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Vibration analysis of rotating functionally graded Timoshenko microbeam based on modified couple stress theory under different temperature distributions

Majid Ghadiri *, Navvab Shafiei

Faculty of Engineering, Department of Mechanics, Imam Khomeini International University, 3414916818 Qazvin, Iran

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ABSTRACT

In this study, thermal vibration of rotary functionally graded Timoshenko microbeam has been analyzed based on modified couple stress theory considering temperature change in four types of temperature distribution on thermal environment. Material properties of FG microbeam are supposed to be temperature dependent and vary continuously along the thickness according to the power-law form. The axial forces are also included in the model as the thermal and true spatial variation due to the rotation. Governing equations and boundary conditions have been derived by employing Hamiltonian's principle. The differential quadrature method is employed to solve the governing equations for cantilever and propped cantilever boundary conditions. Validations are done by comparing available literatures and obtained results which indicate accuracy of applied method. Results represent effects of temperature changes, different boundary conditions, nondimensional angular velocity, length scale parameter, different boundary conditions, FG index and beam thickness on fundamental, second and third nondimensional frequencies. Results determine critical values of temperature changes and other essential parameters which can be applicable to design micromachines like micromotor and microturbine.

1. Introduction

During past few years, functionally graded materials investigations have been widely done by researchers because of their peerless properties and ability of this type of materials to compound different properties of different materials, such as metals and ceramics. At this category of materials the physical and mechanical properties of many phases change continuously which improves materials' strength under huge loadings in high temperature environments. Functionally graded materials are desirable ones that can be and would be used in industrial applications variously such as, biomedicines, electronics, optics and etc. and this requirement has compelled researchers to investigate more on this topic [1,2].

Many researchers have performed studies on static and dynamic behavior of functionally graded beams. Sankar offered a solution for transverse vibration of a Bernoulli–Euler functionally graded beam with simply supported boundary [3]. Also Sankar and Tzeng studied the thermoelastic properties of a functionally graded beam by classic theories and understood that distribution of materials can be designed in a way that minimizes the thermal stresses and maximizes the strength of composition [4], while Aydogdu and Taskin did study on natural frequencies and mode shapes of a functionally graded beam with same boundary conditions as Sankar [5]. Kapuria et al. presented both analytical model based on zigzag theory and experimental test, and investigated natural frequencies beam response to cantilever and simply-supported boundary

* Corresponding author. Tel.: +98 28 33901144 ; fax: +98 28 33780084.
E-mail address: ghadiri@eng.ikiu.ac.ir (M. Ghadiri).

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conditions [6]. Şimşek has investigated the fundamental frequencies of functionally graded beam with different boundary conditions using classical, first and higher order shear deformation theories [7]. Ying et al. proposed an exact solution to analyze vibration of functionally graded beam based on a two-dimensional theory of elasticity regarding that beam rest on a Winkler–Pasternak elastic foundation and investigated effects of aspect ratio, foundation parameters and gradient index on mechanical behavior of functionally graded beam [8]. Wattanasakulpong et al. stu-died the slenderness and material composition effects on vibration of functionally graded beam based on third order shear deformation theory and observed that by increasing temperature, the fundamental frequencies decrease [9]. Fallah et al. investigated elastic coefficient and material inhomogeneity for a Bernoulli–Euler beam assuming Von Kármán's strain displacement relation by proposing an analytical model [10]. Şimşek et al. proposed an analytical solution to study bending and buckling of a functionally graded nanobeam utilizing Timoshenko and Bernoulli–Euler models based on nonlocal theory by applying Navier-type solution and investigated effects of nonlocal parameter, aspect ratio and distribution of materials on nanobeams behavior [11]. Their results represented that proposed model produces larger deflections than expected. Moreover, Rahmani and Pedram studied effects of material gradient index, length scale parameter and slenderness ratio on free vibration of functionally graded Timoshenko beam, based on Eringen's nonlocal theory [12]. Ansari et al. developed a size dependent functionally graded Timoshenko nanobeam model to study power index of material distribution function and slenderness ratio effects on vibrational behavior of nanobeam [13].

