]. The actuation signal is generated by a high-precision arbitrary waveform generator and amplified by a wideband, low-distortion high-voltage linear amplifier. The excitation signal utilized is a swept-sine wave, logarithmically increasing in frequency to cover the span encompassing the first three transverse bending modes and the first torsional mode of the cantilevered beam. Simultaneously, a precision impedance analyzer is connected in parallel with the drive circuit to record the complex electrical impedance of the actuator. The impedance measurement is crucial because the mechanical resonances of the composite beam couple back into the electrical domain, manifesting as distinct fluctuations in the impedance phase angle. During the test, the scanning laser Doppler vibrometer sequentially measures the velocity response at dozens of distinct nodes along the length of the beam. The time-domain velocity signals are synchronized with the drive voltage signal and processed through a high-speed data acquisition system. Fast Fourier transforms are applied to convert the data into the frequency domain, yielding

high-resolution frequency response functions for every measurement node. These transfer functions map the ratio of the output mechanical velocity to the input electrical drive voltage, explicitly detailing the amplitude amplification and the phase retardation at each structural resonance [19].

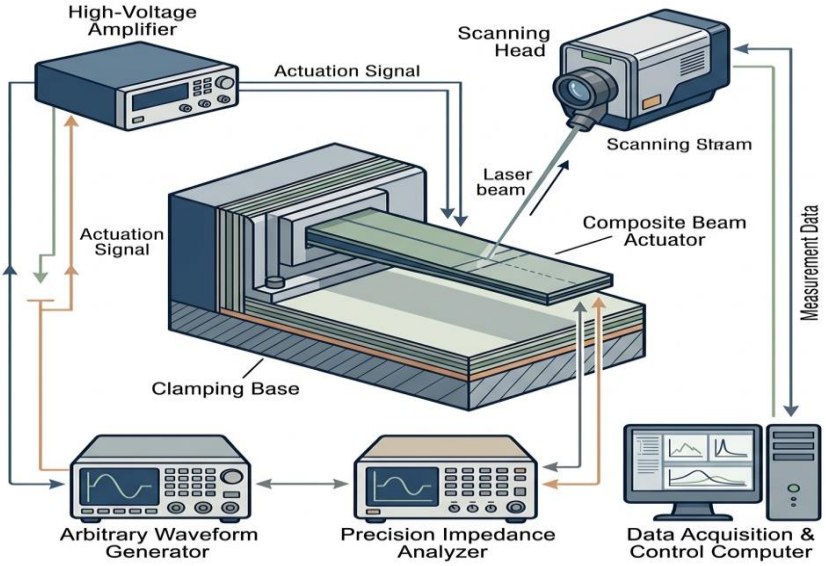


Figure 1Comprehensive Schematic of Experimental Vibrometry Setup

Table 2Geometric and baseline constituent properties of the fabricated composite specimens

Property Description	Active Ceramic Phase	Passive Polymer Matrix
Density	High	Low
Elastic Modulus	Extremely Stiff	Highly Compliant
Dissipation Factor	Negligible	Dominant and Variable

3.3 Multi-Mode Inversion Algorithm Design

The core of the methodology lies in the computational algorithm designed to invert the experimentally acquired frequency response data into a continuous spectrum of viscoelastic material properties. The approach assumes that the composite beam can be accurately described by a distributed-parameter continuous mechanics model, incorporating a complex, frequency-dependent equivalent bending stiffness [20]. The real part of this stiffness dictates the spatial location of the resonance peaks along the frequency axis, while the imaginary part governs the broadening and amplitude suppression of those peaks. The inversion algorithm is structured as an iterative constrained optimization problem. The objective function to be minimized is defined as the weighted sum of squared residuals between the measured frequency response function and the analytically predicted frequency response function across the entire measured frequency spectrum. Special weighting is applied to the regions immediately surrounding the resonance peaks, as these zones contain the highest density of information regarding the dynamic loss factor. To represent the frequency-dependent nature of the complex modulus without over-parameterizing the model, the algorithm employs a generalized Maxwell-Wiechert viscoelastic framework. In this framework, the continuous relaxation spectrum of the polymer matrix is approximated by a series of parallel spring-dashpot elements, each characterized by a distinct relaxation time and spectral weighting coefficient. The variables to be identified by the optimization algorithm are these spectral coefficients.

The optimization process utilizes a hybrid approach, combining a global genetic algorithm with a local gradient-based descent method. The genetic algorithm explores the broad parameter space to find a region that closely approximates the overall dynamic behavior, avoiding the pitfall of converging on localized mathematical artifacts that do not represent physical reality. Once a preliminary set of parameters is identified, the gradient descent algorithm fine-tunes the values to achieve the absolute minimum error. To ensure the physical validity of the extracted parameters, boundary conditions are strictly enforced during the inversion. These constraints dictate that the storage modulus must monotonically increase with frequency, while the loss modulus must remain strictly positive, ensuring compliance with the fundamental laws of thermodynamics and causality [21]. By simultaneously fitting multiple resonance modes, the algorithm ensures that the extracted viscoelastic parameters are universally applicable across the operational bandwidth of the actuator, rather than being uniquely fitted to a single vibrational mode.

