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Isogeometric vibration analysis of functionally graded nanoplates with the consideration of nonlocal and surface effects

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ABSTRACT

Presented in this paper is a size-dependent analysis of the surface stress and nonlocal influences on the free vibration characteristics of rectangular and circular nanoplates. Nanoplates are assumed to be made of functionally graded materials (FGMs) with two distinct surface and bulk phases. The nonlocal and surface effects are captured by the Eringen and the Gurtin-Murdoch surface elasticity theories, respectively. The Mori-Tanaka distribution scheme is also used for obtaining material properties of nanoplate. In addition to the conventional procedure of deriving the formulation, a novel matrix-vector form of the governing differential equations of motion is presented. This form has the capability of being used directly in the finite element method or isogeometric analysis. To show the effects of surface parameters and small scale influences on the vibrational behavior of rectangular and circular FGM nanoplates with various boundary conditions, several case studies are presented.

1. Introduction

Due to the lack of intrinsic length scales, the classical elasticity theories are unable to predict size effects, and applying these theories to micro/nano scale problems leads to inaccurate results. Accordingly, some higher-order continuum theories such as the nonlocal elasticity theory [1–3], couple stress/strain gradient theories [4–7] and modified versions of them [8,9] have been proposed. A literature survey shows that many research works have been presented on the basis of non-classical elasticity theories, for instance [10–17].

Eringen's nonlocal elasticity theory states that the stress field at a point of continuum body depends on the strain field at all points of the body. There are several papers on the nonlocal analysis of nano-scale structures which are widely used in engineering applications like the nano-electro-mechanical systems (NEMS), e.g. [18–23]. Chakraverty et al. [24] employed the nonlocal elasticity theory to peruse the free vibration of isotropic rectangular nanoplates. The solution methodology was based on the Rayleigh–Ritz method and different boundary conditions are considered in paper. Sobhy [25] earned the natural frequencies and critical buckling loads of orthotropic nanoplates resting on Pasternak's foundation based on the nonlocal continuum theory. The free vibration analysis of piezoelectric Kirchhoff nanoplate is presented bay Liu et al. [26]. The nonlocal elasticity theory is adopted to capture size effects and also the influences of coupled thermo-electro-mechanical fields are presented. Based on nonlocal continuum theory, Narendar and Gopalakrishnan [27] used the spectral analysis to detect thermal impacts on the ultrasonic wave propagation characteristics of nanoplates. In order to determine the bucking responses of microtubules, Civalek and Demir [28] developed a size-dependent finite element model on the basis of nonlocal elasticity theory. Also, Civalek and Akgoz investigated the free vibration behavior of annular sectors in micro dimension with consideration of elastic matrix and nonlocal parameter effects [29].

Functionally Graded Materials (FGMs) have been used extensively in many engineering structures because of owing the specific mechanical and thermal advantages of the conventional materials. Functionally graded plates have an important role in enormous applications like the load bearing in aerospace and nuclear reactors or heat resistance in space crafts and nuclear plants [30]. Among the investigations on FGMs, one can mention the work of Shahba and Rajasekaran [31], in which studied the free vibration and stability of axially functionally graded tapered Euler–Bernoulli beams by means of the differential transform element method (DTEM) and differential quadrature element method of lowest-order (DQEL). Huang and Han analyzed the nonlinear buckling and post-buckling problem of axially compressed functionally graded cylindrical shells based on the nonlinear large deflection theory [32]. Ansari et al. applied different higher order elasticity theories as well as the analytical and numerical methods to investigate the static bending, pre- and post-buckling, thermal buckling and post-buckling, pull-in instability, free and forced vibrations behavior of functionally

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graded micro/nano structures [33–39].

The surface effects of a body should be taken into considerations because of the fact that the bulk and surface parts of a solid have different material properties [40,41]. These effects are more appeared in high surface to volume ratios like the thin plates [42] and micro/nano scaled structures [43]. Gurtin and Murdoch [44,45] suggested the surface elasticity theory which is capable of predicting the surface stress effects properly. In recent years, some attempts are made by scientists to figure out surface stress effects on the mechanical behavior of nanostructures [46–54]. For instance, Wang and Feng [47] considered two thin surface layers to investigate the influences of surface elasticity and residual tension on the natural frequencies of microbeams. He and Lilley [48] analyzed the static bending of nanowires incorporating surface energies. They modelled nanowire by Euler-Bernoulli beam with different end conditions. Shaat and Mohamed [55] utilized couple stress and surface elasticity theories to capture the size-dependent results of nonlinear electrostatic model of actuated beams. Chen et al. [56] considered the Timoshenko beam theory to study the effects of surface stresses on the natural frequencies of axially FG nano-cantilever systems. Moreover, free and forced vibration problems of nanowires with surface energies corresponding to different types of boundary conditions were analyzed in the paper of Wu et al. [57].