Due to widespread utilization of this category of materials at micro-scales, during past few years, a lot of experimental tests have been performed and a lot of experimental papers have been published on this topic to get the most compatible theory to analyze their behavior. Fleck et al. investigated the behavior of materials at micro-scales and got that by decreasing size of copper micro-wire the mechanical properties of wire change [14]. Moreover Lam et al. developed an elastic bending theory, and by performing experimental test represented that decreasing thickness of beam up to micro-scales, results in the rigidity of the beam increase [15]. At that period of time, some other researchers like Lam and Chong [16], Ma and Clarke [17], Stelmashenko at al. [18] and others proved that previous classical continuum based theories were not applicable to deal with such micro scaled structures due to their size effect, by providing experimental data. Accordingly, a higher order continuum theory has been required to define material behavior exactly. This need led researchers to find new approaches that consider material size effect and has a material length scale parameter in its formulation.

One of the first higher order continuum models is strain gradient theory that was proposed by Mindlin and Eshle [19]. This theory considers five additional constants that were micro scaled size dependency factors. Lam et al. modified proposed theory [15]. The new theory contained only three length scale parameters. Afterwards the strain gradient theory was applied to many mechanical models.

Another higher order elasticity theory which is a strong approach to analyze models at micro and nano-scales is a couple stress theory which was first proposed and amended by Toupin [20], Mindlin et al. [21] and Koiter [22]. The presented theory consist of two non-classical length scale parameters in addition to Lamé moduli. Yang et al. modified the proposed theory in a structure that contained just one length scale constant. The proposed theory of Young et al. has been named modified couple stress theory [23]. The modified couple stress theory as an applicable theory which considers size effect at micro-scales has been adopted by many researchers that wish to study behavior of material at micro-scales. Miandoab et al. studied modeled polysilicon nanobeam applying both Eringen's nonlocal theory and modified couple stress theory, and compared with experimental results done by other researchers, their results demonstrated that the modified couple stress theory coincides experimental results better than Eringen's nonlocal theory [24]. Sahmani and Ansari investigated the size-dependent buckling analysis of functionally graded third-order shear deformable microbeams including thermal environment effect [25]. Akgöz and Civalek presented a new trigonometric beam model for buckling of strain gradient microbeams [26]. Also, Akgöz and Civalek studied on shear deformation beam models for functionally graded microbeams with new shear correction factors [27]. Also, in other study, they investigated thermo-mechanical buckling behavior of functionally graded microbeams embedded in elastic medium [28]. Size-dependent dynamic pull-in instability of vibrating electrically actuated microbeams based on the strain gradient elasticity theory was investigated by Sedighi [29]. Mohammadabadi et al. studied on size-dependent thermal buckling analysis of micro composite laminated beams using modified couple stress theory [30]. Park and Gao utilized modified couple stress theory to analyze transverse vibration of a Bernoulli–Euler beam model, which could predict size effect at micron scales observed in bending test [31]. Asghari et al. presented and developed a formulation to capture size dependent effects on free vibration of Timoshenko beam model utilizing modified couple stress theory for two cantilever and simply supported boundary conditions and showed that investigating nanobeams vibrational behavior based on modified couple stress theory causes more stiffness than classical theories [32] . In another study, Kong et al. investigated vibration analysis of microbeams based on couple stress theory and represented that obtained natural frequencies are greater that classic ones [33]. Ke et al. studied the temperature change, material length scale parameter, slenderness ratio effects and different boundary conditions based on modified couple stress theory [34]. Moreover Şimşek analyzed microbeam based on modified couple stress with the framework of Bernoulli–Euler beam model [35]. Ke et al. presented a formulation based on couple stress theory utilizing Timoshenko beam model and considering von Kármán's nonlinearity to investigate effects of length scale parameter, power function's index of material distribution and slenderness ratio on vibrational behavior of functionally graded nanobeam and found that when nanobeam's