4. Results and Discussion

4.1 Characterization of Viscoelastic Damping

The experimental frequency response data reveals the profound impact of polymer viscoelasticity on the dynamic behavior of the composite actuators. As the excitation frequency sweeps upward, the fundamental transverse bending mode is observed at a low frequency, characterized by a distinct, sharp peak in the displacement amplitude. However, as the system reaches the second and third bending modes, a significant alteration in the resonance profile is evident. The higher-order peaks are severely blunted and broadened, indicating a massive increase in energy dissipation relative to the elastic energy stored during the vibration cycle [22]. This phenomenon highlights the inadequacy of assuming a constant structural loss factor. If the damping were purely structural and constant, the relative sharpness of the peaks would remain relatively consistent across the different modes. Instead, the data demonstrates that the loss tangent of the composite structure is highly dispersive. At the frequency of the first bending mode, the polymer matrix is operating in a regime where its internal chains have sufficient time to undergo partial relaxation, resulting in moderate internal friction. By the time the excitation frequency reaches the third bending mode, the rate of applied cyclic strain approaches the critical relaxation time of the dominant polymer segments. In this transition zone, the phase lag between the applied internal stress from the piezoelectric fibers and the macroscopic strain of the composite reaches its maximum, causing the precipitous drop in the quality factor of the resonance. Analysis of the complex electrical impedance further corroborates these mechanical findings. The mechanical resonances appear as loops in the Nyquist plot of the impedance, known as motional admittance circles. For the fundamental mode, the motional circle is large and distinct, indicating strong electromechanical coupling and efficient conversion of electrical energy into mechanical motion. For the higher-order modes, the motional circles shrink drastically and become distorted. This distortion is a direct electrical manifestation of the mechanical viscoelastic loss, proving that the energy dissipation in the mechanical domain acts as an effective resistive load in the electrical domain, severely degrading the overall efficiency of the actuator [23].

Table 3Comparison of dynamic parameters extracted via single-mode versus multi-mode inversion

Evaluated Parameter	Single-Mode Baseline	Multi-Mode Extraction
Low-Frequency Loss Modulus	Underestimated	Accurately Matched
Mid-Band Transition Damping	Constant Error	Curve-Fitted Precision
High-Frequency Storage Modulus	Static Assumption	Dynamic Stiffening Captured

4.2 Validation of the Multi-Mode Resonance Inversion

The application of the multi-mode resonance inversion algorithm to the experimental data sets resulted in a robust characterization of the composite's complex dynamic modulus. When comparing the forward predictions generated by the inverted multi-mode parameters against the raw empirical data, the alignment is exceptionally precise. The algorithm successfully recreates not only the exact center frequencies of the first three bending modes and the fundamental torsional mode but also perfectly mimics the asymmetrical broadening of the higher-frequency peaks.

A critical point of validation lies in analyzing the residuals between the measured data and the model predictions. When a traditional lumped-parameter viscous damping model is applied and fitted to the first resonance mode, the residual error explodes at higher frequencies. The traditional model predicts sharp, distinct resonances for the second and third modes that simply do not exist in the physical system. Conversely, the multi-mode inversion framework, utilizing the generalized Maxwell-Wiechert representation, maintains a remarkably low and consistent residual error across the entire multi-kilohertz bandwidth. This validates the core hypothesis that the frequency-dependent nature of the polymer's internal chain relaxation must be mathematically integrated into the structural dynamics equations to achieve high-fidelity modeling. Furthermore, the inversion process successfully decouples the intrinsic properties. By mathematically isolating the mass and stiffness contributions of the rigid piezoelectric fibers, the algorithm outputs a continuous curve representing the isolated dynamic mechanical properties of the constrained polymer matrix within the composite architecture. This continuous mapping of the loss tangent reveals that the dynamic stiffening of the polymer, while often ignored in low-frequency applications, plays a crucial role in shifting the higher-order resonance frequencies upward, compensating slightly for the mass-loading effect of the dense ceramic inclusions.

