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# Micromechanical modeling and experimental characterization of 1-3 piezocomposites subjected to electromechanical loads

R. Jayendiran, A. Arockiarajan *

*Department of Applied Mechanics, Indian Institute of Technology Madras, 600036 Chennai, India*

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ABSTRACT

An experimental and theoretical study is carried out to compare the performance behavior of 1-3 piezocomposites with different volume fractions and bulk piezoceramics. Experiments are conducted to measure the electric displacement and strain on piezocomposites and ceramics under high cyclic electrical loading superimposed with mechanical prestress. Elastic, piezoelectric and dielectric constants are measured using IEEE (weak-field) methods for 1-3 piezocomposites with different volume fractions. A numerical model is developed to calculate the effective properties and the results are compared with experimental measurements. To study the overall behavior of piezocomposites, a micromechanically motivated model is developed based on thermodynamic principles and embedded into an electromechanically coupled finite element formulation. The predicted effective properties are incorporated in the proposed model and the dielectric hysteresis (electric displacement versus electric field) as well as butterfly curves (strain versus electric field) are simulated. Comparison between the experiments and simulations show that this model can reproduce the characteristics of non-linear response. The Figures of Merit (FoM) obtained for various compressive stress and varying fiber volume fraction, compared with different regions in the cyclic electric field, which will be helpful in optimizing the devices for underwater and biomedical applications.



## 1. Introduction

The coupling characteristics between mechanical and electric response is known to make piezoelectric materials unique for sensor, actuator and transducer applications. Above the curie temperature, these materials are in the paraelectric state and their response is linear. But below the curie temperature the materials are in the ferroelectric state and these materials show a linear response at low external fields. However, these materials typically exhibit pronounced nonlinear response upon application of high stress and/or electric field. Microstructural reorientation of domains, called domain switching, is the main source of non-linearity in piezoelectric ceramics (Achuthan & Sun, 2005; Huber, 2005; Kamlah, 2001; Landis, 2004). If piezoelectric materials are used in transducers or actuators, these materials will be subjected to combined mechanical and electrical loads. Hence, it is essential to study the influence of electrical properties under mechanical constraints. The performance behavior under limiting stress fields are reported in the literature (Elhadrouz, Zineb, & Patoor, 2006; Fang & Li, 1999; Fotinich & Carman, 2000; Lynch, 1996; Mauck & Lynch, 2003; Zhou & Kamlah, 2004).

* Corresponding author. Tel.: +91 44 22574070; fax: +91 44 22574052.
*E-mail address:* aarajan@iitm.ac.in (A. Arockiarajan).

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Besides the experimental work, a number of theoretical models have been developed to study the response of piezoceramics under electromechanical loading. This theoretical study will help to optimize the loading conditions or the selection of appropriate materials for the device design. Modeling of constitutive relations can be grouped into two major categories:phenomenological and micromechanical approaches. Phenomenological model takes an analogy between non-linear ferroelectric response and metal plasticity. Generally, these models are described based on flow plasticity theory. Phenomenological (macroscopic) modeling mostly relies on a thermodynamical formulation and experimental data (Chaplya & Carman, 2001; Elhadrouz, Zineb, & Patoor, 2005; Kamlah & Tsakmakis, 1999; Linnemann, Klinkel, & Wagner, 2009; McMeeking & Landis, 2002; Schröder & Romanowski, 2005; Smith & Hu, 2012; Zouari, Ben Zineb, & Benjeddou, 2011). Whereas, the micromechanical models explore the effects of intergranular interactions, orientation of grains and volume changes associated with structural phase changes. Since the origin of this model includes more physical insight into the material, these models are believed to be more appropriate than phenomenological models (Arockiarajan, Sivakumar, & Sansour, 2010; Haug, Huber, Onck, & Van der Giessen, 2007; Huber & Fleck, 2004; Kessler & Balke, 2001; Kim, 2012; Li & Kuna, 2012; Lu, Fang, Li, & Hwang, 1999; Neumeister & Balke, 2011). The electro-mechanical principle of virtual work, to describe the geometrical non-linearity, history-dependent constitutive relations, and the iterative solution procedure are developed and discussed (Kushnir & Rabinovitch, 2008, 2009a, 2009b).

