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Solutions for the magneto-electro-elastic plate using the scaled boundary finite element method

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ABSTRACT

A semi-analytical technique based on the elastic theory is employed to study the deformation of a magneto-electro-elastic plate. Solutions are acquired by applying the scaled boundary finite element method (SBFEM), which requires the discretization of the boundary as in the boundary element method but does not need a fundamental solution. In the whole process, the detailed derivation is based on the three-dimensional governing equation. With the aid of the scaled boundary coordinates, the 3D key partial differential equation is converted into the ordinary differential equation. Only the in-plane dimensions are needed to be discretized, which contributes to reducing the computational effort. Furthermore, utilizing the high order spectral element can do good to obtain high accuracy and efficiency. The components of the magneto-electro-elastic field are solved numerically in the in-plane direction and analytically in the thickness direction. Solutions along the vertical direction are formulated as a matrix exponent which is solved by the Padé series expansion of order (2, 2). Comparisons with the numerical examples are provided to validate the proposed solutions. Meanwhile, other examples are carried out to demonstrate the versatility of the present method.

1. Introduction

In recent years, the study of advanced smart structures has attracted numerous researchers. It is well known that magneto-electro-elastic materials exhibit a specific ability to convert energy of magnetism, electricity or elasticity into another form which is not appeared in a single-phase piezoelectric or piezomagnetic material. Because of the multiple coupling effects, magneto-electro-elastic materials open towards new interesting and effective applications in many technological fields such as sensing and actuating devices, vibrations control, energy harvesting and smart structure technologies. Due to the multi-field behavior of the employed magneto-electro-elastic materials, it seems that the problems related to the magneto-electro-elastic plate are not easy to be properly understood and provided for adequate analysis. Hence, it is essential to develop analytical and numerical techniques to analyze the behavior of a magneto-electro-elastic plate under mechanical, electrical or magnetic loads for its efficient design.

Intensive research on the physical and mechanical properties of the magneto-electro-elastic plate has been carried out by means of analytical and numerical methods. Pan [1] suggested a general method of solving the three-dimensional, anisotropic magneto-electro-elastic, simply supported, and multilayered rectangular plates under both surface and internal static loads. Chen et al. [2] derived the general solutions for the axisymmetric problem of the transversely isotropic magneto-electro-elastic circular plate formulated by four harmonic displacement functions. Wang et al. [3] introduced the state vector equations for the linear theory of three dimensional, orthotropic and magneto-electro-elastic materials with the aim of deriving an efficient analytical method for multilayered magneto-electro-elastic structures. Pan and Heyliger [4] studied the analytical method to the static bending analysis of anisotropic, magneto-electro-elastic, and multilayered plates with simply supported edges. Heyliger and Pan [5] made use of a discrete-layer approximate model to discuss the static behavior of laminates with coupled elastic, electric, and magnetic behavior. Lage et al. [6] considered a new layerwise partial mixed finite element model for static analysis of magneto-electro-elastic laminated plate structures. Heyliger et al. [7] depicted a discrete-layer model for laminated magnetoelectroelastic plates and utilized it to simply-supported laminates in cylindrical bending and single-layer plates under applied electric and magnetic field. Pan