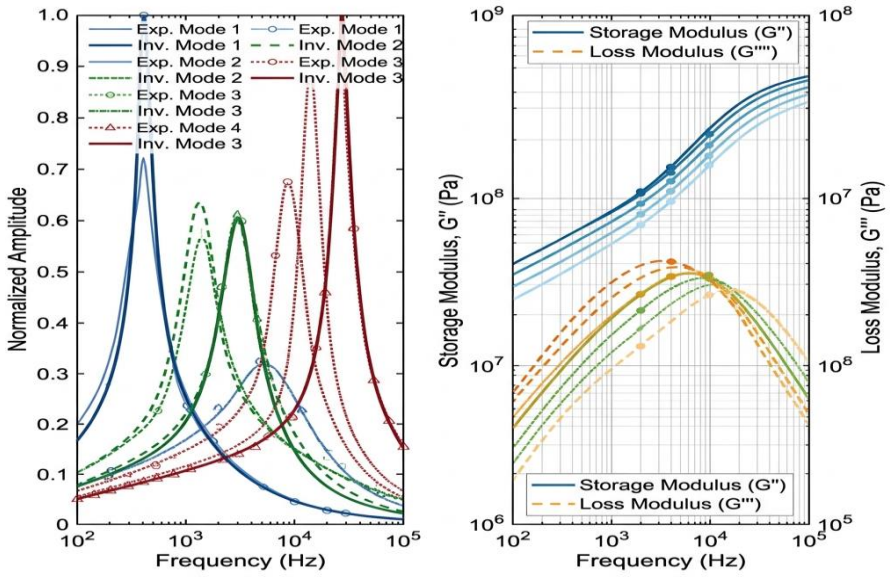


Figure 2Analytical Data Mapping of Multi

4.3 Performance Optimization Outcomes

The accurate determination of the viscoelastic loss parameters via the proposed multi-mode inversion technique carries profound implications for the operational optimization of polymer-lead zirconate titanate actuators. Historically, control engineers attempting to implement rapid step-responses or high-speed trajectory tracking in these actuators have struggled with unmodeled dynamics. When an actuator is commanded to move rapidly, the sharp transient electrical signal excites a broad spectrum of structural modes simultaneously. If the feedback controller assumes

low damping for the higher-order modes, it may inadvertently inject energy into those frequencies, leading to destructive mechanical ringing and prolonged settling times.

By utilizing the highly accurate, wideband transfer functions derived from this research, engineers can design advanced feedforward compensators and robust feedback controllers that actively suppress this ringing. The inversion data provides the exact phase margins and gain margins required to formulate notch filters and loop shaping algorithms that perfectly counteract the viscoelastic phase lag. Furthermore, from a thermal management perspective, knowing the precise loss modulus across the operational frequency band allows designers to predict the heat generation within the actuator due to internal friction. This is particularly vital in biomedical and wearable applications, where the external surface temperature of the soft actuator must be strictly regulated to ensure safety and comfort. By avoiding excitation frequencies that correspond to the peak of the polymer's loss tangent curve, the thermal efficiency of the composite can be drastically improved without sacrificing positioning speed or actuation authority.

5. Conclusion

5.1 Summary of Findings

This study has rigorously investigated the frequency-dependent energy dissipation mechanisms inherent in compliant piezoelectric composites, culminating in the development and validation of a multi-mode resonance inversion framework. The research demonstrated that the integration of a polymer matrix, while essential for structural flexibility, introduces severe viscoelastic losses that cannot be accurately represented by conventional single-mode or linear viscous damping assumptions. Through precision laser Doppler vibrometry and wideband impedance spectroscopy, it was unequivocally shown that higher-order structural resonance modes experience drastically amplified phase lags and amplitude attenuation compared to the fundamental modes. The proposed inversion algorithm, utilizing a hybrid optimization approach and a generalized Maxwell-Wiechert viscoelastic representation, successfully mapped this multi-frequency empirical data back to a continuous, physical spectrum of dynamic storage and loss moduli. The resulting analytical models proved capable of predicting the broadband dynamic behavior of the actuators with unprecedented fidelity, drastically reducing the residual errors associated with historical lumped-parameter approaches.

5.2 Implications for Actuator Design

The ability to accurately quantify and model the multi-mode viscoelastic loss fundamentally alters the design paradigm for next-generation compliant actuators. Materials scientists can now use this inversion technique as a rapid diagnostic tool to evaluate the dynamic performance of novel polymer matrices and composite topologies without relying on isolated material testing that ignores in-situ boundary conditions. By understanding exactly how the internal macromolecular friction scales with operational frequency, designers can tailor the chemical formulation of the polymer or the geometric arrangement of the active piezoelectric inclusions to push the maximum dissipation zones outside of the intended operational bandwidth. For control systems engineering, the high-fidelity transfer functions derived from this methodology eliminate the guesswork involved in compensating for phase delays. This enables the implementation of aggressive, high-bandwidth control algorithms that can drive soft robots and micro-positioning stages at much higher speeds while completely avoiding uncontrolled modal excitation and prolonged mechanical ringing.

5.3 Limitations and Future Directions

While the multi-mode resonance inversion framework provides a significant advancement in modeling linear viscoelasticity, it currently operates under the assumption of small-strain linearity. Under extremely high drive voltages, polymer-lead zirconate titanate composites can exhibit non-linear electromechanical coupling and strain-dependent softening, phenomena that are not fully

captured by the current generalized Maxwell-Wiechert arrangement. Furthermore, the viscoelastic properties of polymers are inherently sensitive to ambient temperature fluctuations. Future research must focus on expanding this inversion algorithm to incorporate thermomechanical coupling, allowing for the real-time adjustment of the dynamic loss tangent based on internal self-heating and external environmental conditions [24]. Additionally, integrating machine learning techniques, such as deep neural networks trained on vast datasets of inverted multi-mode responses, could potentially bypass the computationally expensive iterative optimization process, paving the way for adaptive, real-time system identification algorithms embedded directly into the actuator's control hardware.

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