Eventhough bulk piezoelectric materials are very attractive materials for actuator applications, it suffers from some drawbacks namely low coupled properties, high acoustic impedance and brittleness. Recently, piezocomposites that have been developed can replace bulk ceramics, since they have superior electro-elastic properties, low acoustic impedance and ductility (Nelson, 2002). Also, there is a drive for the rapid development of smart composites, stems from the need for a combination of desirable material properties that often cannot be obtained in single-phase materials (Topolov & Bowen, 2009). The acoustic impedance ($Z$), electromechanical coupling coefficient ($K_t$) and longitudinal acoustic velocity ($V^D$) are the important parameters for the design of ultrasound transducers in biomedical and underwater applications. 1-3 piezocomposites are more promising candidates compared with bulk piezoceramics and henceforth, it has more attention in the above applications (Smith & Auld, 1991). In actuator applications, high electric fields are often applied to induce desired deformations, leading to nonlinear electromechanical behavior. However, it is important to study the non-linear behavior of piezocomposites subjected to high loading conditions. An analytical study reported the overall non-linear behavior of multiphase composites and it shows that the behavior has strong dependence of fiber volume fraction and mechanical loads (Aboudi, 2005). The epoxy matrix used in piezocomposites are viscoelastic in nature and the effects of behavior of piezocomposites under high electric field are limited. Simple and computationally effective models are reported in the literature wherein the effects of viscoelastic polymer matrix on overall electro-mechanical response are considered (Jayendiran & Arockiarajan, 2012; Shindo, Narita, & Watanabe, 2010; Muliana, 2010). The orientation dependent electromechanical behavior of 1-3 piezocomposites has been predicted experimentally and compared with theoretical studies (Zhao & Li, 2009; Zhao, Cao, & Li, 2011).

Literature review shows that 1-3 type piezocomposites can be a good alternative for bulk PZT ceramics for transducer applications wherein piezocomposites are stacked over each other along the thickness direction and subjected to a constant prestress. Though some research work are reported in the literature, the authors are not aware of any published work in determining the performance behavior of 1-3 piezocomposites subjected to coupled electromechanical loading. Hence, the objective of this work is to study the behavior of piezocomposite under electromechanical loading condition. The effective properties of piezocomposites are measured based on IEEE standards with radial (thin disc) and longitudinal (cube) modes configurations. Commercially, there are few fiber volume fraction compositions are available. Hence, a numerical model is developed to predict the effective properties of piezocomposites that varies from 0 to 100% volume fractions. Subsequently, the test samples will be subjected to electro-mechanical loading conditions and the performance behavior such as strain and electric displacements will be measured. To study the performance behavior, a physically motivated micromechanical model will be developed and embedded into a finite element method wherein the calculated effective properties from the numerical model will be used. Simulated performance behavior results from the micromechanical model will be compared with experimental data. This work is also extended to study the FoM in the non-linear region (i.e.,) above the coercive electric field and below the coercive compressive stress for various fiber volume fractions which will help the device designers for the selection of appropriate volume fraction for a particular application. The outline of the paper is as follows: Section 2 describes the electromechanical experimental setup and procedure. Section 3 deals with the experimental and numerical prediction of effective properties of piezocomposites. The proposed non-linear model formulation for 1-3 type piezocomposite is elaborated in Section 4. Finally, the interpretation of experimental results and comparison with the theoretical results are reported in Section 5.

## 2. Experimental description

Experiments have also been performed to measure the required material constants ($C, e, k$) for bulk PZT and 1-3 piezocomposites of different fiber volume fraction based on IEEE standards with weak-field (<0.01 kV/mm) techniques (IEEE, 1988). Piezoelectric transducer materials are commonly characterized by resonance measurements based on IEEE standard. Fig. 1 shows the equivalent circuit for measuring the resonance and anti-resonance frequency of PZT sample and the photograph of impedance analyzer and specimen holder for measuring the resonance frequencies of PZT. A small AC signal is