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Free vibration analysis of magneto-electro-elastic microbeams subjected to magneto-electric loads

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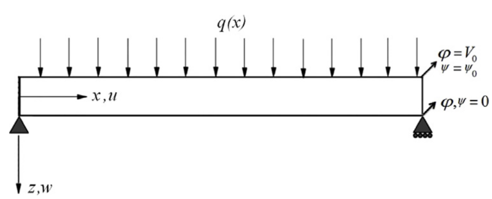
HIGHLIGHTS

- Free vibration of a MEE microbeam is investigated.
- The governing equations and boundary conditions are derived.
- Natural frequencies of the microbeam under electric and magnetic potentials are obtained.
- Critical values of electric and magnetic potentials that lead to buckling are obtained.

GRAPHICAL ABSTRACT

Based on Euler–Bernoulli beam theory natural frequency and critical potential values of a magneto-electro-elastic (MEE) microbeam is analytically derived.



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ABSTRACT

Different types of actuating and sensing mechanisms are used in new micro and nanoscale devices. Therefore, a new challenge is modeling electromechanical systems that use these mechanisms. In this paper, free vibration of a magnetoelectroelastic (MEE) microbeam is investigated in order to obtain its natural frequencies and buckling loads. The beam is simply supported at both ends. External electric and magnetic potentials are applied to the beam. By using the Hamilton's principle, the governing equations and boundary conditions are derived based on the Euler–Bernoulli beam theory. The equations are solved, analytically to obtain the natural frequencies of the MEE microbeam. Furthermore, the effects of external electric and magnetic potentials on the buckling of the beam are analyzed and the critical values of the potentials are obtained. Finally, a numerical study is conducted. It is found that the natural frequency can be tuned directly by changing the magnetic and electric potentials. Additionally, a closed form solution for the normalized natural frequency is derived, and buckling loads are calculated in a numerical example.

1. Introduction

Recently in the field of materials science, there has been a great interest in smart materials that have piezoelectric and piezomagnetic characteristics. These materials, called magnetoelectroelastic (MEE) composites, have the ability of converting energy from one form (among magnetic, electric and mechanical energies) to another and vice versa. Furthermore, they present a magnetoelectric effect that is not observed in single-phase piezoelectric or piezomagnetic materials [1–5]. In more recent studies, composite forms of these materials were utilized.

Since the 1970s when the first MEE composite consisting of the piezoelectric and piezomagnetic phase was reported [6] , MEE composite materials have attracted considerable attention. In the past 10 years, with the trends toward device miniaturization, the MEE nanomaterials (e.g., $BiFeO_3$, $BiTiO_3$–$CoFe_2O_4$, $NiFe_2O_4$-PZT) and their nanostructures (e.g. nanowires, nanofilms,) became an active research subject [7–10]. Compared to MEE bulk composite materials, MEE nanomaterials presented novel electric, magnetic, mechanical and physical properties. They also had a significant

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Nomenclature

A	cross-sectional area of MEE microbeam
B_i	components of magnetic flux
b	width of MEE microbeam
C_{ij}	elastic stiffness tensor
D_i	components of electric displacement
E_i	components of electric field
e_{ij}	piezoelectric coefficients
ε_{ij}	components of linear strain
f_{ij}	piezomagnetic coefficients
ϕ	electric potential
g_{ij}	magnetoelectric coefficients
H_i	components of magnetic field
h	thickness of MEE microbeam
h_{ij}	dielectric permittivity constants
I	second moment of area for MEE microbeam
L	length of MEE microbeam
M	internal bending moment
μ_{ij}	magnetic permittivity constants
N_{cr}	fundamental buckling force for a simply supported MEE microbeam
N_e	normal force induced by the external electric potential
N_m	normal force induced by the external magnetic potential
ω	normalized natural frequency
ω_n	natural frequency
Π_{ex}	virtual work done by the external force
Π_k	kinetic energy
Π_s	strain energy
q	external transverse force
ρ	density
ψ	magnetic potential
ψ_0	magnetic potential between lower and upper surfaces of MEE microbeam
σ_{ij}	components of stress
u	component of displacement parallel to x direction
v	component of displacement parallel to y direction
V_0	electric potential between lower and upper surfaces of MEE microbeam
w	component of displacement parallel to z direction
x	direction along length of microbeam
z	direction along thickness of microbeam

magnetoelectric coupling, and a wide range of potential applications in nanoelectronics, non-volatile memories, NEMS, switchable photovoltaics, etc. [11–13]. After discovering the characteristics of these materials, the next step was using them in different structures.