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and Han [8] created an exact solution for a multilayered rectangular plate made of anisotropic and functionally graded magneto-electro-elastic materials with simply supported along its edges and both mechanical and electric loads applied on the top surface. Bhangale and Ganesan [9] proposed a semi-analytical finite element method to solve the functionally graded, anisotropic and linear magneto-electro-elastic plates under mechanical and electrical loading. Based on the virtual boundary element-integral collocation method, Li and Yao [10] solved the plane problem of magnetoelectroelastic solids. Jiang et al. [11] gained the Green's functions for point forces, point charge and point current acting in interior of a two-phase infinite magneto-electro-elastic plane. Li et al. [12] obtained the three-dimensional analytical solution for the axisymmetric problem of a uniformly loaded, transversely isotropic, circular plate of functionally graded magneto–electro-elastic materials. Dai et al. [13] investigated the three-dimensional couple equations of magneto-electro-elastic structures under Hamiltonian system based on the Hamilton principle. Carrera et al. [14] extended the Carrera's unified formulation and the Reissner's mixed variational theorem to develop finite elements for the static analysis of magneto-electro-elastic plates. Phoenix et al. [15] developed the Reissner's mixed variational theorem for the static and dynamic analysis of magneto-electro-elastic plate problem. Moita et al. [16] applied the higher-order plate theory to demonstrate a finite element model for static and free vibration analyses of magneto-electro-elastic plates. Wang et al. [17] exploited the state space vector, finite Hankel transform and propagating matrix method to acquire the analytical solution for three-dimensional transversely isotropic axisymmetric multilayered magneto-electro-elastic (MEE) circular plates under simply supported lateral boundary conditions. With the aid of a modified Pagano method, Wu et al. [18] obtained 3D solutions of simply-supported, functionally graded magneto-electro-elastic rectangular plates. Based on the 8-node brick elements with integration of the material stiffness, Wang and Pan [19] presented a 3D finite element method program for functionally graded material multiferroic composite. Built on the Kirchhoff hypothesis and classical thin-plate theory, Liu [20] introduced a rather simple analytic solution for the bending problem of the magneto-electro-elastic rectangular thin plate under certain type of applied loads acting on the top or bottom surfaces. Wang et al. [21] carried out a study on the axisymmetric bending of functionally graded magneto-electro-elastic circular plates subjected to axisymmetric loads based on three-dimensional linear theory of such material. Xue et al. [22] developed a nonlinear large-deflection model for the magnetoelectroelastic rectangular thin plate deformation under a static mechanical load. Milazzo [23] took advantage of the first-order shear deformation theory to propose an equivalent single-layer approach for the dynamic analysis of laminated magnetoelectroelastic plates. In the frame of a first order mechanical equivalent single-layer model, Alaimo et al. [24] provided and validated an isoparametric four-node finite element for multilayered magneto-electro-elastic plates. Kondaiah et al. [25] investigated the pyroelectric and pyromagnetic effects on magneto-electro-elastic plate with different boundary conditions under uniform temperature rise. Sladek et al. [26] developed a meshless local Petrov–Galerkin method to analyze nonlinear large-deflections for the magnetoelectroelastic thick plate subjected to a static and time-harmonic mechanical load and a stationary electromagnetic load. At the same time, Sladek et al. [27] firstly proposed a meshless method based on the local Petrov–Galerkin weak-form for bending analyses of functionally graded material plates with integrated magnetoelectroelastic sensor and actuator layer. With the help of an equivalent single-layer model, Alaimo et al. [28] proposed a finite element formulation and solution for multilayered magneto-electro-elastic plates undergoing large deflections. Kattimani and Ray [29] conducted a three dimensional finite element analysis to explore the geometrically nonlinear vibrations of the magneto-electro-elastic plates integrated with the patches of the active constrained layer damping treatment. Milazzo et al. [30] employed an equivalent single-layer approach for the non-linear large deflection analysis of multilayered magneto-electro-elastic laminates under static loads. Sladek et al. [31] utilized the meshless local Petrov–Galerkin method to analyze the problem of circular plate bending with functionally graded magneto-electro-elastic material properties. Xin and Hu [32] proposed the state space approach and the discrete singular convolution algorithm for the analysis of free vibration of simply supported and multilayered magneto-electro-elastic plates. Sladek et al. [33] extended the scaled boundary finite element method to solve 2D boundary value problems for the representative volume element to get effective material coefficients in a porous magnetoelectroelastic solid with regularly distributed voids.

As a universal approach, finite element method (FEM) is suitable for the problem of magneto-electro-elastic plate with arbitrary material properties and geometric shapes. However, 3-D finite element solutions are carried out with high computational costs and cannot be used in the design phase or for the simulation of complex realistic systems. The boundary element method (BEM) is well appropriate to model the magneto-electro-elastic plate. It is computationally efficient because only the boundary needs to be discretized. However, BEM analysis requires the fundamental solution, which is difficult to find for complicated geometry.

The main purpose of the current paper is to utilize a new semi-infinite method named the scaled boundary finite element method (SBFEM) to solve the problem of thin to moderately thick magneto-electro-elastic plate. In SBFEM analysis, the in-plane dimension of the magneto-electro-elastic plate is divided into 2D finite elements, which helps to reduce the computational effort. The scaled boundary finite-element method was firstly introduced by Wolf and Song [34] in the 1990s based on the similarity concept for the dynamic stiffness of unbounded domains. The scaled boundary finite element method combines advantages of the FEM and BEM and possesses its own unique attractions at the same time. Specifically, it only discretizes the boundaries and the spatial dimension of the problem is reduced by one. Unlike the BEM, no fundamental solutions are required. Comparisons with FEM, solutions of the SBFEM are analytical in the radial direction. SBFEM can preserve a high level of accuracy and provide the basis to develop efficient numerical solutions for complex configurations. The novel method can accurately and efficiently simulate the problem of singularities and unbounded domains. Recently, the scaled boundary finite-element method has been successfully used to model the layered soil-structure interaction [35–37], solve the problem of stress singularities of piezoelectric materials [38–41] and simulate heat transfer or conduction problems [42–45]. Meanwhile, this method is extended to carry out a study on plate and laminated composite [46–51]. The remainder of this paper is organized as follows. The detailed theoretical derivation for the magneto-electro-elastic plate is given in Section 2. The solution procedure for the governing equations is presented in Section 3. Section 4 demonstrates the accuracy and efficiency of the proposed numerical model by a list of numerical examples. Finally, the conclusions are drawn in Section 5.

2. Theoretical derivation

The magneto-electro-elastic plate is solved as a 3D structure as shown in Fig. 1. Unknown variables of the magneto-electro-elastic plate include the elastic displacement components along x, y and z directions, the electric potential and the magnetic potential, which