Complexity of size-dependent continuum theories makes it hard to find the closed-form solutions for the structures with different boundary conditions. So, various numerical and semi-analytical techniques are adopted due to the problems requirements. Among them, Finite Element Method (FEM) shows its capability and reliability in wide range of crucial situations [58,59]. The Isogeometric Analysis (IGA) is the FEM-based proposed approach by Hughes et al. [60,61] inspired from the Computer Aided Design (CAD). By employing the Non-Uniform Rational B-Splines (NURBS) as basis functions for approximation of the unknown variables as well as construction of the exact geometry, the new efficient method is born. The advantages of this approach motivated researchers to use IGA in different contexts of problems in recent years [62–64]. As one of the latest works on this category, Nguyen et al. [65] presented the isogeometric analysis on functionally graded nanoplates based on the nonlocal elasticity theory. They used the refined and quasi-3d plate theories to determine the bending, buckling and free vibration characteristics of nanoplates. Moreover, Ansari and Norouzzadeh [66] utilized IGA to capture pre-buckling responses of functionally graded nanoplates. Nonlocal and surface parameters were considered to determine size effects on the pre-buckling of circular, elliptical and skew nanoplates.

Surface stress and nonlocal effects on the free vibration behavior of FG rectangular and circular nanoplates are studied in this paper. Eringen and Gurtin-Murdoch theories are employed to consider the effects of small scale and surface energies. The governing equations of motion are derived in two ways. The reader can easily follow the first way which is in the conventional format of the published literature. In the second way, a novel vector-matrix form of formulation is presented. This form has the capability of being used directly in the finite element method or isogeometric analysis. Some case studies are given to study the influences of surface and nonlocal parameters on the free vibration characteristics of FG nanoplates under different types of boundary conditions.

2. Problem identification

Fig. 1 shows the nanoplates under consideration, including the circular and rectangular geometries in Cartesian coordinate system (x, y, z). Geometrical properties like radius R, length a, width b and thickness h of circular and rectangular plates are indicated. Besides of the bulk part with Young's modulus E, Poisson's ratio ν and mass density ρ, two thin surface layers are considered to examine the surface stress effects on the dynamical behavior of plate-type nanostructures. These layers are consist of Lame's surface constants λ_s and μ_s, surface residual stress τ_s and surface mass density ρ_s. The nanoplate is made of functionally graded materials in which the mechanical properties are varying continuously in thickness direction from the metal characteristics in lower surface ($S^{-}\rightarrow z = -h/2$) to the ceramic ones in upper

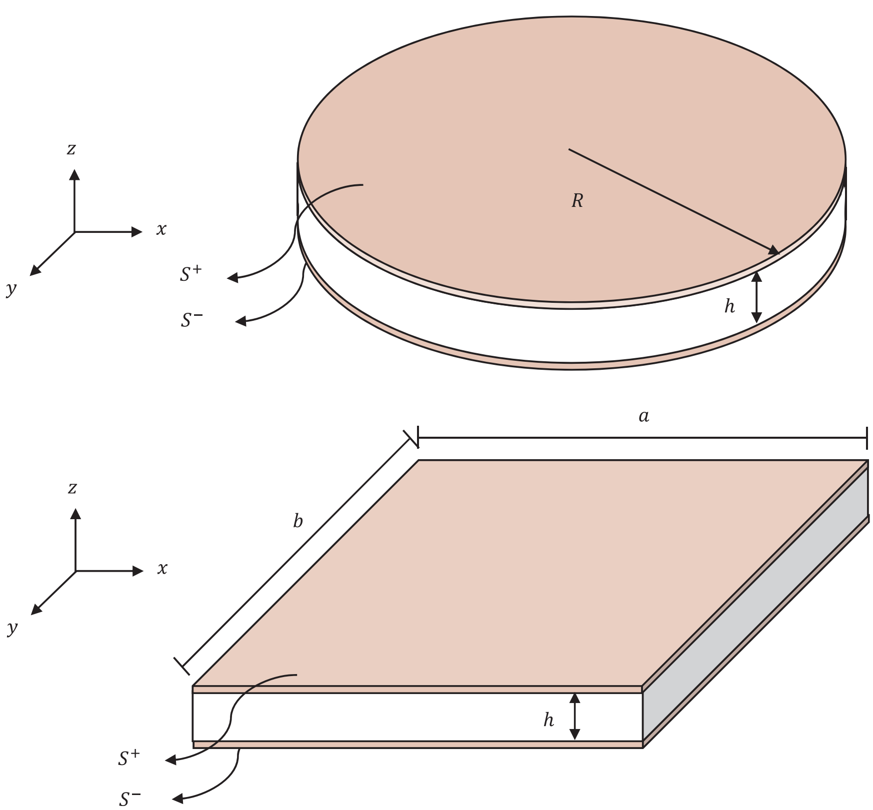

Fig. 1. Schematic of the circular and rectangular functionally graded nanoplates with two surface layers.