Among the structures that are made of MEE materials, at first, much attention has been paid to the structural analysis of the magnetoelectroelastic plate. Liu and Chang [14] presented a closed form solution for the vibration problem of a transversely isotropic MEE plate. Pan [13] presented an exact closed-form solution for the static deformation of a layered MEE plate based on a new and simple formalism resembling the Stroh formalism. Using the state-vector method, Wang et al. [15] obtained an analytical solution for MEE, simply supported and multilayered rectangular plates in the form of infinite series. Later, the state-vector approach was proposed by Chen et al. [16] for the analysis of free vibrations of MEE layered plates. An equivalent single-layer model for the dynamic analysis of MEE laminated plates was presented by Milazzo [17]. Using the meshless local Petrov–Galerkin (MLPG) method, Sladek et al. [18] solved the mechanical problem of the MEE plate under a stationary harmonic load.

More complex models for plates have also been used in previous research studies. Bhangale and Ganesan [19] investigated static analysis of a functionally graded (FG) MEE plate by the finite element method under mechanical and electrical loadings. Wang et al. [20] analyzed the axisymmetric bending of FG circular MEE plates of transversely isotropic materials based on the linear three-dimensional theory of elasticity coupled with magnetic and electric fields. Wu et al. [21] extended the Pagano method for the three dimensional plate problem to the analysis of a simply supported, FG rectangular plate. A nonlinear large-deflection model for MEE rectangular thin plates was proposed by Xue et al. [22]. Despite of these research studies on structural analysis of MEE plates, because of using MEE beams in sensors and actuators etc., structural analysis of MEE beams in micro and nanoscales is also necessary.

A detailed study on MEE beams is crucial because the first steps for future analysis of vibrational characteristics and control are static analysis and also free vibration analysis. MEE beams vibrations have been analyzed in a limited number of research works. Jiang and Ding [23] derived the governing equations of MEE beams and studied their free vibrations. Milazzo et al. [24] analyzed the forced vibrations of MME beams. Ke and Wang [25] used the nonlocal theory to study the free vibrations of MEE beam. In the previous research on beam vibrations, there is a lack of analysis on the critical buckling potentials and instabilities, especially in microbeams. It is necessary to cover this in an independent work that can be used in the design process of new MEMS devices.

In this research, free vibration of a MEE microbeam, based on the magneto-electro-elasticity theory and Euler–Bernoulli beam theory, is investigated. The in-plane electric and magnetic fields are ignored for the microbeam. The governing equations of a MEE microbeam are derived using Hamilton's principle. Finally, as a numerical study, the critical values of magnetic and electric potentials in buckling are calculated.

2. Modeling and formulation

2.1. Geometry of the beam

An MEE microbeam of length L, width b and thickness h that is subjected to a distributed load is depicted in Fig. 1(a). In order to

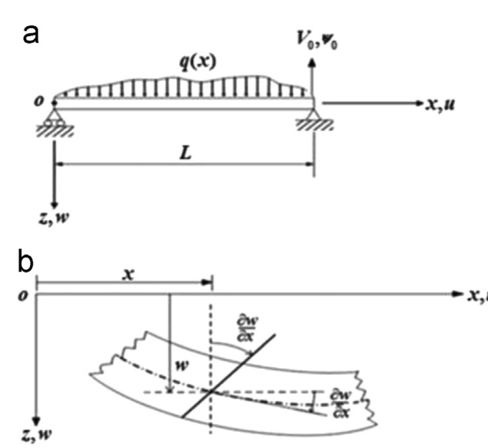

Fig. 1. (a) Schematic of MEE beam and (b) displacement components of the beam [26].